Agenda

1. Project Background
2. Geology
3. Types of Bridge Foundations used in CBIS
4. Drilled Shafts for Bridge Foundation
5. Drilled Shafts Bearing in Rock and in Soil
6. Comparison of Drilled Shafts in Rock vs in Soil
7. Conclusions and Lesson’s Learned
Project Background

- Modernization and Rehabilitation of approximately 18 miles of mainline interstate (I-80, I-29, and I-480)

Source: http://www.councilbluffsinterstate.iowadot.gov/projects/

Project Background

- 15 interchanges
- 59 bridges

- 135 lane miles of highway reconstructed
- Increase from 6 to 12 lanes on dual, divided freeway

Source: http://www.councilbluffsinterstate.iowadot.gov/projects/
Geology- Generalized Subsurface Profile

- The subsurface profile in Pottawattamie County generally consists of loess, alluvium, and glacial till underlain by interbedded layers of shale and limestone.
- At the CBIS project location, the upper soil is primarily composed of recently deposited alluvium. The shallowest bedrock layer is of the Pennsylvanian period of the Paleozoic era and is comprised primarily of limestone and shale (Witzke, et al. 2003).
- Generalized subsurface profile
  - Layer 1 – Clay and Silt (Fill)
  - Layer 2 – Clay and Silt
  - Layer 3 – Silty Sand and Poorly Graded Sand with Silt
  - Layer 4 – Slightly Weathered Limestone Interbedded with Shale

Jacobs Geotechnical Work on CBIS

- Bridge Foundation Design
  - Driven Piles
  - Drilled Shafts
- Retaining Walls Design
  - MSE walls – Granular backfill and Lightweight Foam Concrete Fill (LFCF)
  - Solider Pile and Lagging
- Ground Improvement Design
  - Rigid Inclusion – including load transfer platform
  - Wick Drains
- Geotechnical Instrumentation
- Field inspection and construction support
Bridge Foundations in CBIS

Bridge foundations used in CBIS project are

- Driven Piles
- Drilled Shafts – Rock
- Drilled Shafts – Soil

Source: Iowa DOT Bridge Design Drawings – I-80WB over IA 192 (2016)

Drilled Shafts for Bridge Foundations

- Iowa DOT typically supports only piers on drilled shafts. Abutments (integral) are usually supported using driven piles.

- Drilled shafts used as they
  - have minimal Vibrations and less noise during installation;
  - are more compact compared to driven piles;
  - are likely to fit within divided highway medians and adjacent structures;
  - can provide large lateral load resistances.

- Demonstration shaft usually required to check the equipment and contractor’s installation methods.
Drilled Shafts for Bridge Foundations

In Rock
- List of bridges
- Iowa DOT design guidelines
- Design overview
- Load tests and results
- Production shafts installation

In Soil
- List of bridges
- Design guidelines
- Design example
- Load test and results
- Production shafts installation

Drilled Shafts in Rock

Bridge Foundations supported on Drilled Shafts bearing in Rock were designed and constructed for the following bridges:

1. I-29 over Mosquito Creek
2. US 275 over Mosquito Creek
3. I-29 Widening over Existing I-80 EB

Source: Iowa DOT Bridge Design Drawings – I-80WB over IA 192 (2016)
Drilled Shafts in Rock - Design

• Typically, the DOT requires drilled shafts for bridge support be socketed into rock.
• Shaft design to consider only skin friction within the rock socket. Bearing in rock may be considered only if estimated settlements are small.
• The rock socket length is at least 1.5 times rock socket diameter.

Drilled Shafts in Rock - Design

• Rock socket diameter at least 6 inches less than the diameter in rock.
• The Iowa DOT has accumulated test data for drilled shafts socketed in shale and limestone.
Drilled Shafts in Rock - Design

Generalized Soil Profile

Layer 1: Fat Clay and Lean Clay
SPT N-Values 2 to 11 bpf; 3 bpf (Avg)

Layer 2: Poorly Graded Sand with Silt
SPT N-Values 7 to 13 bpf; 9 bpf (Avg)

Layer 3: Lean Clay
SPT N-Values 2 to 19 bpf; 9 bpf (Avg)

Layer 4: Weathered Shale/Boulders

Layer 5: Slightly weathered Shale and Unweathered Limestone

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Drilled Shafts in Rock - Design

- In accordance with Iowa DOT and FHWA GEC 10 guidelines.
- Bridge loads provided by Bridge Engineers
- Lateral Analyses:
  - FB Multiplier used for lateral analysis of the shafts.
  - p-multiplier considered based on C/C spacing between the shafts and the direction of loading.
- Axial Analyses:
  - No end bearing resistance considered.
  - Rock socket minimum length of 1.5 times the diameter of rock socket considered per Iowa DOT requirement.
  - A 20% reduction applied for non-redundant shafts.
  - Axial group efficiency considered based on C/C spacing between the shafts.
Drilled Shafts in Rock – Load Test

• Two sacrificial load tests were performed in accordance with ASTM D1143 Quick Load Test
  - TS-1: I-29 over Mosquito Creek
  - TS-2: US 275 over Mosquito Creek
• Confirmation boring performed at each test shaft location.
• Test shafts instrumentation:
  - Four telltales from top of O-cell to ground level
  - Nine levels of sister bar strain gages

Drilled Shafts in Rock – Load Test

A quick comparison of the two test shafts

<table>
<thead>
<tr>
<th></th>
<th>TS-1</th>
<th>TS-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-29 over Mosquito Creek</td>
<td>6.0 feet dia. in soil; 5.5 feet dia. in rock</td>
<td>6.5 feet dia. in soil; 6.0 feet dia. in rock</td>
</tr>
<tr>
<td>US 275 over Mosquito Creek</td>
<td>96.2 feet long shaft</td>
<td>96.7 feet long shaft</td>
</tr>
<tr>
<td>Rock Socket: Weathered Shale</td>
<td>34-inch diameter O-Cell located 2.8 feet above the shaft base</td>
<td>34-inch diameter O-Cell located 1.7 feet above the shaft base</td>
</tr>
</tbody>
</table>
Drilled Shafts in Rock – Load Test

TS-1, I-29 over Mosquito Creek
Iowa, 7/31/2014

TS-2, US 275 over Mosquito Creek
Iowa, 8/18/2014

Excerpts from Report(s) on Drilled Shaft Load Testing by LoadTest, Aug and Sep 2014
Drilled Shafts in Rock – Load Test Results

Equivalent Top Load-Displacement Curve

TS-1, I-29 over Mosquito Creek

TS-2, US 275 over Mosquito Creek

Mobilized Upward Net Unit Side Shear

TS-1, I-29 over Mosquito Creek

TS-2, US 275 over Mosquito Creek

Excerpts from Report(s) on Drilled Shaft Load Testing by LoadTest, Aug and Sep 2014
Drilled Shafts in Rock – Load Test Results

Mobilized Unit End Bearing

TS-1, I-29 over Mosquito Creek  
TS-2, US 275 over Mosquito Creek

End bearing resistance not fully mobilized

Excerpts from Report(s) on Drilled Shaft Load Testing by LoadTest, Aug and Sep 2014

Drilled Shafts in Rock – Load Test Results

Based on the load tests multiple cases analyzed prior to developing final tip elevations

- Case 1: Assuming drilled shaft socketed into Limestone and no base resistance assumed
- Case 2: Assuming drilled shaft socketed into weathered Shale and no base resistance considered
- Case 3: Assuming drilled shaft socketed into weathered Shale and base resistance considered

Conservatively, based on Case 2, 7 feet of rock socket was recommended and no base resistance was considered.
Drilled Shafts in Rock – Production Shafts

- A total of 98 drilled shafts installed between September 2014 and March 2015.
- The length of the shafts varied between 90-105 feet.
- The shaft diameter and rock socket diameter varied between 4 to 6.5 feet and 3.5 to 6.0 feet, respectively.
- The installation time per shaft varied between 2 and 7 days.

Drilled Shafts in Rock – Production Shafts

The production rate for shafts extending into rock was slow due to
- Mechanical issues in the rig.
- Issues with temporary casing extraction.
- Additional deeper temporary casing required to maintain hole stability in some shafts.
- Abandoned foundation H-piles encountered during drilling.
- Weather delays.
Drilled Shafts for Bridge Foundations

Drilled Shafts Supported

- In Rock

  ✓ List of bridges
  ✓ Iowa DOT design guidelines
  ✓ Design overview
  ✓ Load tests and results
  ✓ Production shafts installation

- In Soil

  ✓ List of bridges
  ✓ Design guidelines
  ✓ Design example
  ✓ Load test and results
  ✓ Production shafts installation

Drilled Shafts in Soil

Bridge Foundations with Drilled Shafts in Soil were designed and constructed for the following bridges:

- I-29 NB and SB over IA 192
- I-80 EB and WB over IA 192
- Ramp D over IA 192

Source: Iowa DOT Bridge Design Drawings – I-80WB over IA 192 (2016)
Drilled Shafts in Soil

- A drilled shaft foundation tipped in soil has to be approved by the Soils Design Section and the Bridge Office.
- Due to depth of the Top of Rock (>140 feet) drilled shafts tipping in soil was recommended for this area.

Drilled Shafts in Soil - Design

Sample Design Case: I-80 WB Bridge Pier 1

- Pier
  - Approx. 75 feet wide
  - Approx. 20 feet high
- Foundation
  - Four drilled shafts
  - 60 inches diameter
  - 90 feet long shafts
  - C/C spacing 19 feet
  - 5 feet thick pile cap

Source: Iowa DOT Bridge Design Drawings – I-80WB over IA 192 (2016)
Drilled Shafts in Soil – Design

- In accordance with AASHTO LRFD and Iowa DOT guidelines
- For lateral analysis a p-multiplier of 0.9 to 0.5 was used based on the C/C spacing between the shafts and the direction of loading.
- Axial group efficiency of 1.0 was used
- Resistance Factors used in the Analyses
  
<table>
<thead>
<tr>
<th>Resistance Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial side resistance in cohesive and cohesionless soils for drilled shaft (static load test)</td>
<td>0.7</td>
</tr>
<tr>
<td>Drilled Shaft Flexural Resistance Factor- Strength</td>
<td>0.9</td>
</tr>
<tr>
<td>Drilled Shaft Flexural Resistance Factor- Extreme II</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Generalized Soil Profile

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Depth (El)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1: Clay and Silt (Fill)</td>
<td>El. 974</td>
</tr>
<tr>
<td>SPT N-Values 4 to 6 bpf; 5 bpf (Avg)</td>
<td>El. 970</td>
</tr>
<tr>
<td>Layer 2: Fat Clay and Lean Clay</td>
<td>El. 965</td>
</tr>
<tr>
<td>SPT N-Values 2 to 6 bpf; 3 bpf (Avg)</td>
<td>El. 954</td>
</tr>
<tr>
<td>Layer 3: Silty Sand and Poorly Graded Sand with Silt</td>
<td>El. 830</td>
</tr>
<tr>
<td>SPT N-Values 8 to 41 bpf; 23 bpf (Avg)</td>
<td>&gt;140 feet bgs</td>
</tr>
<tr>
<td>Layer 4: Slightly Weathered Limestone Interbedded with Shale</td>
<td></td>
</tr>
</tbody>
</table>
### Drilled Shafts in Soil - Loads

<table>
<thead>
<tr>
<th>Location</th>
<th>Loading Combination</th>
<th>Axial (kip)</th>
<th>Moment X-X (kip-ft)</th>
<th>Moment Y-Y (kip-ft)</th>
<th>Shear Y (kip)</th>
<th>Shear X (kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-80 WB Pier 1</td>
<td>Strength I - γp Max</td>
<td>5,562</td>
<td>6,950</td>
<td>16,194</td>
<td>230</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Strength I - γp Min</td>
<td>4,144</td>
<td>6,640</td>
<td>16,193</td>
<td>230</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Strength III - γp Max</td>
<td>4,709</td>
<td>6,913</td>
<td>2,415</td>
<td>264</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>Strength III - γp Min</td>
<td>3,292</td>
<td>6,601</td>
<td>2,415</td>
<td>264</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>Strength V - γp Max</td>
<td>5,367</td>
<td>7,176</td>
<td>13,610</td>
<td>249</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Strength V - γp Min</td>
<td>3,950</td>
<td>6,865</td>
<td>13,609</td>
<td>249</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Extreme Event II, CT - Case 1 - γp Max</td>
<td>4,953</td>
<td>1,602</td>
<td>12,267</td>
<td>23</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Extreme Event II, CT - Case 1 - γp Min</td>
<td>3,536</td>
<td>1,312</td>
<td>12,267</td>
<td>23</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Extreme Event II, CT - Case 2 - γp Max</td>
<td>4,953</td>
<td>3,624</td>
<td>12,013</td>
<td>178</td>
<td>580</td>
</tr>
<tr>
<td></td>
<td>Extreme Event II, CT - Case 2 - γp Min</td>
<td>3,536</td>
<td>3,320</td>
<td>12,012</td>
<td>178</td>
<td>580</td>
</tr>
<tr>
<td></td>
<td>Service I</td>
<td>4,203</td>
<td>6,392</td>
<td>10,198</td>
<td>225</td>
<td>29</td>
</tr>
</tbody>
</table>

**Notes:**
- X: direction perpendicular to the direction of travel.
- Y: direction parallel to the direction of travel.

- Loads provided by the Bridge Designer for the load cases listed in the table.
- Loads acting at the center and bottom of the cap.

### Drilled Shafts in Soil – Lateral Analyses

<table>
<thead>
<tr>
<th>Structure</th>
<th>Pier 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>60-inch-diameter drilled shafts</td>
</tr>
<tr>
<td>Drilled Shaft Top Elevation</td>
<td>970.2</td>
</tr>
<tr>
<td>Drilled shaft length (feet)</td>
<td>90</td>
</tr>
</tbody>
</table>

**FB-Multiplier Results**
- Maximum lateral deflection at the bearing location—Service (inches): 1.45
- Maximum lateral deflection at the top of the Drilled shaft Cap—Service I (inches): 0.65
- Maximum axial force on a single shaft Perpendicular to traffic—Strength III, Case 2 (kips): 1,730
- Maximum Shear Force Perpendicular to traffic—Strength III, Case 2 (kips): 115
- Maximum Shear Force Parallel to traffic—Strength III, Case 2 (kips): 70
- Maximum moment on a single shaft Parallel to traffic—Strength I (kip-feet): 1,705
- Maximum moment on a single shaft Perpendicular to traffic—Strength III, Case 2 (kip-feet): 2,200
- Maximum Shear Force Perpendicular to traffic—Extreme II (kips): 205
- Maximum moment on a single shaft—Extreme II (kip-feet): 2100
- CDR for flexural Resistance—Strength I: 1.1
- CDR for flexural Resistance—Extreme II: 2.2

Screenshots from lateral analyses FB-Multiplier V4.18 by BSI
Drilled Shafts in Soil – Axial Analyses

<table>
<thead>
<tr>
<th>Substructure</th>
<th>I-80 WB, Pier 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Service Compression Load, F_{service} (kips)</td>
</tr>
<tr>
<td></td>
<td>1,300</td>
</tr>
<tr>
<td></td>
<td>Total Factored Compression Load, F_{strength} (kips)</td>
</tr>
<tr>
<td></td>
<td>1,730</td>
</tr>
<tr>
<td></td>
<td>Nominal Side Resistance (kips)</td>
</tr>
<tr>
<td></td>
<td>2,992</td>
</tr>
<tr>
<td></td>
<td>Nominal End Bearing Resistance (kips)</td>
</tr>
<tr>
<td></td>
<td>811</td>
</tr>
<tr>
<td></td>
<td>Factored Axial Resistance, R_{f} (kips)</td>
</tr>
<tr>
<td></td>
<td>2,663</td>
</tr>
<tr>
<td></td>
<td>Estimated Shaft Length (feet)</td>
</tr>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Estimated Shaft Tip Elevation (feet)</td>
</tr>
<tr>
<td></td>
<td>880.2</td>
</tr>
</tbody>
</table>

- Resistance factor of 0.7 was used as site-specific load test was planned.
- Axial group efficiency of 1.0 was used as C/C distance more than 4 times shaft diameter.
- Analysis ignored the side resistance within one diameter from the top of the shaft due to presence of clay in the upper layer.
- The Nominal Unit Skin Resistance varied between 0.4 – 3.2 ksf.
- The Nominal End Bearing Resistance 41 ksf.

Drilled Shafts in Soil – Load Test

- Confirmation boring performed at the test shaft location.
- Test Shaft:
  - 5.0 feet diameter
  - 90 feet long shaft
  - Installed using polymer slurry
  - 24-inch diameter O-Cell installed 26.8 feet above the shaft base
  - Paired telltale
  - Eleven levels of sister bar strain gages
Drilled Shafts in Soil – Load Test

Excerpt from Report on Drilled Shaft Load Testing by LoadTest, Aug 2016
Corresponding to the depth at which the O-Cell was installed
Based on Load Test:
1,325 kips - 0.46 inches
2,650 kips - 1.36 inches

Mobilized Downward Unit Side Shear

Mobilized Upward Net Unit Side Shear
Drilled Shafts in Soil – Load Test Results

Mobilized Unit End Bearing

- End bearing resistance not fully mobilized based on the %Strain (<2% of Shaft Dia.).
- In separating the end bearing from the lower side shear, we assume that the unit shear below Strain Gage Level 1 is the same as that calculated for the zone between Strain Gage Levels 1 and 2 as the same displacement.

Excerpt from Report on Drilled Shaft Load Testing by LoadTest, Aug 2016
Drilled Shafts in Soil – Production Shafts

Based on the Load Test Results, no change in the design tip elevation for the production shafts.

Conclusions: Drilled Shafts in Rock vs in Soil

- The shaft installation duration was substantially longer for drilled shafts that extended to rock when compared to the drilled shafts in soil.
- The drilled shafts supported in soil had significant cost savings with each shaft saving over $25,000.
- The soil bearing layers are suitable for base grouted shafts, which can further optimize the shaft lengths. Base Grouting has been used in Iowa before with mixed results. Time to give it another chance!
- Specifying newer equipment Installation equipment such as Rotator and Oscillator casing will greatly reduce the shafts installation time and provide better quality shafts.
Construction Equipment - Rotator/Oscillator

General Lesson’s Learned

- Adequate Subsurface Investigation is Paramount. For every $1 you can Spend you maybe to Save $30-$50 in Construction Cost.
- For Design, use DOT specific design methodology if required, but always use FHWA GEC-10 design method as a secondary check.
- Contractor qualification requirements is a minimum for all projects and prequalification of contractor should be considered for large projects.
- Concrete placed using pump line is incompatible with the use of temporary casing method.
- Quality Control by requiring Qualified Inspectors, in addition to quality assurance method CSL, PIT, TIP, and/or Load Testing.
- Split Responsibility between Drilling the Shafts and Pouring the Concrete Must be Avoided. The Shaft Construction Must be Completed by Qualified Contractor including the Concerting.
- It is Important to Complete Trial(also called test, or technique) Shaft Successfully! If Schedule Pressure Eliminates This Step, the Project Scheduled will Suffer Because Remediation Is Costly and Time Consuming.
- Qualified Integrity Testing Company is crucial. Many Integrity test methods require interpretation and qualified testing company can be the difference of meaningful results or inconclusive results.