Construction Considerations in the Selection and Design of Drilled Shaft Foundations for Bridges

By: Paul Axtell, P.E.

Dan Brown and Associates, PLLC
www.danbrownandassociates.com

Overview

- Drilled Shaft Applications for Bridges
- New Machines and Capabilities
- Slurry Advancements
- Design of Rock Sockets
- Base Resistance
- Concrete & Reinforcing
### Characteristics of Bridge Foundations

- Congested sites, existing structures & utilities
- Many equipment moves & difficult access
- Owner specifications & review, often in a design-build environment
- Extensive performance verification; structural integrity and axial resistance
- How do we build it?

### Drilled Shaft Applications

- Bridges where small footprint is needed
- Usually minimal impact on nearby structures
Drilled Shaft Applications

Bridges constructed over water; single shaft per column may avoid cofferdam

Drilled Shaft Applications

Very large foundation loads
Drilled Shaft Applications

Foundations with deep scour or potential liquefaction, lateral spreading

Larger, More Powerful Machines
Influence of Slurry on Axial Resistance

Data from Auburn University

Data from Cape Fear Bridge, Wilmington, NC

Rock Sockets

- Rock excavation can be expensive
- Structural capacity of shaft may govern design
- Axial:
  - End bearing + side shear
- Lateral:
  - Perform sensitivity analysis
Rock Socket – Axial

Ductility of Side Shear Resistance

Butt Displacement

Load vs. Displacement from Statnamic Test
Tampa, Florida

Side Shear vs Displacement from Statnamic Test
Segment 3 (38.25 ft to -50.25 ft) Limestone
Tampa, Florida

End Bearing Load vs. Toe Displacement from Statnamic Test; Tampa, Florida

Approximate yield point 13.4 ksf at 0.29 inches of displacement (tangent approximation).

Note: Includes 2” of side shear.
Rock Sockets - Lateral

6’ Dia. Shaft
40’ Lse to Med Dse Sand over Sandstone (500psi = q_u)

Bottom Cleanout & Inspection

Techniques for slurry or underwater construction
**Base Resistance & Cleanliness**

- It is possible to get a reasonably clean base under water or slurry
- It is not possible to get a perfectly clean base in any circumstances
- Attempts to require a “dry hole” for end bearing may be counterproductive

**Base Resistance in Sands**

- Cohesionless sands may never indicate sound base
- Base grouting can be very effective to enhance base resistance & QA
Base Grouting

- Enhance Axial Resistance
- Improve Reliability
- Mitigate Imperfections in Base Conditions

The Base Grouting Process

1. Shaft Constructed
2. Base Grout Pressure Applied
3. Some Relaxation Occurs
4. Structural Load Applied
Base Grouting Apparatus

- Tube à Manchette
- (using CSL tubes)
- Cover Plate
- CSL Tube

Criteria

- Target Pressure
- Minimum Net Volume
- Limit Upward Shaft Movement
Concrete & Reinforcing

- Constructability Issues that can be significantly reduced during structural design
- Workability and passing ability of concrete
- Reinforcing cage congestion
- Time required to place cage and concrete (full slurry exchange)
  - Our slurry specs aren’t tight enough for large shafts
Structural Design of Drilled Shafts

AASHTO (Article 10.8.3.9.1) :
‘The structural design of drilled shafts shall be in accordance with the provisions of Section 5 for the design of reinforced concrete’

But . . . with adequate consideration of drilled shaft constructability

Drilled Shaft Concrete

- Unique Requirements
  - Workability
  - Workability Retention
  - Passing ability
  - Segregation resistance
  - Bleeding characteristics
  - Heat of hydration (in large diameter shafts)
Need for Workability and Passing Ability

Congested Cage, Concrete with inadequate workability

Concrete with good workability and filling ability

Potential Problem w/ Inadequate Concrete Workability

Tremie
Slurry
Fresh, fluid concrete
Trapped Laitance
Old, stiff concrete
**Characteristics of HPDSC**
*(High Performance Drilled Shaft Concrete)*

- 18”-24” Slump Flow
- Smaller, Rounded Coarse Aggregate
- Increased Sand/Coarse Agg. Ratio
- Supplementary cementing materials (SCM)
  - Fly ash
  - Slag cement
- Extensive use of chemical admixtures

**Chemical Admixtures**

- Air-Entraining Admixture
- Set-Controlling Admixture
  - Retarder
  - Hydration stabilizer (Type D)
- Water Reducing Admixture
- Viscosity Modifying Admixture (VMA)
## Lumber River, Coastal South Carolina

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I/II Cement</td>
<td>500 pcy</td>
</tr>
<tr>
<td>Class F Fly Ash</td>
<td>250 pcy</td>
</tr>
<tr>
<td>Sand</td>
<td>1366 pcy</td>
</tr>
<tr>
<td>#67 Gravel</td>
<td>1071 pcy</td>
</tr>
<tr>
<td>#789 Gravel</td>
<td>395 pcy</td>
</tr>
<tr>
<td>Water</td>
<td>306 pcy</td>
</tr>
<tr>
<td>w/cm</td>
<td>0.41</td>
</tr>
<tr>
<td>Air</td>
<td>2%</td>
</tr>
<tr>
<td>Delvo Stabilizer</td>
<td>8 oz/cwt</td>
</tr>
<tr>
<td>Glenium 3030 NS</td>
<td>8-12 oz/cwt</td>
</tr>
<tr>
<td>Rheomax VMA 358</td>
<td>2 oz/cwt</td>
</tr>
<tr>
<td>Slump Flow</td>
<td>18&quot;-24&quot;</td>
</tr>
</tbody>
</table>

## Mullica River, Atlantic City, NJ

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Cement</td>
<td>526 pcy</td>
</tr>
<tr>
<td>Class F Fly Ash</td>
<td>132 pcy</td>
</tr>
<tr>
<td>Sand</td>
<td>1363 pcy</td>
</tr>
<tr>
<td>#8&quot; CA</td>
<td>1500 pcy</td>
</tr>
<tr>
<td>Water</td>
<td>267 pcy</td>
</tr>
<tr>
<td>w/cm</td>
<td>0.405</td>
</tr>
<tr>
<td>Air</td>
<td>7.5%</td>
</tr>
<tr>
<td>HRWRA (Sika 2100 SP)</td>
<td>7 oz/cwt</td>
</tr>
<tr>
<td>Retarder/Water Reducer (Sika Plastiment)</td>
<td>4 oz/cwt</td>
</tr>
<tr>
<td>Spread</td>
<td>18&quot;-24&quot;</td>
</tr>
</tbody>
</table>
**Strategies for Constructable Cages**

- Use larger diameter shaft
- It’s a compromise (big openings = big bars; small bars for durability).
- Reduce reinforcement below high moment
- Bundle bars (hoops, too) to increase openings
- Use permanent casing for confinement (instead of tight spirals)
- Use 6” cover for tolerance to match column
- Locate column splice above pour cutoff

**Congested Rebar Cage**
Constructability Problems with Congested Reinforcing Cages

<table>
<thead>
<tr>
<th>Essentials of Cage Design for Constructability</th>
</tr>
</thead>
<tbody>
<tr>
<td>♦ Clear Spacing Between All Bars ≥ 5 D of Largest Coarse Aggregate or 6 inches, (whichever is larger)</td>
</tr>
<tr>
<td>♦ Use Only Lap or Mechanical Splices</td>
</tr>
<tr>
<td>♦ Locate Splices As Deep As Possible</td>
</tr>
</tbody>
</table>
Limits on Longitudinal Steel

AASHTO 5.7.4.2:

\[ 1% \leq \rho_s \leq 8\% \]

\[ \frac{A_s f_y}{A_g f'_{c}} \geq 0.135 \]

Seismic Zones 2, 3, and 4:

\[ \rho_s \leq 6\% \]

Practical Limits for Drilled Shafts

- Typically: \[ 1\% \leq \rho_s \leq 2\% \]
- High seismic: \[ 2\% \leq \rho_s \leq 3\% \]
- As the value of \( \rho_s \) approaches 4\% it becomes impossible to ensure flow of concrete and should be avoided (constructability)
- For axial loading only, when cross-section is larger than required:
  \[ \text{minimum } \rho_s \geq 0.5\% \]
Bundle Bars

Partial Length Cage
Permanent Casing

- Often exists to help with constructability, particularly for water crossing bridges
- Provides confinement
- Increases flexural stiffness and capacity
- Consider corrosion losses
- Not fully utilized near ends of casing

Summary

- Bigger shafts are possible
  - may avoid need for coffer dam
  - may reduce impact on adjacent structures
- Count on base and side resistance
  - demonstrate with load test
  - reduces socket length
  - don’t get carried away with lateral design
- Concrete & reinforcing designed considering constructability
Thanks for Listening!