Analysis and Design of the Kingdom Tower Piled Raft Foundation

George Leventis, PE, Managing Principal, Langan
Alan Poeppel, PE, Senior Principal, Langan
Project Team

- **Owner:** Jeddah Economic Company and Kingdom Holdings, Jeddah KSA
- **Architect:** Adrian Smith + Gordon Gill Architecture, Chicago, USA
- **Structural Engineer:** Thornton Tomasetti, Chicago, NYC, USA
- **Civil, Geotechnical, Traffic, & Parking Engineer:** Langan International, NYC, USA, Dubai, UAE
- **Building Systems:** EDS, Chicago, USA, Dubai, UAE
- **Piling Contractor:** Saudi Bauer
Kingdom Tower – Site Location

Rendering © Jeddah Economic Company/Adrian Smith + Gordon Gill Architecture
# Basic Statistics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Height</td>
<td>1,000+ m</td>
</tr>
<tr>
<td>Raft Area</td>
<td>3,200 sq m</td>
</tr>
<tr>
<td>Total Gravity Load</td>
<td>860,000 tonnes</td>
</tr>
<tr>
<td>Total Pressure</td>
<td>2.65 Mpa</td>
</tr>
<tr>
<td>Piles</td>
<td>270 No.</td>
</tr>
<tr>
<td></td>
<td>1.5 m dia</td>
</tr>
<tr>
<td></td>
<td>32 MN avg service load</td>
</tr>
<tr>
<td>Raft</td>
<td>4.5 m to 5 m thick</td>
</tr>
</tbody>
</table>
Boring Location Plan

LEGEND
- B-101: 200m DEEP BORING
- B-102: 150m DEEP BORING
- B-201: 120m DEEP BORING
- B-303: 40m DEEP BORING
## Summary of Field and Lab Tests

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borings</td>
<td>50</td>
</tr>
<tr>
<td>Core Samples</td>
<td>2,377</td>
</tr>
<tr>
<td>Pressuremeter Tests</td>
<td>187</td>
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<tr>
<td>Packer Tests</td>
<td>28</td>
</tr>
<tr>
<td>P-S Suspension Logging</td>
<td>3 Borings</td>
</tr>
<tr>
<td>Electrical Resistivity Tomography (ERT)</td>
<td>12 x 200-m lines</td>
</tr>
</tbody>
</table>
General Subsurface Conditions

- <0.5 to 2 m thick: Silty Sand (SM)
- 45 to 50 m thick: Vuggy Coralline Limestone
- 2 to 10 m thick: Mudstone / Gravel
- Interlayed in base of limestone
- 35 to 50 m thick: Decomposed Sandstone
- 3 to 9 m thick: Gravel and Conglomerate
- Up to 200 m: Sandstone
Vuggy Coralline Limestone
Mudstone and Gravel Inclusions

*BH: 103, Depth: 52.60-57.90m*
Sandstone

BH: 103, Depth: 85.20-90.20m
Rock Compressive Strength

Summary of UCS Values (MPa)

<table>
<thead>
<tr>
<th>Strata</th>
<th>Range</th>
<th>Average</th>
<th>Median</th>
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</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>0.32-14.8</td>
<td>2.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Decomposed Sandstone</td>
<td>0.09-4.87</td>
<td>1.5</td>
<td>0.94</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.01-29.3</td>
<td>2.7</td>
<td>1.9</td>
</tr>
</tbody>
</table>
ROCK STIFFNESS

E (MPa)

Elevation (m)

-175
-155
-135
-115
-95
-75
-55
-35
-15

5

0 500 1,000 1,500 2,000 2,500 3,000 3,500 4,000

ACES PMT E0

E50 from instrumented UCS

ACES PMT Er

Sandstone

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Technical Excellence       Practical Experience       Client Responsiveness
Full Scale Field Load Tests

• Substantiate Rock Bearing Capacity
• Substantiate Individual Pile Capacity
• Side resistance and deformation modulus of coralline limestone and decomposed sandstone
• Evaluation of Constructability (especially of deep elements)
Footing Load Test
Footing Load Test – Load Settlement Plot

MOBILIZED BEARING PRESSURE = 3.3 MPa
Full Scale Pile Load Test
Pile Load Test – Mobilized Skin Friction in Limestone using Natural Slurry

ULIMATE SIDE = 500 SHEAR (Kpa)

ULIMATE SIDE = 500 SHEAR (Kpa)
Design Modulus of Deformation

In-situ, Laboratory and Load Test Moduli of Deformation and Design Values (MPa)

- E50 from instrumented UCS
- ACES PMT Er
- E50 from CD and repetitive tx
- Load Test Data - E50
- 8% of very low strain E
- 15% of very low strain E
Foundation Design
# Geotechnical Capacity of Limestone

<table>
<thead>
<tr>
<th>Ultimate Bearing Capacity</th>
<th>Type of Loading</th>
<th>Factor of Safety</th>
<th>Allowable Bearing Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 MPa</td>
<td>Gravity</td>
<td>3.0</td>
<td>0.83 MPa</td>
</tr>
<tr>
<td>2.5 MPa</td>
<td>Transient</td>
<td>2.0</td>
<td>1.25 MPa</td>
</tr>
</tbody>
</table>
# Geotechnical Capacity of Single Pile, 45 m Depth

<table>
<thead>
<tr>
<th>Ultimate Side Shear</th>
<th>Type of Loading</th>
<th>Factor of Safety</th>
<th>Geotechnical Pile Allowable Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 kpa</td>
<td>Gravity</td>
<td>2.5</td>
<td>42 MN</td>
</tr>
<tr>
<td>450 kpa</td>
<td>Transient</td>
<td>2.0</td>
<td>50 MN</td>
</tr>
</tbody>
</table>
Soil-Structure Interaction
FEM Analysis
**General Foundation Configuration**

1. **Fully Piled Foundation**
   - 270 bored piles
   - 1.5 m diameter
   - 4.5 m thick structural raft (6 m deep depression at the center and 5 m thick at the edges)

2. **Initial Pile Lengths:** 45 m

3. **Estimated Average Load on the Pile:** 32 MN
Foundation Response

Flexible Foundation
- Settlement
- Stress Distribution

Rigid Foundation
Soil-Structure Interaction Model

Determine critical parameters such as:

- Raft geometry
- Rock Modulus of deformation
- Locations, geometry of piles
- Soil/pile interface properties
  - Shear strength
  - End bearing capacity
  - Stiffness
Iterative Process General Steps

Structural Engineer

Column Loads

Foundation Settlements
Winkler Springs

Structural Deformation

New Winkler Springs,
New Foundation Settlements

Geotechnical Engineer

New Foundation Settlements

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Structural System

Credit: Thornton Tomasetti

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Typical Loading Conditions

- Soil/Foundation/Structure Self Weight

- Column/Wall loads as
  - Point Loads
  - Line Loads
  - Pressure Loads
Geotechnical Finite Element Model

- CORALLINE LIMESTONE LAYER
- DECOMPOSED SANDSTONE LAYER
- SANDSTONE LAYER
### Foundation and Geologic Profile

<table>
<thead>
<tr>
<th>Material</th>
<th>E (Mpa)</th>
<th>$\nu$</th>
<th>$\gamma$ (kN/m$^3$)</th>
<th>$\varphi$</th>
<th>c (kpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coraline Limestone +4 to -10</td>
<td>500</td>
<td>0.35</td>
<td>18</td>
<td>24</td>
<td>170</td>
</tr>
<tr>
<td>Coraline Limestone -10 to -40</td>
<td>500</td>
<td>0.35</td>
<td>18</td>
<td>24</td>
<td>170</td>
</tr>
<tr>
<td>Coraline Limestone -40 to -47</td>
<td>440</td>
<td>0.35</td>
<td>18</td>
<td>24</td>
<td>170</td>
</tr>
<tr>
<td>Coraline Limestone -47 to -54</td>
<td>325</td>
<td>0.35</td>
<td>18</td>
<td>24</td>
<td>170</td>
</tr>
<tr>
<td>Gravel -54 to -60</td>
<td>200</td>
<td>0.35</td>
<td>17</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Decomposed Sandstone -60 to -90</td>
<td>150</td>
<td>0.35</td>
<td>20</td>
<td>24</td>
<td>300</td>
</tr>
<tr>
<td>Decomposed Sandstone -90 to -110</td>
<td>150 to 500</td>
<td>0.35</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sandstone -110 to -125</td>
<td>900 to 1,200</td>
<td>0.30</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sandstone -125 to -200</td>
<td>1200</td>
<td>0.30</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Pile parameters:
- $E=36,700$ Mpa
- Diameters: 1.5m and 1.8m
- Termination elevation: -44
- Ultimate side shear stress: 0.5 Mpa
First Settlement Prediction

Angular Rotation: 1:900

108 mm

173 mm

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Multi-Step Winkler Spring Adjustment

ITERATION 1

ITERATION 2

ITERATION 3

Technical Excellence       Practical Experience       Client Responsiveness

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Geotech Pile Loads and Vertical Stresses on Rock Under Raft RIGID FOUNDATION

Pile-center-to-raft-Center Distance (m)

0.0 10.0 20.0 30.0 40.0 50.0 60.0

0 -10,000 -20,000 -30,000 -40,000 -50,000 -60,000

Axial Load

Vertical Stresses along north leg

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Observed Increased Wall Stresses at the Wings

Wing Stress/ Center Stress = 2.25:1

Credit: Thornton Tomasetti
Final Analyses/Design

- D=1.5M, L=45M
- D=1.8M, L=45M
- D=1.5M, L=65M
- D=1.5M, L=85M
- D=1.5M, L=105M
FEM Cross-Section

<table>
<thead>
<tr>
<th>Material</th>
<th>E (MPa)</th>
<th>ρ (kN/m³)</th>
<th>φ (deg.)</th>
<th>c (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coralline Limestone -44 to -10</td>
<td>500</td>
<td>0.35</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Coralline Limestone -10 to -40</td>
<td>500</td>
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<td>24</td>
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<td>0.35</td>
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</tr>
<tr>
<td>Coralline Limestone -47 to -54</td>
<td>325</td>
<td>0.35</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>Gravel -54 to -60</td>
<td>200</td>
<td>0.35</td>
<td>17</td>
<td>38</td>
</tr>
<tr>
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<td>150</td>
<td>0.35</td>
<td>20</td>
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<td>0.35</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Sandstone -110 to -125</td>
<td>900 to 1,200</td>
<td>0.30</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Sandstone -125 to -200</td>
<td>1200</td>
<td>0.30</td>
<td>20</td>
<td>-</td>
</tr>
</tbody>
</table>

Pile Parameters:
E=36,700 Mpa
D:1.5m and 1.8m
Termination Elevation: 45 to -105 MSL

Pile-Soil Interface Parameters:
Coralline Limestone/Natural Slurry:
\( t_{ult}=1,000 \) kPa, \( K_t=2,500 \) Mpa
Coralline Limestone/Polymer Slurry:
\( t_{ult}=500 \) kPa, \( K_t=500 \) Mpa
Dec Sandstone/Polymer Slurry:
\( t_{ult}=450 \) kPa, \( K_t=500 \) MPA
Settlement Contour Progression as Wall Load Changed
Converged Settlement Contours

LANGAN AND TT CONVERGED WITHIN 5 MM
Raft Settlement Plots

- Compare foundation response without any iterations
- The 45m scheme leads to significant redistribution of wall loads
- The deeper scheme leads to minor redistribution
Converged Pile Loads (MN)

Note: Pile loads taken at bottom of raft
Notes: 1. All units are in kilopascals (kPa).
2. All pressures are approximate.
Vertical Strains – Block Behavior
Wall Stresses

Wing Stress/Center Stress = 1.6:1
Axial Pile Loads for Converged Models

45m long pile scheme

45m/65m/85m/105m
Final Remarks

- The geotechnical model governs the ground settlements.
- The iterative process gives insight on the redistribution of column/wall loads.
- The geotechnical engineer does not have to attempt to model the stiffness of the superstructure.
- The redistribution is more pronounced when the superstructure is “stiff” compared to the foundation.
- The redistribution necessitated “stiffening” the foundation by using longer piles at the center.
- The longer piles are not needed for increased soil bearing capacity, they are needed to alleviate the increased outer wall stresses in the superstructure.
In Memory
Dr. Khaldoun Fahoum, PE, PhD