Site Investigation for Kingdom Tower

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Presentation Outline

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- Conclusions & Comparison of Field & Laboratory Measurements
Kingdom Tower

Location:
Jeddah – Kingdom of Saudi Arabia

Developer:
Jeddah Economic Company (Kingdom Holding) – Emaar was client at time of study

Architect:
Adrian Smith + Gordon Gill Architecture
Dar Al Handasa (Architect of Record)

Geotechnical consultant:
Langan International

Structural Engineer:
Thornton Tomasetti

Contractor:
Saudi Bin Laden

Project description
Ultra-Tall Tower +1000m (167 floors)
Podium +4 levels of basements+ services

To Be the World’s Tallest Building
Tall Buildings-Geotechnical Challenges

- Remarkable increase in the rate of construction of tall buildings.
- Structural and geotechnical design challenges.
- Sophisticated and state-of-the art methods instead of traditional empirical methods.
- Rigorous process of foundation design.
- Nature of soil and rock deposits (Middle East).
- Characteristics that influence foundation design:
  - Weight
  - Differential settlement
  - Lateral forces and moments (cyclic & dynamic loading)

- Piled raft system: effective and relatively economical foundation solution.
Drilling & Sampling

- 3 phases: 81 boreholes (~20m - 200m).
- Rotary drilling using mud/water flush.
- Disturbed, undisturbed & split spoon samples.
- SPT in soil; continuous coring in rock.
- Conventional\wireline & double\triple core barrels.
- Coring systems: PWF, PQ/PQ3, HQ/HQ3 & T2-76.
Field Testing & Instrumentation

- Standard penetration test (SPT).
- Permeability (packer) testing (total 40 test).
- Pressuremeter testing (total 232 test).
- Geophysical Survey Down-hole test (total 3 tests down to 180m).
- Installation of standpipe piezometers (total 16).
Laboratory Testing

- Classification & index testing.
- Strength testing (instrumented USC; point load).
- Advanced tests (CD triaxial with volume change measurements and repetitive cyclic tests) – Surrey Lab.
- Chemical testing.
Geology and Site Conditions

Horizontally stratified profile of marine sediments which are complex and highly variable.

- **Stratigraphy:**
  - Soil Cover.
  - Coral.
  - Conglomerate/Gravel.
  - Sandstone/Sand.
  - Conglomerate/Gravel.
  - Sandstone.
- voids/cavities in S.st (~173m).
**Subsurface Stratigraphy**

- **Coral Reef (~50m)**
  - Fossiliferous silty sand with many fragments of broken shells, corals.
  - Very weak to weak, buff white, unweathered to partly weathered, intermittently fractured, porous and vuggy Coral.

- **Soil Cover (~1.7m)**
  - Gravel in fine to medium sand matrix with local inter-layers of reddish brown siltstone.
  - Poorly consolidated Sands with gravel and local patches/pockets of consolidated sand.
  - Gravel to sand with gravel; with thin (10-30cm) interlayers of poorly consolidated sand.
  - Poorly consolidated, Sandstone/Sand with interlayers of Gravels/Conglomerates of ~1m thickness.
  - Gravel/Conglomerate with interbeds of hard, slightly weathered gritty Sandstone of 1-4m thickness.
  - Greenish grey coarse, gritty Sandstone with Coral fragments.

- **Gravel (~53.13m-56.92m)**
  - Dark grey to greenish grey, poorly consolidated, fine grained Sandstones/Sand.

- **Soft Sandstone/Sand (92.7m-98.0m)**

- **Sandstone (148.25m-153.25m)**

- **Fine grained Sandstone (196.25m-200m)**

- **Coral Reef (15.2m-20.0m)**

- **Sandstone (148.25m-153.25m)**

- **Conglomerate (63.0m-67.0m)**
Permeability Packer Tests - BS 5930-1999

- 40 double packer tests.
- Various depths (~3.0-18.5m)
- Tests carried out in Coral Layer.
- Permeability $1.23 \times 10^{-5}$ to $8.38 \times 10^{-5}$ m/s.
Pressuremeter Tests - ASTM D 4719

- High Pressure Dilatometer (HPD) tests in Coral and Sandstone/Sand.
- Total 232 tests at various depths ~3.0m-149m below ground level.
- Calibration ~ pressure & volume.
- Test section drilled/prepared using T2-76 core barrel.

Mainly to obtain modulus: \[ G = \frac{1}{2} \times \frac{dP}{d\varepsilon_c}; \quad E = 2G (1+\nu) \]
Down-Hole Geophysics

- PS suspension carried out to acquire P-S wave velocities to derive dynamic soil properties (E, G, v).
- Density estimated from lab tests.
- Borehole cased, grouted & filled w/ water.

\[ G = \rho V_s^2 \quad , \quad G = \frac{E}{2(1+\nu)} \quad , \quad \nu = \frac{(V_p/V_s)^2}{2 \left( (V_p/V_s)^2 - 1 \right)} \]
Compressive Strength

- Empirical relationships to estimate deformation modulus from uniaxial compressive strength.
- Hoek & Brown (1997)
- Direct measurements of the intact Young’s Modulus from the instrumented UCS.
- Consolidated-Drained Triaxial Compression Test (Surrey Lab)

\[ E_m(GPa) = \sqrt{\frac{UCS (MPa)}{100 \times 10^{(GSI-10)/40}}} \]
Conclusions & Comparison

- 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.

- Stiffness from the pressuremeter (reload cycle) compared relatively well with those obtained from the UCS and triaxial tests.

- The stiffness from the seismic testing were about 6-10 times those of the pressuremeter and UCS tests.

- Factors affecting stiffness include strain level, joint structure, disturbance, etc.
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