Site Investiagtion for Kingdom Tower

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Abstract— **This paper describes the site investigation campaign carried out for the Kingdom Tower in Jeddah, Kingdom of Saudi Arabia. The height of the tower is expected to exceed 1,000m, which will make it the tallest building in the world. The site investigation was carried out in three phases and included 81 boreholes in which the deepest borehole was drilled down to 200m. Extensive field tests were carried out including permeability packer, high-pressure dilatometer, and PS suspension down-hole geophysics. The laboratory tests ranged from routine index and classification tests to more complex tests like instrumented unconfined compression and advanced consolidated drained triaxial tests. The site-specific ground conditions will be addressed and discussions on field and laboratory tests results will be made, in particular variations of results with depth and comparisons between field and laboratory test results.**

Keywords; Kingdom Tower; elastic modulus; in-situ tests; laboratory tests; site investgation; tall buildings

I. Introduction

The Kingdom Tower site is located in the coastal city of Jeddah near both the Red Sea and the mouth of the Obhur Creek where it widens as it meets the Red Sea. The proposed mixed-use development project consists of an ultra-tall tower of over 1000m above grade (around 167 floors), surrounded by a podium structure consisting of 4 levels of basements for parking, services, etc. If completed as planned, the tower will reach unprecedented heights, becoming the tallest building in the world, as well as the first structure to reach or exceed the one-kilometer-high mark (the final exact height is kept private while in development). The tower was initially planned to be 1.6 kilometers (1 mile) high, however, it was then scaled down mainly due to the geology of the area as well as other operational factors. Fig. 1 shows an impression of Kingdom Tower when complete.

The project developer is Jeddah Economic Company (main partner includes Kingdom Holding). The architect is Adrian Smith + Gordon Gill Architecture (Architect of Record is Dar Al-Handasa Shair & Partners). The structural engineer is Thornton Tomasetti and the civil/geotechnical engineer in Langan International. The main contractor is Saudi Bin Laden Group.

This paper describes the comprehensive and integrated geotechnical investigation works carried out by Arab Center for Engineering Studies (ACES) for the Kingdom Tower (client at the time of investigation was Emaar Properties PJSC). The site investigation was carried out in 3 phases and comprised 81 boreholes ranging in depth from 20-200m. The field tests comprised standard penetration tests (SPTs), permeability, pressuremeter and seismic geophysical methods including PS suspension down-hole techniques. A comprehensive laboratory testing program was carried out to determine the ground material characteristics. Some geological and geotechnical characteristics will be discussed. Comparisons between field and laboratory test results will be presented.

Figure 1. Impression of Kingdom Tower when Complete

II. Tall Buildings-Geotechnical Challanges

There has been a remarkable increase in the rate of construction of tall buildings in excess of 150m in height in the past two decades. The total number of “super-tall” buildings (over 300m) was 15 in 1995 and expected to reach 116 in 2015, whereas the total number of “mega-tall” buildings (over 600m) was nil in 1995 and expected to reach 5 in 2015 [1]. Fig.2 shows a comparison in height between the Kingdom Tower and other well-known tall buildings. A significant number of these tall buildings have been constructed in the Middle East. Dubai has now the tallest building in the world, Burj Khalifa, which is about 828m high. It should be noted that ACES was also involved in the site investigation campaign for Burj Khalifa.

Figure 2. The Kingdom Tower versus other Well-Known Buildings

Super-tall buildings are presenting new challenges to engineers, particularly in relation to structural and geotechnical design. Many of the traditional design methods cannot be applied with any confidence since they require extrapolation well beyond the realms of prior experience, and accordingly, structural and geotechnical designers are being forced to utilize more sophisticated methods of analysis and design. In particular, geotechnical engineers involved in the design of foundations for super-tall buildings are leaving behind empirical methods and employing state-of-the art methods increasingly [2]. All this necessitates rigorous process of foundation design, which starts from a thorough desk study and comprehensive site investigation (including elaborate in-situ and laboratory testing programs) to the formulation of a geotechnical model and detailed foundation analysis and design. In-situ foundation testing and monitoring of performance are also important with such tall buildings.

Some of the characteristics of tall buildings that can have a significant influence on foundation design include the building weight (substantial vertical load), differential settlement (as high-rise buildings are often surrounded by low-rise podium structures), lateral forces and moments imposed by wind loading as well as cyclic and dynamic loading. The nature of soil and rock deposits in the Middle East gives rise to additional potential problems, including generally weak to very weak founding conditions, a greater tendency for cyclic degradation, the possibilities of cavities within some of the deposits, and the absence of hard rock layers on which end bearing piles can be founded. Because of these difficulties, piled raft systems, with their high level of redundancy, have proved to be an effective and relatively economical foundation solution [2].

As for the Kingdom Tower, the structure for the tower will use predominantly reinforced concrete elements with the inclusion of structural steel elements for the spire portion of the tower. The podium and tower level structures will utilize reinforced concrete construction. The foundations system for the tower will include a reinforced concrete mat supported by high capacity large diameter, deep reinforced concrete piles/barrettes (foundation system similar to Burj Khalifa, but larger). Special considerations will be required for the control of ground water conditions and most importantly the protection of all reinforced elements against the corrosion potential of existing ground water and subsurface soils.

III. GOTECHNICAL INVESTIGATION AND TESTING

The ground investigation was undertaken by ACES and consisted of drilling 81 boreholes, field and laboratory testing (including specialist testing) on selected samples. The investigation was carried out in three phases as follows:

- *Phase 1*: 17 boreholes (1490 linear meters), in-situ SPT's, 16 packer tests, 95 pressuremeter tests (down to 150m depth), installation of 7 standpipe piezometers, 2 PS suspension down-hole tests (down to 179m depth), laboratory testing (including specialist laboratory testing) – 3rd May to 22nd June 2010.
- *Phase 2*: 34 boreholes (1780 linear meters), in-situ SPT's, 12 packer tests, 92 pressuremeter tests (down to 120m depth), installation of 6 standpipe piezometers, 1 PS suspension down-hole tests (down to 100m depth), laboratory testing (including specialist laboratory testing) – 15th June to 22nd July 2010.
- *Phase 3*: 30 boreholes (680 linear meters), in-situ SPT's, 12 packer tests, 45 pressuremeter tests (down to 30m depth), installation of 3 standpipe piezometers, laboratory testing – 24th August to 25th September 2010.

The drilling was carried out using cable percussion techniques with follow-on rotary drilling methods with water/mud circulation to depths between 20-200m below ground level. Disturbed, undisturbed and split-spoon samples were obtained from the boreholes for logging and laboratory testing. Continuous coring was carried out in rock and hard materials whereas SPT was conducted in soils. The 'undisturbed' core samples were obtained using conventional double tube (T2-76 series [core diameter ~ 62mm]; PWF series [core diameter ~ 92mm]) and wireline (HQ/HQ3 series [core diameter ~ 61-63mm]; PQ/PQ3 series [core diameter ~ 83-85mm]) core barrels.

Standard Penetration Tests (SPTs) were carried out at various depths in the boreholes and were generally carried out in the overburden soils and weak rock. In-situ permeability tests in rock were carried out at specified depths using double packer system. Pressuremeter testing, using an OYO Elastometer, was carried out down to depths ~ 150m below ground level. Down-hole suspension P-S seismic tests were carried out down to 180m below ground level to acquire compression (P) and shear (S) wave velocities through the ground profile.

The laboratory testing included the following standard and specialist tests:

- Standard classification and index tests, including moisture content, Atterberg limits, particle size distribution, specific gravity, bulk density, unconfined compressive strength (including instrumented tests), point load index, and chemical test.
- Sophisticated tests, including consolidated drained triaxial (with volume change measurements) and repetitive cyclic tests. These tests were carried out in approved specialist testing laboratory in the United Kingdom.

IV. GEOLOGY AND SITE CONDITIONS

The project area is located in the southern part of the Hijaz geographic province, close to the rifted western margin of the Arabian Shield at the coastal area [3]. The coastal area of Saudi Arabia has been essentially a broad structural terrace, associated with the rifting event that led to the development of the Red Sea during the Tertiary period. Consequently, marine sediments were deposited during the intermittent submergence of the area throughout that period [4]. In the Quaternary period, Pleistocene to Holocene reef grew along the seaward edge of the coastal plain and was partly raised during the second stage of Red Sea uplift movement [5]. Alluvial, eluvial, and eolian sands and gravels of variable thicknesses were deposited in Holocene times, which included at least two periods of increased run-off. Tectonically, the Arabia Sheild has not been stable since its formation in the Precambrian due to the plate movement. The project site is considered to be located within a seismically active area.

The subsurface conditions based on the site investigation for the Kingdom Tower have shown a horizontally stratified profile of marine sediments which are complex and highly variable (see Fig. 3). The deep drilling for the proposed project has revealed an approximately 50m thick Quaternary Coral Reef formation under ~1.7m thick fossiliferous silty sand, soil cover. The Coral Reef is underlain by a 70m thick succession of mid to late Tertiary deposits consisting primarily of poorly consolidated Conglomerate/Gravel beds interbeded with poorly consolidated/lithified, calcareous Sandstone/Sand deposits down to a depth of 120m. This layer is underlain by early Tertiary sediments composed of gritty calcareous Sandstone to a depth of 200m (end of boring).

The main stratigraphic units are described briefly below, and a generalized columnar section is illustrated in Fig. 4. The project site is totally covered by soil deposits composed of light brown, medium to fine fossiliferous silty sand with many fragments of broken shells, corals. The fossiliferous sand is rich in gastropods and is a mixture of wind-blown sand, beach sand, and back-reef lagoonal fauna. The Coral Reefs are generally very weak to weak, light brown to buff white, unweathered to partly weathered. The Coral is intermittently fractured, porous and vuggy (cavernous), with occasional solution channels. Destructured weathered zones of decomposed Coral are seen at various depths in the form of pockets. Partial to complete water loss was encountered during drilling indicating the fracture and porous nature of the formation.

The mid to late Tertiary sediments encountered under the Coral Reef are composed of variable Conglomerate/Gravel interlayers ranging in thickness between 4.0m to 13m alternated with poorly consolidated (poorly lithified) Sandstones/Sand layers with approximate thicknesses ranging from 13m to 44m. The Conglomerate/Gravel interlayers (G1, G2 & G3) are composed of subrounded to subangular gravels of basic rocks, coral and sandstone/quartizite within sandy matrix. Local inter-layers of Siltstone and Sand/Sandstone were encountered at various depths within these layers. The core recoveries of the Conglomerate beds indicate highly weathered nature.

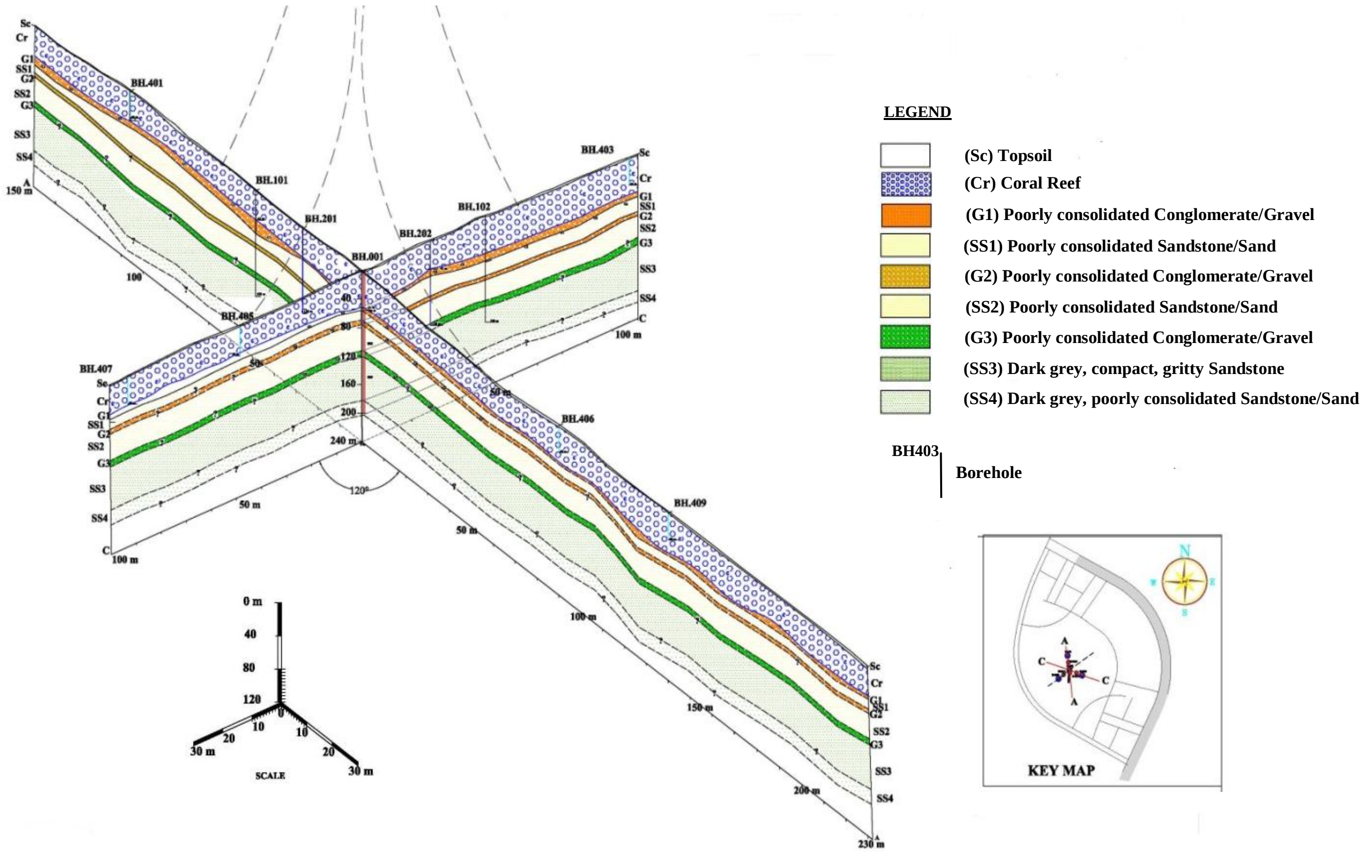

Figure 3. Generalized Subsurface Profile

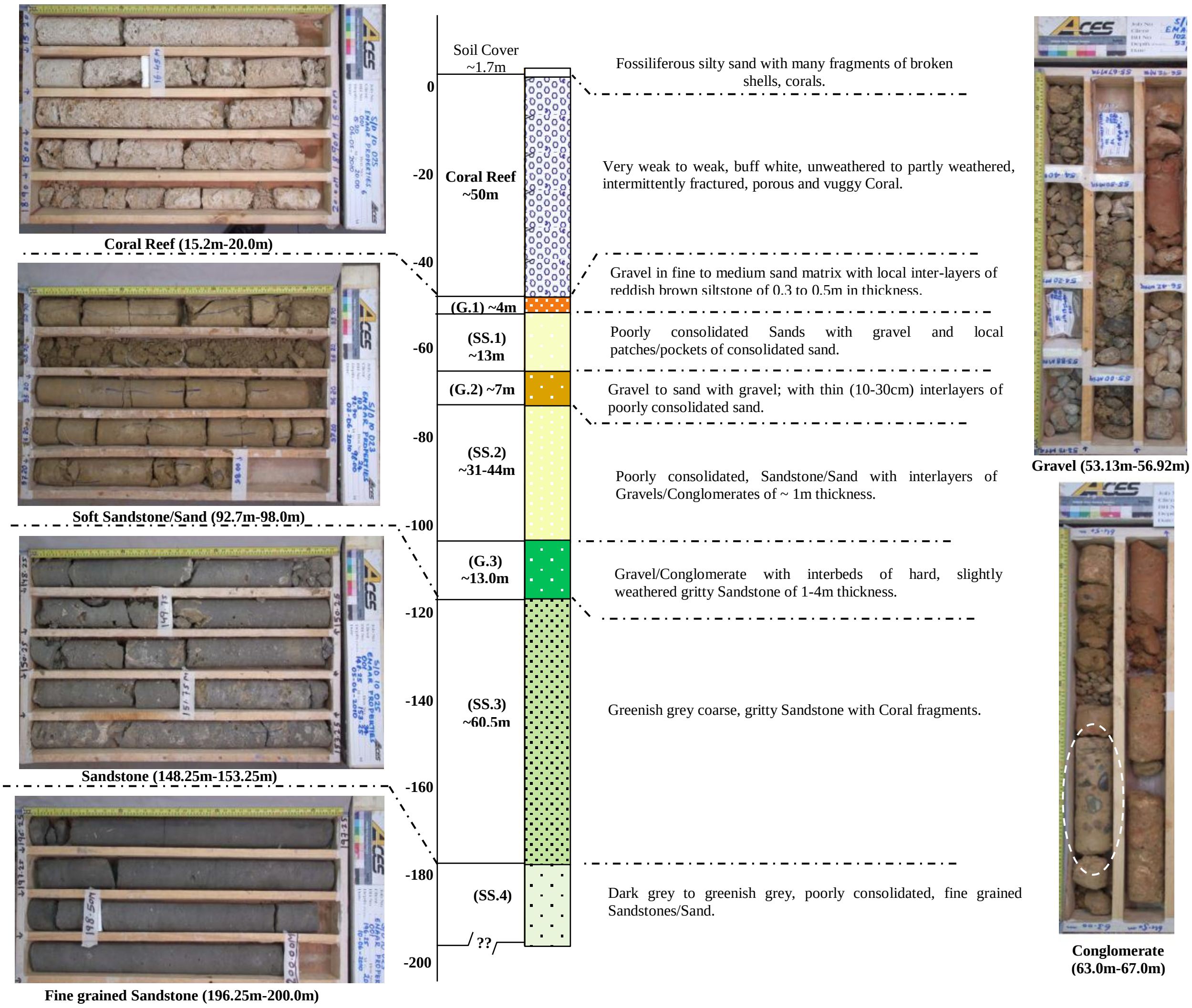

Figure 4. Generalized Columnar Section for Subsurface Stratigraphy

The poorly consolidated Sandstone/Sand layers (SS.1 & SS.2) encountered between the Conglomerate/Gravel beds are composed of reddish-grayish brown, fine to medium grained, poorly consolidated (poor lithification), calcareous Sand/Sandstones with gravels of basic rocks and coral. Intermittent core recoveries indicate local patches/pockets of consolidated/lithified sands (especially in SS.1 layer). Interlayers of Gravels/Conglomerates of about 1m thickness were observed at different depths in the SS.2 layer.

The late Tertiary Sandstone encountered under the poorly consolidated sediments are composed of grayish to greenish gray, compact, medium to coarse, gritty, calcareous Sandstone with many voids and solution cavities/channels (SS.3 ~ 60.5m thickness). The embedment of coral fragments was observed profusely between approximate depth of 153-169m and 176-181m in the deep borehole. A free fall of drilling rod in this layer was encountered at approximate depth of 172.9-173.3m indicating the possibility of cavities in the rock mass. The coarse gritty calcareous Sandstone (SS.3) grades to fine grained poorly consolidated dark grey to greenish grey sandstone (SS.4 ~ approximate depth 181-200m [end of borehole]). The SS.4 Sandstones are embedded profusely with fragments of broken shells and corals at 181m and 191m depths. In general, the sound rock line is estimated in the underlying gritty Sandstone layers at depth of 122m.

Groundwater table was encountered at approximate depths ranging from 3.6m to 5.26m in all drilled boreholes.

V. Field Testing Program

A. *Standard Penetration Tests (SPT)*

Standard Penetration Tests (SPT) were performed to assess the relative densities of the ground materials. The tests were carried out mostly in the upper 1.5m depth of the boreholes and at various depths thereafter particularly in the weak zones (where core recoveries were low) based on the encountered materials at the site (reached 140m below ground level). The tests were performed in accordance with ASTM D 1586-08a [6].

The SPT values ranged between 12 and 50 in the upper 1.5m, increasing to >50 at depths greater than 20m (some random 'low' values were encountered in the Coral material). The nature of the ground material at the project site is somewhat complex as poorly consolidated (unlithified) Sand was encountered at great depths. Although the SPT results indicate "dense" material, the test itself is considered unrepresentative/unreliable at such depths as the weight of the rods becomes significant and hence, the impact of the SPT hammer reduces.

B. Permeability Packer Tests

Double packer tests were performed at the project site at various depths ranging from 3 to 18.5m in the Coral materials for in-situ determination of formation permeability. The test was performed in accordance with BS 5930-1999 [7]. The test comprises the measurement of water volume that can escape from an uncased section (~1m) in borehole at a given time under a given pressure. The flow is confined between known depths by means of two packers to seal the test section from bottom and top. The test is carried out in 5 stages, being cycled up to a maximum head and then down again (1/3, 2/3, 1, 2/3, and 1/3 of the maximum pressure). The permeability value is determined from the slope of flow versus pressure graph.

In total, 40 packer tests were performed in the three investigation phases. A graphical presentation of the test results verses depth is shown in Fig. 5. The permeability values ranged from 1.23×10^{-5} to 8.38×10^{-5} m/s.

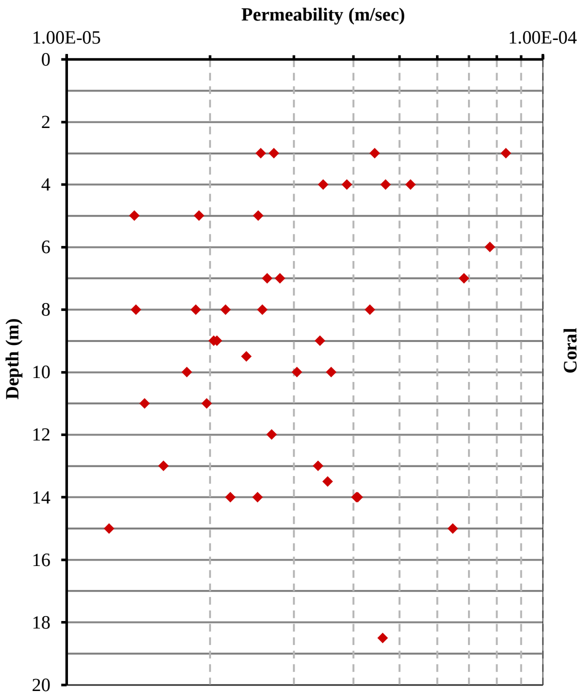

Figure 5. Permeability Packer Test Results

C. Pressuremeter Tests

Borehole expansion (High Pressure Dilatometer-HPD) tests were conducted in Coral and Sandstone/Sand at depths ranging between 3 and 149m below ground level in accordance with ASTM D 4719 [8]. The tests were conducted at 5m intervals down to 120m, and at 10m intervals thereafter until reaching 150m depth. Note that it was not possible to perform the test at areas where soil materials (sand or gravel) were encountered at relatively large depths due to the instability of the test pocket.

The tests were performed using OYO Elastmeter 2 HQ Sound (Model-4180), which has 0-20 MPa pressure range. The test probe has expandable length of 700mm and deflated diameter of 74mm whereas the test was performed in a borehole section with nominal diameter of 76mm (prepared using smaller core barrel - T2-76 series). The test pressure (applied in equal increments) was held for a minimum period of 60 seconds at each increment to allow for the deformation to stabilize. Loading was done using the high-pressure hand pump and the displacement for the pressure applied was recorded. Two unload/reload cycles were performed before reaching the maximum pressure (~7 MPa) after which the membrane was deflated (end of test). The internal displacement calipers and the rubber membrane were calibrated as per the manufacturer's instructions and relevant standards. The instrument was calibrated before each use for both pressure and volume losses.

The typical parameters generally obtained from conventional pressuremeter tests include modulus of deformation, coefficient of lateral earth pressure, yield and limit pressures, among others. The modulus can be determined from the initial loading, unloading and reloading portions of the stress-strain graphs. Figs. 6 and 7 show a graphical presentation of the calculated reloading and unloading moduli, respectively, from the various cycles performed during the test. The initial modulus is generally found to be significantly lower (about 5-10 times less) than the unload and reload modulus. On the other hand, the unload modulus is fairly higher than the reload modulus, as might be expected.

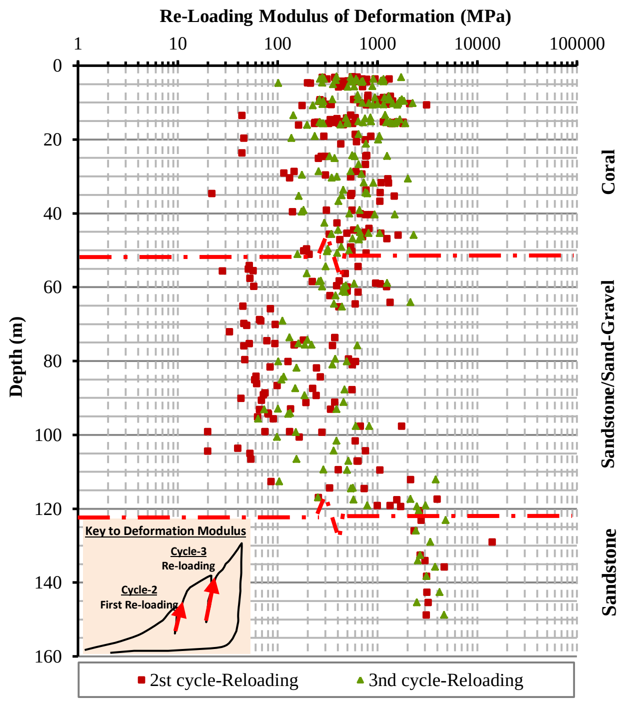

Figure 6. Reloading Moduli from Pressuremeter Tests

A total of 232 pressuremeter tests were performed during the site investigation campaign for the Kingdom Tower. The results presented in Figs. 6 and 7 show that there is scatter in data, especially in the Sand/Sandstone layer encountered between 52-122m depth due to the variability of the material. The modulus values are generally lower in this layer than the Coral above and Sandstone below. The Sandstone layer encountered below depth of 122m showed relatively higher modulus values than the other layers.

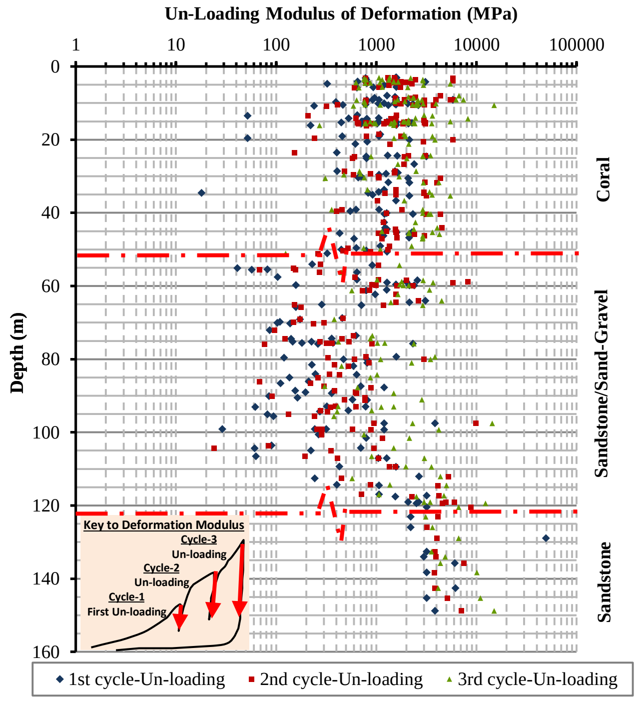

Figure 7. Unloading Moduli from Pressuremeter Tests

D. Down-Hole Geophysics

Down-hole suspension P-S velocity logging was carried out to acquire primary compressional (P) and secondary shear (S) wave velocities as function of depth which in turn can be used to derive dynamic elastic soil properties such as Young's modulus, shear modulus and Poisson's ratio. The test was performed in 3 boreholes down to approximate depths of 100-180m below ground level (logging performed every 1m interval). The single borehole probe encompasses the seismic source (generating P & S waves) and two receivers (three-component geophones) with spacing of 1m between the two receivers. This allows the travel time to be determined from waveforms detected at both sensors from the same hammer blow. The borehole was cased with PVC threaded pipes with one-way valve at the bottom end, and the annular space outside the PVC pipes was grouted with cement-bentonite grout with bottom-up grouting technique. The test was carried out in a borehole filled with water.

The shear modulus of the rock can be determined from the shear wave velocity using the following relationship

$$G = \rho V_s^2 \tag{1}$$

where ρ is the bulk density and V_s is the shear wave velocity. It should be noted that the density was assumed based on the laboratory results. From this, the elastic Young's modulus was determined using equation (2) and employing the Poisson's ratio (v) values estimated from P & S wave velocities using equation (3).

$$G = \frac{E}{2(1+v)} \tag{2}$$

$$v = \frac{(V_p/V_s)^2}{2\left\{(V_p/V_s)^2 - 1\right\}} \tag{3}$$

where Vp is the compressional wave velocity.

The results of the P-S logging measured using OYO Suspension System are provided in Fig. 8 (results for the two deep tests [BH-001 & BH-102] are only shown for illustration purposes).

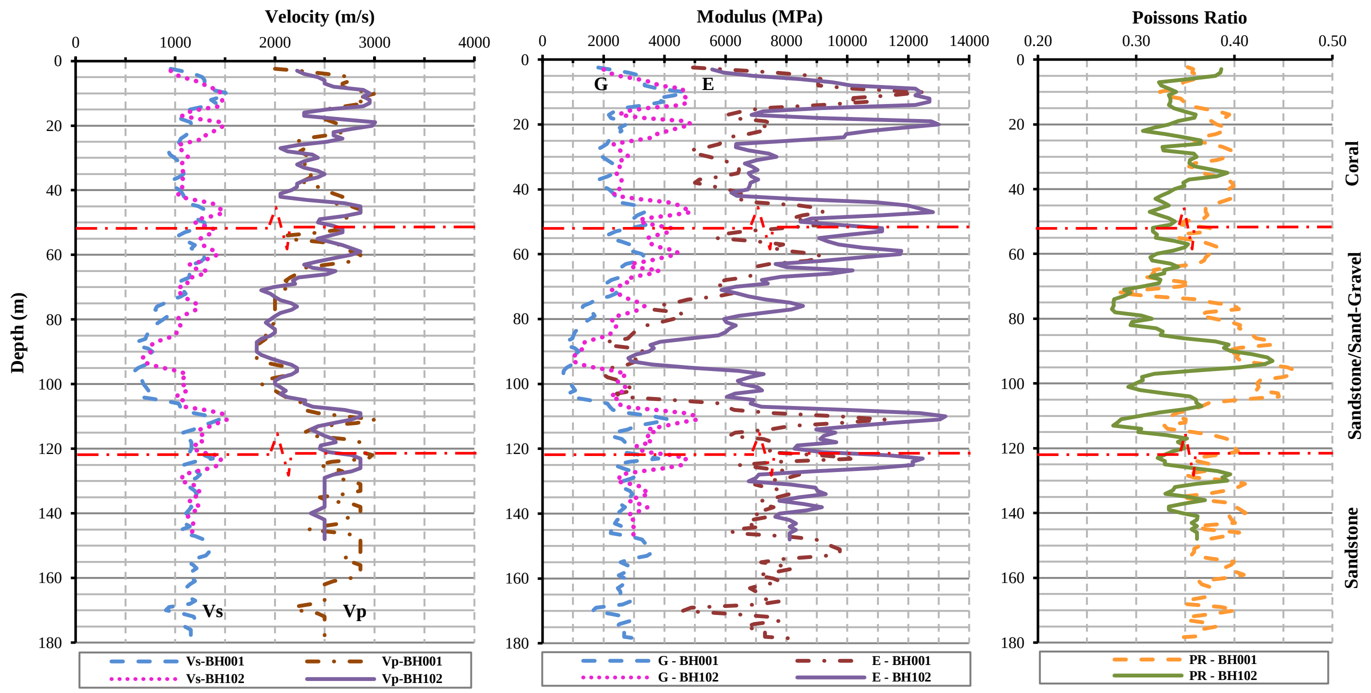

Figure 8. Results of Down-Hole PS Suspension

The figure shows graphs of P & S velocities, dynamic moduli (shear and Young), and Poisson's ratio versus depth. The variation of results was noticed to be based on the materials type and degree of weathering as well as presence of voids and/or fractures. The succession layer (Sandstone/Sand-Gravel) has showed the lowest shear velocity values especially at zones where silty sand-gravel interlayers and 'soft' destructed sandstone were encountered. The bottom Sandstone layer has showed relatively high velocity values and thus the highest modulus values.

VI. Laboratory Testing Program

A. *Uniaxial Compressive Strength (UCS) Tests*

Uniaxial Compression Strength (UCS) test was carried out on intact rock specimens retrieved from the drilled boreholes in accordance with ASTM D 7012 [9]. Fig. 9 shows the compressive strength results from uniaxial compression tests. The UCS values in the Sandstone/Sand-Gravel layer (52-122m depth) are scattered and somewhat lower than the other layers. In general, the tested material can be classified as extremely weak to weak based on the UCS results.

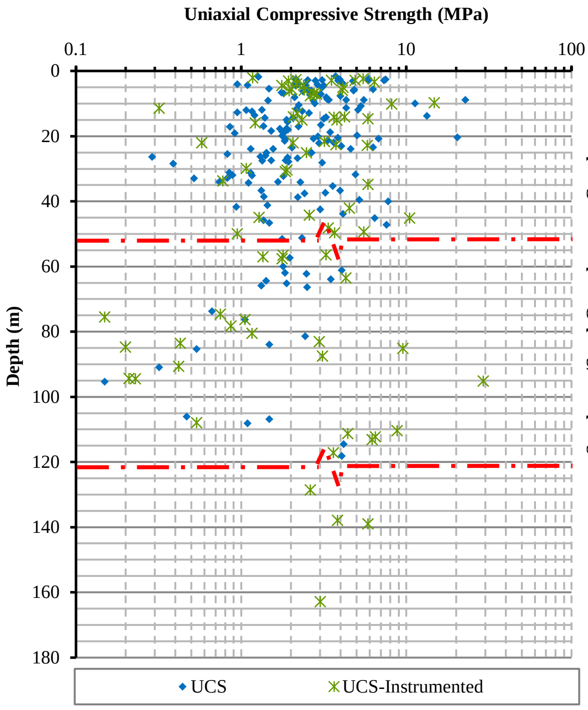

Figure 9. Results of Uniaxial Compressive Strength

It is possible to obtain an 'indirect' estimate of the deformation modulus of a jointed rock mass from empirical relationships with the uniaxial compressive strength of the intact rock. Reference [10] proposed a relationship between the in-situ modulus of deformation (Em) and uniaxial compressive strength employing Geological Strength Index (GSI) classification system as follows:

$$E_m(GPa) = \sqrt{\frac{UCS\ (MPa)}{100}}\,10^{\left(\frac{GSI-10}{40}\right)} \qquad (4)$$

Instrumented compressive strength tests provide a direct measurement of the strain and hence the elastic Young's modulus of the intact sample. The instrumented UCS tests were carried out in accordance with ASTM D 7012-07 Method D [9]. Four strain gauges were fixed on each sample for lateral and vertical strain measurements in which two gauges were installed on opposite sides near the mid-height of the sample for vertical strain and the other two for lateral strain measurements (hence, Poisson ratio values can be directly estimated). The axial load was measured with a load cell.

The direct measurements of the intact Young's Modulus values from the instrumented UCS tests as well as the rock mass deformation modulus values estimated using equation 4 above versus depth are presented in Fig. 10. Based on the rock type and mass structure GSI values in the range of 35-45 were used in equation 4 for the Coral and Sandstone/Sand layers.

B. *Consolidated-Drained Triaxial Compression Tests*

Consolidated-Drained (CD) triaxial compression tests were carried out on selected samples of Coral and Sandstone from various depths to determine the strength and deformation properties of the material. The tests were performed by a specialist laboratory in the UK (Surrey Geotechnical Consultants Limited) in accordance with ASTM D 7181 [11]. The specimens were isotropically consolidated and then sheared with drainage at a constant rate of strain (~0.006%/min). A total of three specimens were sheared per test. The measured values of the drained Young's modulus from the CD triaxal tests are presented in Fig. 10.

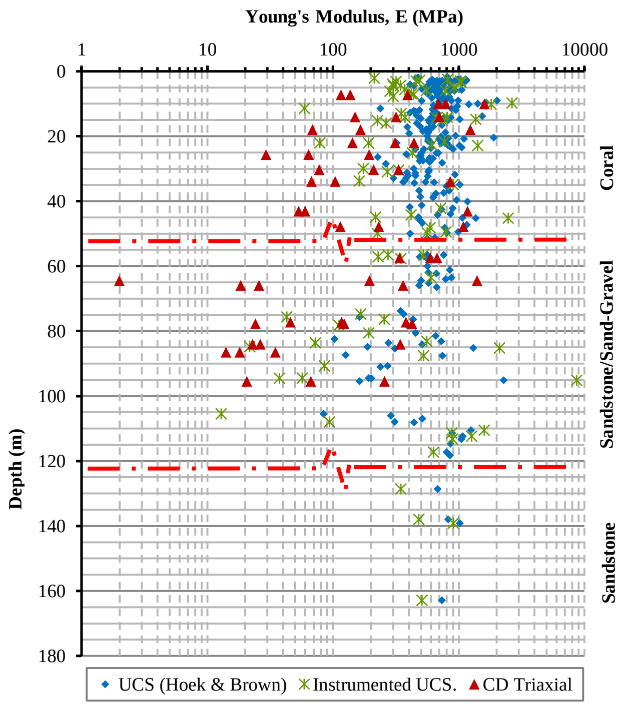

Figure 10. Results of Deformation Modulus from UCS and Triaxial Tests

VII. Comparison of Field and Laboratory Measurements

Fig. 11 presents and compares the elastic Young's modulus values from field and laboratory measurements. The modulus derived from the uniaxial compressive strength results was estimated using: 1) direct measurement from instrumented UCS tests on intact samples; and 2) Hoek and Brown [10] empirical relationship. The laboratory Young Modulus was also measured from consolidated-drained triaxial tests. The in-situ pressuremeter modulus presented in Fig. 11 represents the reload cycle carried out during the test. The seismic geophysical down-hole surveys were carried out to obtain the dynamic modulus of the in-situ rock mass.

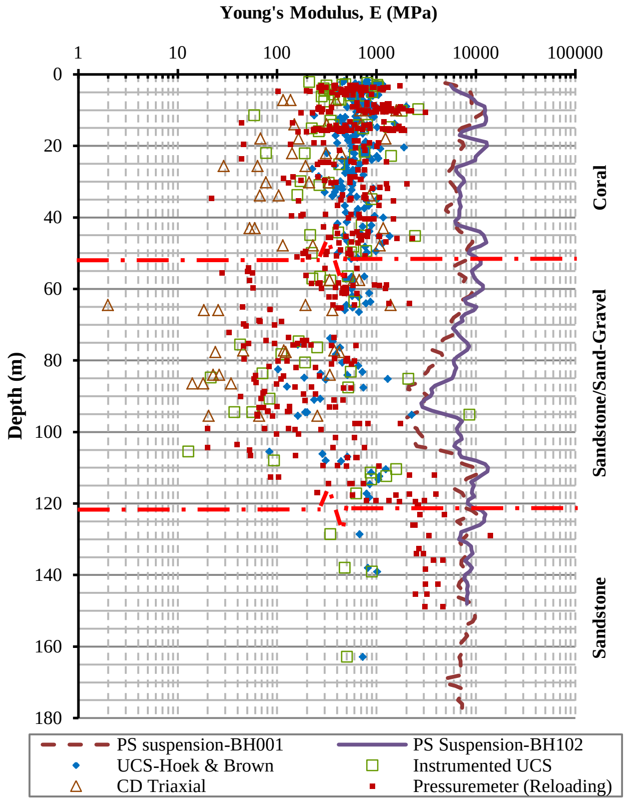

Figure 11. Comparison of Young's Modulus Values from Field and Laboratory Measurements

In general, the dynamic small-strain stiffness is expected to be higher than those obtained from the static tests. In addition, the in-situ rock mass stiffness ought to be lower than intact values due to the presence of joints and other defects in the overall rock mass. One of the main factors controlling the stiffness is the strain level, where stiffness parameters may be considered constant (i.e., linear) at very small strains (< 0.001%), but can be expected to reduce from the maximum value as strains increase above this level (Fig. 12). Note that the strain levels around well-designed geotechnical structures such as retaining wall, foundations and tunnels are generally small [12].

The stiffness results from the laboratory and field measurements show that there is some scatter in data especially in the Sandstone layer at depths ~ 52-122m due to the variability of the ground materials. The stiffness values are also somewhat lower in this layer than the Coral above and Sandstone below. There is generally fair correlation between the estimated stiffness profiles from the pressuremeter and the laboratory UCS and specialist triaxial testing. The values from the seismic testing were generally about 6-10 times those of the pressuremeter and UCS tests, a similar finding to that of Poulos [2] and Abdulhadi & Barghouthi [13].

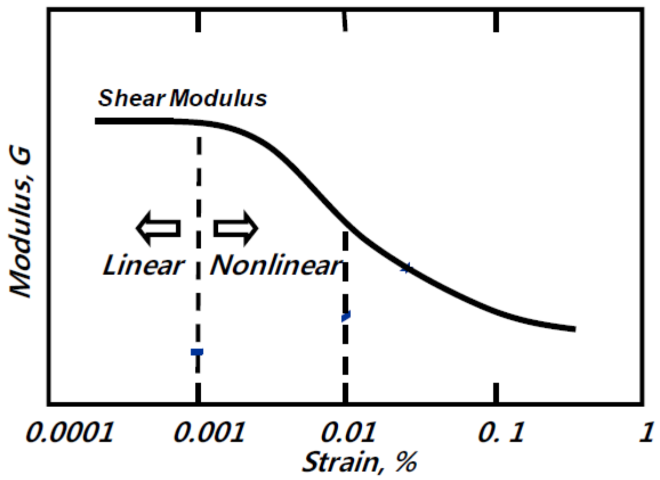

Figure 12. Nonlinear Deformation Characteristics

VIII. Conclusion

A detailed and comprehensive site investigation and testing program was carried out by Arab Center for Engineering Studies (ACES) for the ultra-tall Kingdom Tower, which is set to become the tallest building in the world. The site investigation comprised 81 boreholes where the deepest borehole was drilled down to 200m. Modern methods of in-situ and laboratory testing were carried out to characterize the ground materials at the tower site.

The design of foundations for high-rise buildings in the Middle East involves a number of challenges from a geotechnical viewpoint. The foundation system is subjected to large vertical, lateral and moment loadings, which incorporate cyclic and dynamic components. The nature of soil and rock deposits in the Middle East gives rise to additional potential problems, including generally weak to very weak foundation ground, a greater tendency for cyclic degradation, the possibilities of cavities within some of the deposits, and the absence of hard rock layers on which end bearing piles can be founded.

The subsurface conditions at the Kingdom Tower site are quite complex and highly variable. The sound rock line is estimated in the underlying Sandstone layer at depth of 122m below ground level. The exploration reveals about a 50m thick Coral Reef formation (very weak to weak) under 1.5m thick soil cover. Underlying the Coral, a 75m thick pile of poorly consolidated (poorly lithified) Sandstone/Sand with an intervening poorly consolidated Conglomerate/Gravel beds at different depths. This layer is underlain by consolidated Sandstone formation until the end of the borehole (~ 200m depth). The Sandstone between depth 181 and 200m is less lithified/consolidated and may contain some solution cavities in the formation.

The field tests comprised standard penetration tests (SPTs), permeability, pressuremeter and seismic geophysical methods including PS suspension down-hole techniques. A comprehensive laboratory testing program was carried out to determine the ground material characteristics, including unconfined compressive strength (UCS) tests and consolidated drained triaxial compression tests, among others. The stiffness values from the pressuremeter (reload cycle) compared relatively well with those obtained from the UCS and triaxial tests. The stiffness values from the seismic testing were about 6-10 times those of the pressuremeter and UCS tests.

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