Lessons Learned: Design and Construction of Large Diameter Drilled Shafts

Dan A. Brown, P.E., Ph.D.
Outline

- Reasons for Using Large Diameter Shafts
- Design Considerations and Construction Challenges
- Selected Case Histories (woven throughout)
Advantages of Large Diameter Shafts

- Elimination of Cofferdams or Footings
- Congested Sites – Small Footprint
- Very High Strength (esp. overturning)
- Extreme Events
  - Deep Scour
  - Seismic and Liquefaction
Elimination of Cofferdams or Footings
Congested Sites – Small Footprint
Congested Sites – Nearby Structures
High Strength - Axial
High Strength - Flexural
Example – Stan Musial Bridge, St. Louis

- 1500ft span wide deck = high axial
- Scour to rock with very high seismic, vessel collision forces
- ATC Foundation Design:
  - 2x3 group @ 12ft dia
  - Small footprint with 55ft x 88ft pilecap
  - Load testing program
Example – Stan Musial Bridge, St. Louis

Over 40ksf avg mobilized unit side resistance

450ksf base resistance mobilized at < ¼ inch displ

1.5D socket length controlled by flexure
Example – Beck St. Bridge, Salt Lake City

- Wide interstate bridge over multiple RR tracks
- Many utilities: water main, petroleum pipeline, natural gas
- Big seismic loads with liquefaction, lateral spreading
Example – Beck St. Bridge, Salt Lake City

- Lateral forces from liquefaction-induced lateral spreading

Estimated lateral spread of up to 7 ft
Example – Beck St. Bridge, Salt Lake City

- Oscillator method minimized impact on adjacent structures
Design & Construction Considerations

- Lack of Redundancy
- Constructability
- Limitations of Size, Depth
- Support Fluid Issues
- Tremie Concrete
Design & Construction Considerations

- Lack of Redundancy
  - Need for High Degree of Reliability
    - More intensive investigation
    - Closer inspection
Design & Construction Considerations

- Lack of Redundancy
  - Need for High Degree of Reliability
  - Integrity Testing is required
  - AASHTO resistance factor reduction

Section 10.5.5.2.4

Where the resistance factors provided in Table 10.5.5.2.4-1 are to be applied to a single shaft supporting a bridge pier, the resistance factor values in the Table should be reduced by 20 percent. Where the resistance factor is decreased in this manner, the $\eta_R$ factor provided in Article 1.3.4 shall not be increased to address the lack of foundation redundancy.
Design & Construction Considerations

- Constructability
- Column/Shaft Connection
Design & Construction Considerations

- Constructability
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Design & Construction Considerations

- Constructability
- Column/Shaft Connection

Beck St. Bridge, Salt Lake City
Design & Construction Considerations

- Constructability
  - Column/Shaft Connection
  - Reinforcement - splices
Design & Construction Considerations

- Constructability
  - Column/Shaft Connection
  - Reinforcement – cage handling

From the Huey P. Long Bridge, New Orleans
Design & Construction Considerations

- Constructability
  - Column/Shaft Connection
  - Reinforcement
    - AASHTO Design Code now allows up to 100ksi yield strength
    - Need to mitigate congestion for constructability
Design & Construction Considerations

- Constructability
  - Column/Shaft Connection
  - Reinforcement
  - Casing Installation

Temp inside Permanent:
- Audubon Bridge
- Benetia-Martinez
We won't do this detail again!
Design & Construction Considerations

- Constructability
  - Column/Shaft Connection
  - Splices
  - Casing Installation

Permanent extension below temp casing: Tilikum Crossing, Portland, OR
Design & Construction Considerations

- Lack of Redundancy
- Constructability
- Limitations of Size, Depth

Examples:
- Tilikum Crossing – Casing at limits, high oscillator forces on work platform
- Schuyler-Heim Bridge, Long Beach (photo)
Gilmerton Bridge, Chesapeake, VA
Base Bid Design

- Full length 12ft dia. permanent casing
- Low vibration req’d
- Tip at -170ft
- VDOT engineer objected to having teeth on the casing
Our VE Design

- Temp casing full length (115ft)
- 115ft sufficient for lateral extract to perm level (65ft)
- 3ksf unit side in Yorktown
- Base grout to 350psi (51ksf) to achieve base resistance

<table>
<thead>
<tr>
<th>Shaft Number</th>
<th>Maximum Sustained Grout Pressure (psi)</th>
<th>Maximum Grout Volume (cubic feet)</th>
<th>Estimated Net Grout Volume (cubic feet)</th>
<th>Maximum Upward Displacement (Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pier 9 – SW Shaft</td>
<td>380</td>
<td>110.5</td>
<td>100.5</td>
<td>0.063</td>
</tr>
</tbody>
</table>

(1) Net volume calculated as follows:
Net Volume = Gross Volume - Theoretical Volume of Grout Tubes (cu. ft.)
Theoretical volume per tube = 2.5 cu. ft./tube x 4 tubes = 10.0 cu. ft.
Our VE Design

- PCL had a claim re: constructability ($\approx$2m)
- Our VE saved PCL money
- Eventually accepted as a no-cost change

(A secret: the base grout was really just for show)
Case History – Goethals Bridge

![Diagram of Goethals Bridge with legend and borehole data]

- New Jersey Test Shaft Locations
- P1NJ
- P1NY
- New York Anchor Piers
- P2NY
- New York Test Shaft Locations

**Boring Legend**

<table>
<thead>
<tr>
<th>KEY</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>Fill</td>
</tr>
<tr>
<td>②</td>
<td>Organic Clay &amp; Peats</td>
</tr>
<tr>
<td>③</td>
<td>Glacial Clays and Silts and Gravel</td>
</tr>
<tr>
<td>④</td>
<td>Weathered Bedrock</td>
</tr>
<tr>
<td>⑥</td>
<td>Bedrock</td>
</tr>
</tbody>
</table>

**Example of Thick Weathered Rock**

**Table of Boring Data**

<table>
<thead>
<tr>
<th>Boring</th>
<th>Run</th>
<th>Depth (ft)</th>
<th>%C</th>
<th>%M</th>
<th>%L</th>
<th>%R</th>
<th>%T</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>66.8-61.8</td>
<td>54%</td>
<td>100%</td>
<td>90%</td>
<td>0%</td>
<td>5%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>61.8-66.8</td>
<td>55%</td>
<td>95%</td>
<td>76%</td>
<td>5%</td>
<td>3%</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>68.8-71.8</td>
<td>60%</td>
<td>100%</td>
<td>90%</td>
<td>5%</td>
<td>5%</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>71.8-76.8</td>
<td>60%</td>
<td>100%</td>
<td>36%</td>
<td>82%</td>
<td>5%</td>
<td>5%</td>
<td></td>
</tr>
</tbody>
</table>

- Goethals Bridge Replacement
- Staten Island, New York
- Haley & Aldrich
- Jersey Boring and Drilling
- 7/85-7/86

**Box 1 of 2**

- X-Mechanical Break
- Continued in Box 2 of 2
Case History – Goethals Bridge

Fig. 6. Loading conditions and moment diagram considering seismic and lateral spread effects.
Case History – Goethals Bridge

Static Lateral Load Test Setup
Case History – Goethals Bridge

Statnamic Lateral Load Test Setup
Case History – Goethals Bridge

Static and Statnamic Lateral Load Results

[Graph showing static and statnamic lateral load results with various loads labeled and displacement at load point elevation indicated.]
Goethals Bridge - Keys

- Permanent casing into rock
- Allowance for weathered rock zone near surface
- Maintain fluid – avoid dewatering
Design & Construction Considerations

- Lack of Redundancy
- Constructability
- Limitations of Size, Depth
- Support Fluid Issues
  - Time required for construction

Missouri River Bridge, Kansas City:
- Polymer slurry used to preserve shale

<table>
<thead>
<tr>
<th>Sample</th>
<th>Natural Moisture Content (%)</th>
<th>Slake Durability Index</th>
<th>Durability Rating Based on Shear Strength Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>River Water</td>
<td>8.3</td>
<td>II</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Polymer Slurry</td>
<td>8.3</td>
<td>II</td>
<td>Hard, more durable</td>
</tr>
</tbody>
</table>

Table 1: Slake Durability Test Results.
Case History: St. Croix Bridge, Minnesota
1995 Load Test

- Rock socket drilled with water
- Some caving difficulties
- Hole open for 17 days
- Bottom cleaning with bucket only
- Conventional concrete placed w/ 4” pump line

Figure from Mike O’Neill’s Report on Load Testing
Recommended Design Values for sandstone:

- $f_s = 6.6$ ksf, top 30ft
- $f_s = 9$ ksf, below 30ft
- $q_b = 19$ ksf, below 30ft
- Base grouting recommended for consideration to improve base resistance
2012 Load Test

- Base grouting considered, but not employed
- Socket drilled with Polymer slurry
- Air lift cleaning of base with mini-SID inspection
- Tremie concrete, 24” spread
- Integrity testing with CSL to verify concrete quality

Figure E7 – Green gray sandstone cuttings (Reno Sandstone)
2012 Load test

- 8ft dia x 45ft long rock socket
- avg $f_s = 30$ ksf @ 0.2” displacement
- $q_b = 275$ ksf @ 1”, 400 ksf @ 1.3” (without base grouting)
Lesson from St. Croix

- Performance tied to installation methods
- Polymer fluid helped minimize sloughing in weak sandstone layers
- Contractors work more carefully with close supervision
Design & Construction Considerations

- Lack of Redundancy
- Constructability
- Limitations of Size, Depth
- Support Fluid limitations
  - Time required for construction
  - Polymer v Bentonite

Data from Cape Fear Bridge, Wilmington, NC (Brown, Muchard, & Khouri 2002)
Design & Construction Considerations

- Lack of Redundancy
- Constructability
- Limitations of Size, Depth
- Support Fluid limitations
  - Time required for construction
  - Polymer v Bentonite
  - Limitations in pervious strata

Honolulu Elevated Rail
Case History: Adaptable Design

Sellwood Bridge, Portland, OR
Piers 4, 5, 6 in Willamette River

- 4 to 6 drilled shafts at each pier, 10ft dia.

- Highly variable stratigraphy, great uncertainty w.r.t. conditions at each shaft location

- Constructability risk with great depth, cobbles & boulders
Value Engineering Design at Sellwood

- Construct using segmental casing to mitigate risk of caving
- Rely on performance in Troutdale, CFD based on measurements from other nearby project
- Multi-path to acceptance at each drilled shaft location based upon field observation
## Value Engineering Design at Sellwood

| Pier 4 | 1. For competent basalt bedrock encountered between Elevations -70ft and -90ft:  
|        |   a. Minimum 15ft of length in basalt bedrock of Grade R2 or better.  
|        | 2. For competent basalt bedrock encountered below Elevation -90ft:  
|        |   a. Minimum 12.5ft of length in basalt bedrock of Grade R2 or better.  
|        | 3. In all cases, Tip Elevation must be -85ft or deeper. |
| Pier 5 | 1. Minimum 10ft of length in Troutdale, basalt bedrock, or any combination of the two with material of Grade R1 or better; and  
|        | 2. Tip Elevations must be -140ft or deeper. |
| Pier 6 | 1. For bedrock with overlying Troutdale or weathered rock:  
|        |   a. Minimum 7ft of length in Troutdale or other bedrock of Grade R1 or better; plus  
|        |   b. Minimum 12ft of length in basalt bedrock of Grade R2 or better.  
|        | 2. For bedrock without overlying Troutdale or weathered rock:  
|        |   a. Minimum 15ft of length in basalt bedrock of Grade R2 or better.  
|        | 3. In all cases, Tip Elevation must be -25ft or deeper. |
Design & Construction Considerations

- Lack of Redundancy
- Constructability
- Limitations of Size, Depth
- Support Fluid Issues
- Tremie Concrete
  - Increased demand for workability

Guide to Tremie Concrete for Deep Foundations

By the joint EFFC/DFI Concrete Task Group
From the Tremie Guide

SLUMP FLOW CURVE RELATED TO YIELD STRESS AND RECOMMENDED RANGE FOR TREMIE CONCRETE (SEE APPENDIX A.1.1 AND FIGURE 6)

Yield Stress

SLUMP Flow [mm]

200 300 400 500 600 700

medium yield stress

lower tolerance value

upper tolerance value

Specified Target Value

Example

medium/low yield stress

Range for Target Values

specific consideration of stability

specific consideration of filling ability

18”

22”
“Good Looking” Tremie Concrete

- Good cohesion
- Good Visual Stability:
  - No wet sheen on surface
  - Uniformly spread aggregate
  - No water or paste halo
- Good Flow

Note: Source of photograph unknown
Summary: Large Diameter Drilled Shafts

- Opportunities thanks to equipment, construction innovations
- Design must consider reliability, constructability
- Careful planning of construction to mitigate risks