Drilled Shafts Defects, Detection & Effects

SPONSORS

- FHWA
- ADSC

Copyright © M. Iskander
Background

- Growth in Drilled Shaft Usage
  - NDT
  - Seismic Considerations
  - Equipment

- QA/QC
  - Difficult
  - Interpretation

- Capacity of Defected Shafts?
Objectives

- Defects
  - What is the smallest detectable defect size?
  - Which NDT methods are most reliable?
  - Detection of multiple defects

- Effects of Defects Capacity

- Adequacy of Statnamic Load Testing in Varved Clay
  (Not Shown)
Integrity Testing Methods

- **Down Hole Techniques**
  - Crosshole Sonic Logging (CSL)
  - Single Hole Sonic Logging (SSL)
  - Crosshole Tomography (CT)

- **Surface Techniques**
  - Sonic Echo (Pulso echo, Acoustic Wave Reflections)
  - Sonic Mobility (Impulse Response)

- **Gama-Gama**
  - Not used

Copyright © M. Iskander
Project Layout

- Reaction Shafts
- Load Test Shafts
- Statnamic Shaft

Copyright © M. Iskander
Soil Profile

- NGES UMASS Site
  - 12 feet over-consolidated crust
    - OCR = 6 – 10
    - N = 5–15

- Soft Grey Connecticut Valley varved clay
  - PI = 17 – 22
  - Su= 700 – 800 psf (34 – 38 kPa)
  - N = 1–2

Copyright © M. Iskander
Construction

- 36 in. augured hole to approximately 20 feet
- 40-Inch OD temporary casing inserted into augured hole
- Remainder augured to 47 feet without casing or slurry
- Holes remained open for several hours
- Full length Reinforcement inserted into hole
- Concrete placed using free fall and tremie techniques
- 3 ft. section of casing used to form the shaft above grade
Shaft Dimensions

- **Above Grade**
  - Diameter = 36 Inches
  - Length = 1–3 ft

- **Top Section**
  - Diameter = 40 inches
  - Length = 20 ft

- **Bottom Section**
  - Diameter = 36 inches
  - Length = 27 ft

- **TOTAL EMBEDDED LENGTH = 47 ft**
Built in Defects

- **Built in Defects**
  - Area = 0.4 – 1.4 ft²
  - Length 1 – 4 ft
  - Necking reduces diameter to 22 in.
  - Attached to rebar cage

- **Construction Defects**
  - Soft Bottom

- **Locations**
  - Along the shaft length
  - Multiple defects per shaft
NDT Access Tubes

- 2-inch black iron NDT pipes in all shafts.
- All shafts (except Shaft 3) had 4 access tubes.
- Shaft 3 had 3 access tubes.
Instrumentation

- **Shaft 2 and 4**
  - 5 levels of strain gages
  - 5 levels of telltales
  - Inclinometer casing

- **Shaft 1, 3, and 5**
  - 2-5 levels of strain gages
  - 2 levels of telltales
  - Inclinometer casing

- **Shaft 6**
  - 5 levels of strain gages
  - Inclinometer casing

- **2-inch black iron NDT pipes in all shafts**
Class-A Defect Prediction

- Olson Engineering
- Geosciences Testing and Research
- STS Consultants
- Construction Technologies Laboratories (CTL)
- Prof. Finno, Northwestern University and Prof. Gassman, University of South Carolina
- GZA Geoenvironmental
- B&A
- GRL

Copyright © M. Iskander
### Shaft 2

**Soft Bottom**
- 1.5 (5)
- 3.0 (10)
- 4.6 (15)
- 6.1 (20)
- 7.7 (25)
- 9.2 (30)
- 10.7 (35)
- 12.2 (40)
- 13.7 (45)
- 15.2 (50)

**Structurally Sound**
- No visible defects

#### Table: Shaft 2

<table>
<thead>
<tr>
<th>Depth, m (ft)</th>
<th>No.</th>
<th>Legend</th>
<th>1 - ST</th>
<th>2 - DHT</th>
<th>3 - ST</th>
<th>4 - DHT</th>
<th>5 - DHT</th>
<th>6 - MULT</th>
<th>7 - DHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 (5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 (10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.6 (15)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1 (20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7 (25)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.2 (30)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.7 (35)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.2 (40)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.7 (45)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.2 (50)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Shaft 3

#### As Built

<table>
<thead>
<tr>
<th>Depth, m (ft)</th>
<th>No.</th>
<th>Legend</th>
<th>1 - ST</th>
<th>2 - DHT</th>
<th>3 - ST</th>
<th>4 - DHT</th>
<th>5 - DHT</th>
<th>6 - MULT</th>
<th>7 - DHT</th>
<th>8 - MULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 (5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 (10)</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.6 (15)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1 (20)</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7 (25)</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.2 (30)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.7 (35)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.2 (40)</td>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.7 (45)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.2 (50)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### NDT Testers - Testing Technique

- **Void**
- **Necking**
- **Soil**
- **Change in diameter**
- **Low Density Concrete**
- **Shaft Oversize**
- **Defect**
- **Minor defect**

---

**3 NDT Tubes**

---

Copyright © M. Iskander
Shaft 4

<table>
<thead>
<tr>
<th>Depth, m (ft)</th>
<th>As Built</th>
<th>NDT Testers - Testing Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Legend</td>
</tr>
<tr>
<td>1.5 (5)</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>3.0 (10)</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>4.6 (15)</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>6.1 (20)</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>7.7 (25)</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>9.2 (30)</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>10.7 (35)</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>12.2 (40)</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>13.7 (45)</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>15.2 (50)</td>
<td>F</td>
<td></td>
</tr>
</tbody>
</table>

- Void
- Necking
- Soil
- Change in diameter
- Low Density Concrete
- Shaft Oversize
- Defect
- Minor defect

- Voids & soil inclusions
- 5–45% of cross section

Copyright © M. Iskander
# Shaft 5

<table>
<thead>
<tr>
<th>Depth, m (ft)</th>
<th>Legend</th>
<th>1 - ST</th>
<th>2 - DHT</th>
<th>4 - DHT</th>
<th>5 - DHT</th>
<th>6-MULT</th>
<th>7-DHT</th>
<th>8-MULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 (5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 (10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.6 (15)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1 (20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7 (25)</td>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.2 (30)</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.7 (35)</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.2 (40)</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.7 (45)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.2 (50)</td>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Legend:
- **Void**
- **Necking**
- **Soil**
- **Change in diameter**
- **Low Density Concrete**
- **Shaft Oversize**
- **Defect**
- **Minor defect**

*Copyright © M. Iskander*
Shaft 6

<table>
<thead>
<tr>
<th>Depth, m (ft)</th>
<th>As Built</th>
<th>NDT Testers - Testing Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Legend 1 - ST</td>
</tr>
<tr>
<td>1.5 (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 (10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.6 (15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1 (20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7 (25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.2 (30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.7 (35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.2 (40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.7 (45)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.2 (50)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Void**
- **Necking**
- **Soil**
- **Change in diameter**
- **Low Density Concrete**
- **Shaft Oversize**
- **Defect**
- **Minor defect**

Copyright © M. Iskander
Conclusions, Down Hole Methods

- Defects larger than 10% of cross-section were EASILY detected.
- Defects smaller than 5% of cross-section were NOT detected.
- Unable to locate defects outside cage, including soft bottoms.
- Soil inclusions were more difficult to detect than voids.
- False positives were common.
Conclusions, Surface Methods

- Better than previous studies.
- Able to locate VOIDS down to 6% of cross section!
- Able to locate SOIL INCLUSIONS down to 17% of cross section.
- Up to 3 defects were located per shaft.
- Difficult to detect soft bottom.
Load Tests

- **Static load tests**
  - 2 shafts
  - 4 tests (shafts re-tested 8 hours later)
  - Quick incremental test method
  - Continuous rate of loading (not shown)

- **Statnamic testing (not shown)**
  - 3 shafts
  - 5 tests

- **Capacity predictions**
  - H. Poulos won
Load Test — Shaft 2

- Soft Bottom
- No Structural Defects
- Davidson’s Capacity = 1000 kN (225 kips)
- Capacity @ 5% of diameter = 1200kN (270 kips)
- Mobilized Cu in end bearing = 34 kPa (710 psf)
- Unit skin friction = 17.4 kPa (360 psf)
Load Test — Shaft 4

- Structural Defects
- Davidson’s Capacity = 950 kN (213 kips)
- Capacity @ 5% of diameter = 1060 kN (238 kips)
- Mobilized Cu in end bearing = 51 kPa (1065 psf)
Load Test — Shaft 4-Reload

- 8 hours later
- Davidson’s Capacity = 880 kN (198 kips)
- Capacity @ 5% of diameter = 1000 kN (225 kips)
- Mobilized Cu in end bearing = 42.5 kPa (890 psf)
- Unit skin friction = 11.7 kPa (245 psf)
Effects on End Bearing

- Shaft 2 (soft bottom) had 5-10\% higher capacity than Shaft 4 (Structural defects)
  - Undocumented variation in construction

- Mobilized Cu in End Bearing
  - 51 kPa - Shaft 4
  - 42.5 kPa - Shaft 4 (Reload)
  - Reloading caused 20\% reduction
  - 34.5 kPa - Shaft 2
    - soft bottom
    - 4 months after construction
  - 33\% lower than virgin loading
  - 20\% lower than reloading

Copyright © M. Iskander
Effects on Skin Friction

- **Mobilized Skin friction**
  - 17.4 kPa Shaft 2 virgin loading
  - 11.7 kPa Shaft 4 reload

- **30% reduction**
  - Breakage of Cementation
  - Remolding of Clay
  - Structural Defects
Conclusions

- **Soft bottom shaft had higher capacity**
  - Skin friction dominated capacity
  - Soft bottom resulted in 33% reduction in capacity
  - Undocumented differences in construction

- **End Bearing**
  - Reloading: 20% reduction in capacity
  - Soft Bottom: 33% reduction in capacity

- **Skin Friction**
  - Reloading: 30% reduction in capacity

- **Defects appear to have a small effect on capacity, but further research is needed.**
Publications

Acknowledgments

- Douglas Roy, PE
- Jim Maxwell, Hub Foundation Company, Inc.
- Gill Peel, American Equipment and Fabricating Corporation
- A. Grey Mullen, USF
- Mike O’Neill, U of H
- Pierre Gouvin, Rock Test
- Slope Indicator Company
- Rich Finno Northwestern University
- S. Gassman, Univ. of South Carolina
- Bob Mokowa, UMASS
- Alan Lutenegger, UMASS
- UMASS Students
- Polymer Drilling Systems Co.
- Shawn Kelley, UMAS
- Carl Ealy, FHWA
- Al Dimillio, FHWA
- Scot Litke, ADSC
- Olson Engineering
- Construction Technologies Laboratories (CTL)
- STS Consultants
- Geosciences Testing and Research
- GZA Geoenvironmental
- GRL
- B&A
- Polymer Drilling Systems Co.
- Geo Institute Deep Foundations Committee

Copyright © M. Iskander