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# Overview of the dual foundation system of the Dubai Creek Tower

## Aperçu du double système de fondations de la Dubai Creek Tower

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**ABSTRACT:** This paper presents the main aspects of the dual foundation system of the Dubai Creek Tower. The cable-stayed tower, currently under construction, will complement Dubai's Burj Khalifa in taking us to new heights, and its novel structural and architectural features required the adoption of innovative foundation solutions. The tower's foundations comprise two different systems, each addressing specific requirements: on one hand, those of the very slender vertical stem; on the other, those of the post-stressed cable stays stabilizing it. The foundations of the stem, which resists very high compression, consist of deep, tightly packed rectangular barrettes. For their part, the cable array foundations are subjected mainly to shear with significant cyclic component, leading to the implementation of very wide, shallow barrettes. The paper details the development of the design and the challenges of construction. The general geotechnical context, Dubai's weak rock rheology and the experience feedback from previous projects are addressed. Various types of 3D numerical modelling are covered, focusing on aspects of soil-structure interaction, group effect and behaviour under cyclic loading. The load tests used for validation of the design, including record-breaking vertical Osterberg load tests and world-first horizontal Osterberg barrette tests, are briefly described. Finally, the progress of the construction works is presented.

**RÉSUMÉ:** Cet article présente les aspects principaux du double système de fondation de la Dubai Creek Tower. Cette tour haubanée, actuellement en construction, complémentera la tour Burj Khalifa en nous amenant vers de nouveaux horizons, et ses caractéristiques structurelles et architectoniques ont nécessité l'adoption de solutions de fondation novatrices. Les fondations de la tour comprennent deux systèmes différents, répondant à des besoins spécifiques : ceux du pylône central, très élancé ; et ceux des ancrages des câbles post-contraints qui le stabilisent. Les fondations du pylône, soumises à des compressions très élevées, sont constituées par un réseau dense de barrettes profondes. Les fondations des ancrages des câbles sont essentiellement soumises à des forces horizontales, avec composante cyclique significative, ce qui a amené à l'adoption de barrettes de très grande inertie et profondeur réduite. L'article décrit le développement des études et les défis de la construction. Le contexte géotechnique, la rhéologie du rocher de Dubai et le retour d'expérience de projets précédents sont abordés. Différents types de modélisation 3D sont traités, en se concentrant sur les aspects d'interaction sol-structure, d'effets de groupe et de comportement sous actions cycliques. Les essais de chargement utilisés pour validation du concept, incluant un record mondial de charge verticale par cellule Osterberg, ainsi qu'une première mondiale pour un test Osterberg de barrettes sous charge horizontale, sont brièvement décrits. Finalement, l'avancement de la construction est présenté.

**Keywords:** Barrettes, Deep Foundations, Ultra High Rise Buildings, Dubai, Load testing.

# 1 INTRODUCTION

The Dubai Creek Tower is an Ultra High Rise Structure currently under construction. It was conceived primarily as an observation tower and it will be at the centre of a new development by Emaar, the Dubai Creek Harbour, located immediately by the Creek and the Ras Al Khor Wildlife Sanctuary. When complete, it will join the Burj Khalifa, also an Emaar development, as a landmark of Dubai; setting it apart will be its extremely high slenderness and it being cable-stayed. Soletanche Bachy was in charge of the design, testing and construction of the foundations, with Aurecon working with Calatrava International (the lead architects and engineers on the Dubai Creek Tower project) being responsible for the integrated tower design, design coordination and construction supervision. The specificities and challenges of the tower's foundation design and construction will be presented in the following sections.

# 2 GEOTECHNICAL CONTEXT

Dubai geology was mostly formed by the deposition of marine sediments associated with sea level changes during the Quaternary and Pleistocene periods, with young rocks classified as sandstone, calcarenite and calcisiltite being commonly found. A comprehensive summary of Dubai's geotechnical conditions can be found in Poulos (2009). At the site (with a surface exceeding 20ha), an extensive geotechnical investigation comprising 68 boreholes of various depths and various in situ and laboratory tests was specified by Aurecon and implemented by Fugro Middle East. In broad terms (see Table 1), the stratigraphy comprises a superficial layer of sand, followed by a thin layer of sandstone and alternate layers of calcisiltite, conglomerate and conglomeratic calcisiltite. At approximately 110m, materials become finer grained, with successive layers of siltstone, claystone and mudstone. As is frequently the case in Dubai, water sits close to the surface level (approximately 0.0mDMD).

*Table 1. General stratigraphy and selected parameters (Best Estimate values)*

| **Stratum** [-] | **Top level** [mDMD] | **UCS** [MPa] | **$E_0$** [GPa] |
|---|---|---|---|
| // Sand // | +2.5 | - | <1 |
| // Sandstone / / Calcisiltite / / Conglomerate // | -12.0 | 3.5 | 6.0 |
| // Siltstone / / Claystone / / Mudstone // | -109.0 | 3.5 | 4.5 |

Although an extensive number of in situ and laboratory tests were implemented on the upper sand layer, most of the boreholes focused on the properties of the weak rock up to 200m in depth. Among the in situ testing were implemented high pressure pressuremeter tests and cross-hole sonic tests; among the laboratory testing both static and cyclic triaxial tests and CNS (constant normal stiffness) test of grout-rock interfaces were implemented, along with UCS and point load tests. These are very weak rocks, with UCS typically below 5MPa and unit weight around 21kN/m$^3$.

# 3 STRUCTURAL CONCEPT

Designed by the world-renowned architect and engineer Santiago Calatrava and based on Emaar's experience with super structures (the

Burj Khalifa is still the world’s tallest building) the tower is not destined to housing or office space. Instead, it will be an observation tower with panoramic views over the Dubai Creek Harbour, the Creek and the Wildlife Sanctuary.

*Figure 1. Illustration of the Dubai Creek Tower*

Structurally, the tower will comprise a hollow reinforced concrete cylinder with an external diameter of 25m (the “stem”), overmounted by the panoramic terrace and the spire. The stem will be at least 700m in height, leading to a very slender structure. Such a svelte structure cannot be free-standing; therefore, two arrays of post-tensioned cables are used to stabilize the tower horizontally. The foundation system of the tower is represented in Figure 2. In the centre, the foundation of the stem (the “core”); to the left and right of centre, the foundation of the cable array structures.

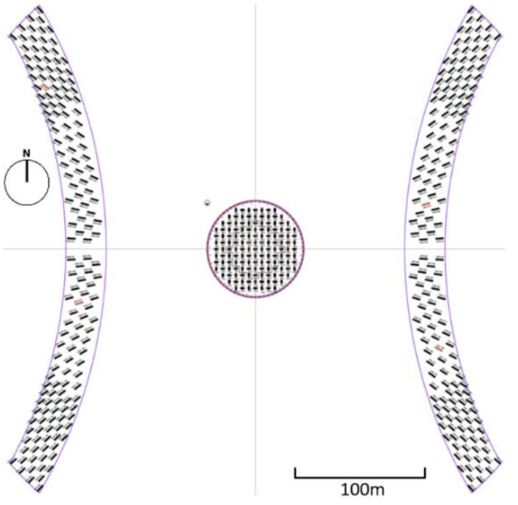


*Figure 2. Layout of the barrette foundation system*

The design of the structure and its foundations is performed according to the Eurocode suite of structural standards (UK national annexes), with inputs adapted to Dubai’s specific requirements, for example concerning earthquake and wind action.

# 4 CORE FOUNDATION

## *4.1 Foundation system*

The foundation of the core consists of 145 barrettes 2.8m*1.5m in size, excavated with Hydrofraise rigs to -72mDMD for 58m long barrettes, and arranged into a dense grid of 5m*5m (requiring stringent verticality control). A massive, wedding cake-shaped cast in situ pile cap up to 20m in height transfers the loads from the stem to barrettes; in order to allow the construction of the pile cap, a 72.5m diameter circular diaphragm wall shaft was used as temporary shoring. Barrette cut-off level is at -14mDMD.

Because the tower is stabilized by the cable arrays, the loads acting on the stem are essentially vertical; as such, moment at the tower base is very small and load eccentricity is virtually non-existent. The total load acting on the barrettes exceeds 9000MN, with most being dead load, and less than 1% of it being due to surcharge loads. These loads induce very high stresses in the barrettes (up to 25MPa in serviceability conditions) requiring the use of C70/85 concrete which, in conjunction with the aggressive nature of Dubai's ground and the durability criteria, posed challenging conditions for concreting.

## *4.2 Soil-structure interaction*

The dense arrangement of the barrettes made it essential to assess the impact of group effects on capacity and, above all, on the stiffness of individual barrettes. In order to capture soil-structure interaction in the most efficient way, the models integrated the complete foundation system, including both barrettes and pile cap.

Rock mass strength was defined according to two different approaches: in one approach, it was modelled as a Tresca material, with shear strength representing the bond yield strength of the rock (Haberfield, 2008), defined in this case as UCS/2. In the other, the rock mass was defined as a Mohr-Coulomb material with cohesion and friction angle derived from the Hoek - Brown failure criterion, modified for the case of weak rocks as per Carter et al. (2008). The results were not significantly different in both cases.

A variety of load cases were investigated to ensure soundness of process and to establish the most likely design scenarios. Furthermore, all calculations were performed for a short term (high stiffness) hypothesis for concrete modulus, and for a long term (low stiffness, cracked) hypothesis. Best estimate stiffness for gravity loadings was assumed as $E_{gravity}=0.2E_0$, derived from generic degradation curves for weak sandstone (Thompson and Leach, 1985) and actual estimated strain levels (additional details can be found in Pereira et al., 2017). During serviceability conditions the design tested limits for concrete loading, rock bond strength, and mobilised skin friction not exceeding ultimate skin friction at any time. For ultimate limit state the analysis verified concrete strength, as well as a block failure and global failure mechanism of the foundation.

Several numerical models were implemented by both Soletanche Bachy and Aurecon. After initial assessment based on axisymmetric models, in which the barrette grid was transformed into a series of concentric rings with equivalent properties, the analysis was pursued with full 3D models, implemented with the PLAXIS 3D code. Soletanche Bachy's FEM analysis explicitly modelled the barrettes as volumetric elements, with interface elements between the barrette and the soil. Furthermore, dummy beams were added at the centroid of each barrette element, to facilitate result extraction. Taking into account the symmetry of both the foundation and loads, only half of the geometry was modelled (see Figure 3) in order to optimize computational efforts.

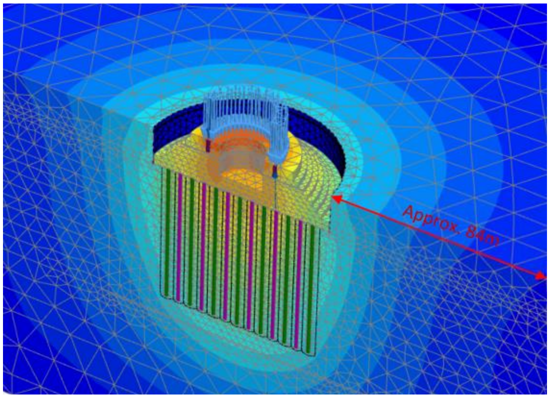


*Figure 3. SB FEM mesh (volumetric elements) of the core superposed with settlement contours*

Taking an alternative approach, Aurecon modelled the complete foundation, modelling the barrettes and their interaction with the ground with embedded beam elements (accounting for directional properties of the barrettes). As in the case of the fully volumetric models, a gap was allowed below the pile cap to ensure that 100% of the load was transferred to the barrettes.

An example of settlement output is shown below (Figure 4). In general, the results of the separate approaches showed adequate agreement.

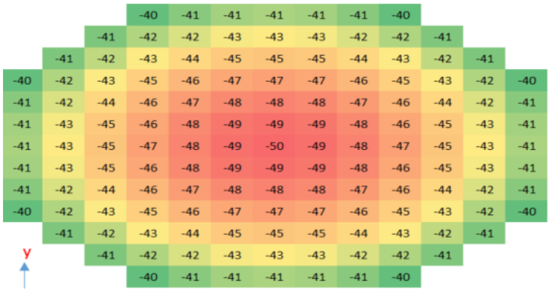


*Figure 4. Settlement results for Best Estimate – short term settlements (SB model)*

Single barrette vertical stiffness (derived from a specific FEM model and showing good agreement with the results of the Osterberg load tests measured in the field) is approximately 7GN/m, while best-estimate short term stiffness for barrettes in the pile cap varies between 1GN/m and 1.9GN/m depending on the position of the barrettes in the layout. This compares well with results found in similar projects (Pereira et al., 2017) but remains subject to confirmation with the analysis of real foundation settlements.

### 4.3 *Load testing*

In order to validate the assumptions, load tests were implemented by Fugro Loadtest on three preliminary barrettes. Considering the length of the barrettes (between 54m and 91m) and the corresponding capacities, the only practical option was the use of Osterberg cells. In the case of the longest barrette, a world record test load of 363MN was attained. Ultimate skin friction was reached only on limited segments of the barrettes, at values close to 600kPa. This value was considered in the design of the barrettes, as it exceeded the preliminary estimates. Using a relation for ultimate skin friction of the type:

$$q_s = a \cdot UCS^{0.5} \text{ [MPa]} \quad (1)$$

one obtains a≈0.32. This is somewhat larger than a=0.25 (Horvath and Kenney, 1980), a hypothesis frequently used in Dubai for preliminary estimates (Alrifai, 2007; Pereira, 2017). Final barrette depth was established at 75m below surface level, a significant optimisation from the 100m initially envisaged.

## 5 CABLE ARRAY FOUNDATIONS

### 5.1 *Foundation system*

The structural role of the cable array foundations is to anchor the vast number of post-tensioning cables, and therefore to resist the shear and tensile components of the corresponding forces. In order to eliminate tension loads on barrettes during service conditions, the CAF structure is ballasted. As such, the barrettes will mostly work in shear, with forces up to 11MN per barrette in Ultimate Limit State. After several iterations of the design, both in terms of foundation solutions and layout, the adopted solution consisted of 328 high stiffness barrettes, 1.2m wide and 6.2m long. The layout of the barrettes is radial, with all the barrettes pointing towards the core (see Figure 2.). This arrangement aligns the barrettes with the cable arrays, in order to maximize the stiffness and to minimise forces on the weak axis. The barrettes are heavily reinforced and possess a single reinforcement cage (fully monolithical), a demanding aspect in terms of cage construction and installation. Barrettes reach a depth of -23mDMD, substantially shallower than the core barrettes.

### 5.2 *Soil-structure interaction*

Although the barrettes are very stiff in in-plane bending (on the main axis, the moment of inertia is approximately 24m$^4$, equivalent to that of a pile 4.7 m in diameter), the CAF structure is stiffer still, and provides significant moment fixity on the barrette head. Due to the relatively close distance between barrettes, a degree of group effect was to be expected; moreover, a significant part of the loads is cyclic in nature, further complexifying the behaviour. In the analysis of soil-structure interaction, the soil is usually modelled either as non-linear springs (p-y and t-z methods) or as a continuum (volumetric or plane finite elements); due to the complexity of the project, both methods were systematically implemented. With the CAF superstructure's analysis ongoing, Soletanche Bachy's models focused on the sole foundation elements (i.e. not including the superstructure of the cable array), based on reference load cases provided by Aurecon; in parallel, Aurecon continued to develop and ensure the coherence of the results by developing fully integrated models.

### *5.2.1 FEM Modelling*

Different types of FEM models were implemented. As in the case of the core, the rock was modelled both as a Tresca material and as a Mohr-Coulomb material; due to the small overburden of the CAF barrettes, the Mohr-Coulomb criterion was more unfavourable and governed the design. Soletanche Bachy's analysis started by assessing the behaviour of the most heavily loaded area, comprising 39 barrettes at the corner of each quadrant (see Figure 5). This detailed approach used volumetric elements for the barrettes, with interface elements modelling skin friction between the barrettes and the ground.

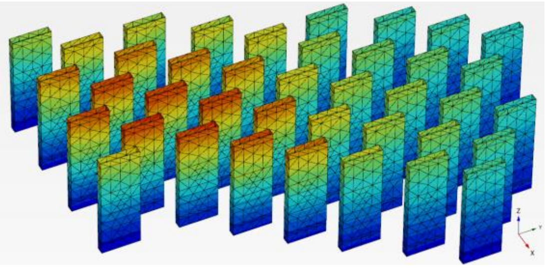

*Figure 5. SB FEM mesh of max load area (volumetric elements), superposed with displacement contours*

In order to assess group effects in the CAF, a FEM model of half a crescent was then developed, comprising 82 barrettes modelled as plate elements, once again equipped with interfaces (see Figure 6.). These models showed that group effects on stiffness inside the CAF were substantial: depending, among others, on the distance between barrettes and on the direction of loading, horizontal stiffness varied between 30% and 100% of the stiffness of an isolated barrette.

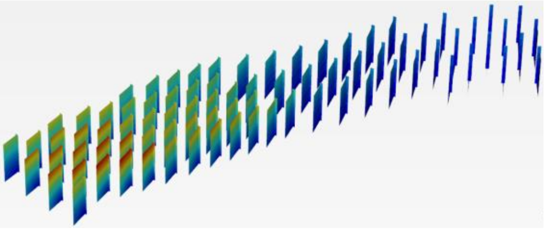

*Figure 6. SB FEM mesh of a half crescent (plate elements), superposed with displacement contours*

Aurecon modelled one complete crescent shape foundation of the CAF foundation in its entirety (164 barrettes). This model aimed to account for the complex superstructure geometry of the crescent box structure to ensure more accurate interpretation of loads transferred to the foundation. Similar to the core foundation, specific serviceability and ultimate limit states were tested to ensure compliance of design. These limits are the same as for the core foundation, with the exception of the global mechanism tested to verify global safety.

At the time of design, it was contemplated that construction of the cable array structure might need to be sequential. This means that some cables are stressed before the entire cable array structure is complete. The Aurecon model (Figure 7) captured the likely effects and minimum foundation lengths to have been installed to ensure safe construction and support of the stem.

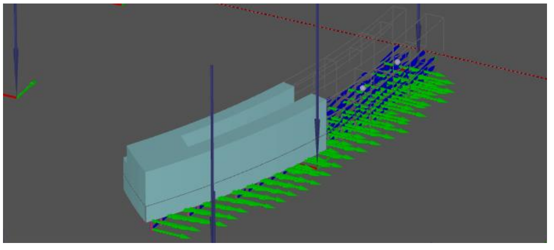

*Figure 7. Aurecon FEM: construction staging of CAF box structure and barrette*

Due to the sheer size of the foundations, Aurecon continued to analyze the full soil-structure interaction, modelling the cable box structure and loads, as well as the foundations (as shown in Figure 8). This was a required progression to link the otherwise decoupled models of the core and the CAF.

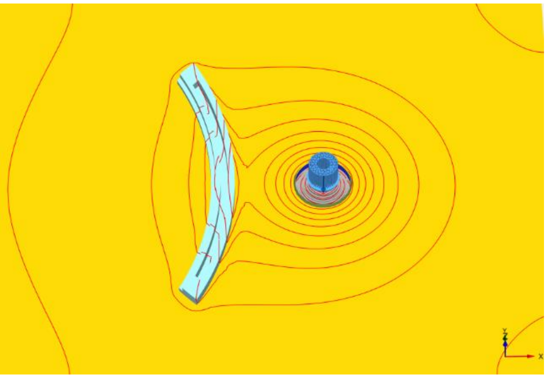

*Figure 8. Displacement contours illustrating interaction of CAF and core in combined FEM model*

From the results of this study it was concluded that there is some interaction between the Tower Core and CAF foundations. Although the interaction undoubtedly changes the anticipated movements and loads in the barrettes, the effects have been found to remain within design limitations. The actual construction sequence being very influential in the real interaction effects, it may be a worthwhile endeavour to study the actual consequence with the predictions made in the design as construction unfolds.

### *5.2.2 P-y curve modelling*

P-y curves were used as an additional check to the FEM analysis already described. To the authors' knowledge, the only p-y curves specifically developed for barrettes are those proposed by Appendix C5 of the French code NF P 94-262. These curves take into account both the frontal reaction and the lateral skin friction of the foundation element and also consider, albeit in a simplified way, group effects between adjacent barrettes. The stiffness of isolated barrettes estimated with the p-y curves is always higher than that obtained from FEM results (typically between 10% and 70% stiffer). According to the p-y formulation, group effects on stiffness were negligible, a conclusion that is not in agreement with the FEM results already discussed.

## *5.3 Cyclic behaviour*

With the barrette's cut-off level at -6.0mDMD, the barrettes would, in normal conditions, derive a large part of their passive resistance from the carbonated sand layer present up to -12mDMD. However, doubts regarding the long term cyclic behaviour of these materials persisted, and a reliance on these weak and heterogeneous soils for external stability of the foundation did not seem acceptable.

Amongst the methods used to approximate the cyclic behaviour of the foundation under lateral loads, the provisions of the new SOLCYP recommendation (Puech and Garnier, 2017) were implemented, based on conservative estimates of cyclic load patterns. In particular, the SOLCYP-L local method was used, in which the contribution of uppermost materials is reduced for the horizontal behaviour of the barrettes. In the case of the CAF, this equated to neglecting the contribution of the carbonate sand, and also on reducing the strength and stiffness of the underlying rock mass.

The final depth of the barrettes was governed by long term horizontal stability. The conservatism of this approach was illustrated in the cyclic horizontal load tests conducted on full scale barrettes.

## *5.4 Load testing*

Load testing should aim to model as closely as possible the real load conditions of the structure. In the case of the CAF barrettes, the objective was to test the barrettes and their interaction with the ground as close as possible to the levels at which the loads would be applied by the superstructure (i.e. the cut-off level at -6.0mDMD).

In order to allow this, a novel system was devised in which an O-cell was installed between two barrettes at level -6.0mDMD, pushing the two barrettes apart. The tests were cyclic in nature, with several load-unload sequences in order to approximate long term behaviour.

The results, both monotonic and cyclic, are more favourable than expected, in particular regarding horizontal response, which is much stiffer than predicted by both FEM and p-y curves. Although more detailed analyses are ongoing, it seems that ground stiffness (and, to a smaller extent, concrete stiffness) is substantially larger than predicted and approaching values coherent with the small-strain domain of behaviour.

## 6 CONCLUSIONS

At the time of writing, the construction is ongoing, with the massive pile cap being fully completed. More work is now needed to monitor the behaviour of the foundation as the tower is being constructed. As the podium structure between the crescents and the core is designed and implemented, the complex foundation system between the core, the podium and the CAF crescents make for a challenging interaction model. The level of analyses conducted in this project is deemed to be at the cutting edge of what is being done in the world today and is entirely appropriate for a project of this nature.

## 7 ACKNOWLEDGEMENTS

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