Advances in the Design and Construction of Drilled Shafts in Rock

John Turner, Ph.D., P.E., PG, D.GE

ADSC Mid-Atlantic Section
Drilled Shaft Seminar
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Key Points

- Reliable analytical tools for selecting design values of side and base resistances have evolved and are supported by results of load tests
- Side and base resistances can be combined
- Design rock sockets to be as large as needed and not larger
- Keys to successful design and construction are:
  - Site characterization
  - Construction means and methods that allow the contractor to control quality (QC) and which facilitate verification of quality (QA)

Design Equations: Axial Compression

Reference:
Drilled Shafts: Construction Procedures and LRFD Design Methods
FHWA GEC 10, 2010

LRFD Design Equation:
\[ \sum \gamma_i Q_i \leq \sum \phi_i R_i \]
\[ \sum \phi_i R_i = \sum \phi_{SN,i} R_{SN,i} + \phi_N R_{BN} \]

Unit Side Resistance in Rock

Most recent analysis of existing data shows that for design of “normal” rock sockets:
C = 1.0 mean value

“Normal” Rock Socket:

Can be excavated using conventional rock tools (augers, core barrels) without caving and without the use of casing or other means of support (e.g., grouting ahead of excavation)
- C = 1.0 recommended
- \( q_u \) limited to compressive strength of concrete

AASHTO: Reduction for Lower Quality Rock

Reduce side resistance on the basis of RQD:

<table>
<thead>
<tr>
<th>RQD%</th>
<th>Reduction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Closed Joints</td>
</tr>
<tr>
<td>100</td>
<td>1.00</td>
</tr>
<tr>
<td>70</td>
<td>0.85</td>
</tr>
<tr>
<td>50</td>
<td>0.60</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
</tr>
<tr>
<td>20</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Experience suggests the above is applicable only when a rock socket cannot be excavated without support.
Rock: Base Resistance

in terms of uniaxial compressive strength:

\[ q_{BN} = N_{cr}^* \times q_u \]

\[ N_{cr}^* = \text{bearing capacity factor} \]

For design in “competent” rock:

\[ q_{BN} = 2.5 \times q_u \]

Base Resistance in Jointed or Fractured Rock Mass

Strength of fractured rock mass, and bearing resistance, can be characterized using the Hoek-Brown strength criterion.

Combining Side and Base Resistances

‘Strain Compatibility’ between side and base resistance of rock sockets

- often cited as a reason to neglect one or the other
- Is it real?

AASHTO 7th Ed.

10.8.3.5.4a-General

Drilled shafts in rock subject to compressive loading shall be designed to support factored loads in:

- Side-wall shear comprising skin friction on the wall of the rock socket; or
- End bearing on the material below the tip of the drilled shaft; or
- A combination of both

"... Where end bearing in rock is used as part of the axial compressive resistance in the design, the contribution of skin friction in the rock shall be reduced to account for the loss of skin friction that occurs once the rock shear strength begins to drop to a residual value."

Illustrative Case 1: Goethals Bridge

Elizabeth, NJ to Staten Island, NY

AASHTO 7th Ed.

C10.8.3.5.4d – Commentary (added in 2015)

. . before making a decision to omit tip resistance, careful consideration should be given to applying available methods of quality construction and inspection that can provide confidence in tip resistance. Quality construction practices can result in adequate clean-out at the base of rock sockets, including those constructed by wet methods. Inspection tools, such as the Shaft Inspection Device (SID), probing tools, borehole calipers, and others, can be applied more effectively to ensure quality of rock sockets prior to concrete placement (Crapps and Schmertmann 2002, Turner 2006). In many cases, the cost of quality control and assurance is offset by the economies achieved in socket design by including tip resistance. Load testing provides a means to verify tip resistance in rock.
Passaic Formation (Triassic-Jurassic)

Reddish brown siltstone, w/ interbedded sandstone and shale

9-ft Dia Test Shaft w/ permanent casing to rock, 8.5-ft dia rock socket

Load Test at Goethals 8.5-ft Diameter Socket

Results of O-Cell Test, NJ 9-ft Shaft

<table>
<thead>
<tr>
<th>Socket Diameter</th>
<th>8.5 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socket length</td>
<td>25 ft</td>
</tr>
<tr>
<td>Avg side resistance above O-cell</td>
<td>36 ksf @ .53 inch</td>
</tr>
<tr>
<td>Base resistance</td>
<td>335 ksf @ .60 inch</td>
</tr>
<tr>
<td>Design concrete $f_c'$</td>
<td>5,000 psi</td>
</tr>
</tbody>
</table>

Mean $q_u = 8,000$ psi > design $f_c' = 5,000$ psi
by GEC 10: $f_{sn} = 39$ ksf, with $C = 1$ and using concrete strength
Compared to mobilized $f_{sn} = 36$ ksf at .53 inch

Bearing zone: $q_u = 8,000$ psi > design $f_c' = 5,000$ psi
Based on ACI design eq. for nominal strength of R/C, $q_{sn}$ would be limited to $\approx 520$ ksf
Compared to 335 ksf mobilized at .60 inches (0.6% diameter)
Design $d_{sn} = 300$ ksf

Illustrative Case 2: Dulles Metro Silver Line

Single columns on monoshaft foundations

Illustrative Case 2: Dulles Metro Silver Line*

Elevated Guideway at Dulles Airport

* Photos and load test information for Dulles Metro courtesy of Schnabel Engineering
Monoshafts in Balls Bluff Formation Siltstone

Balls Bluff Formation (Triassic-Jurassic)

Reddish brown siltstone with interbedded v. fine to mdm grained sandstone and silty shale and shale

Three Load Tests on 6-ft Dia Test Shafts permanent casing to rock

Load Test at Dulles on 6-ft Diameter Socket

Test Shaft No. 2

Summary of Results of O-Cell Tests Dulles 6-ft Shaft

<table>
<thead>
<tr>
<th>Socket Length (ft)</th>
<th>TS-1</th>
<th>TS-2</th>
<th>TS-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Mobilized Unit Side Resistance (ksf)</td>
<td>15.8</td>
<td>22.8</td>
<td>20.9</td>
</tr>
<tr>
<td>Max Mobilized Unit Side Resistance (ksf)</td>
<td>27.4</td>
<td>28.8</td>
<td>21.6</td>
</tr>
<tr>
<td>Upward Displacement (in)</td>
<td>0.21</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>Mobilized Unit Base Resistance (ksf)</td>
<td>293</td>
<td>299</td>
<td>288</td>
</tr>
<tr>
<td>Downward Displacement (in)</td>
<td>1.41</td>
<td>0.07</td>
<td>0.13</td>
</tr>
<tr>
<td>Design Concrete Strength, f'c (psi)</td>
<td>4,000 psi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Summary Analysis of Load Test Results Dulles 6-ft Shafts

For Test Shaft 1:
Mean qn = 3,200 psi < design f'c = 4,000 psi
by GEC 10: fmn = 31 ksf, with C = 1 and using rock strength (qR)
Compared to mobilized fmn = 27 to 32 ksf at .20 to .31 inch

Bearing zone: qn = 4,000 psi = design f'c = 4,000 psi
Based on ACI design eq. for nominal bearing strength of concrete, qmn
would be limited to = 290 ksf
Compared to 288 to 299 ksf mobilized in test shafts

For comparison: Design Allowable qB = 72.5 ksf for RQD < 50
qB = 36.0 ksf for RQD > 50
Illustrative Case 3: Fore River Bridge

Quincy to Weymouth, MA

Weymouth Formation
Argillite (Cambrian)

Load Test at Fore River Bridge
5.5-ft Diameter Socket

Quincy Test Shaft

Results of Quincy O-Cell Test at FRB

Diameter 5.5 ft
Socket length 24.5 ft
Avg side resistance above O-cell 53 ksf @ .27 inch
Base resistance 296 ksf @ .30 inch
Design concrete $f' = 4,000$ psi

Over test shaft, average $q_u = 5,080$ psi > design $f'_u = 4,000$ psi
by GEC 10: $f_{w1} = 35$ ksf, with $C = 1$ and using concrete strength
Compared to mobilized $f'_{w1} = 53$ ksf at .27 inch

Bearing zone: $q_u = 6,000$ psi > design $f'_u = 4,000$ psi
Based on ACI design eq. for nominal strength of R/C, $q_{BN}$ would be
limited to $q_{BN} = 0.4 (6,000$ psi) = 2,400 psi = $345$ ksf
Compared to 296 ksf mobilized at .30 inches (0.5% of diameter)

Additional Projects Illustrating the Following Aspects of Rock Socket Behavior

1. Validity of design equations for nominal unit side and base resistances
2. Mobilization of side and base resistances at compatible displacements

The Bridge at Antlers

I-5 North of Redding, CA
Sacramento River – Lake Shasta

Bragdon Formation (Mississippian)
- Metasandstone, metashale, and metaconglomerate
- Sloped bedding/foliation, 25-45 degrees from horizontal
### Results of O-Cell Test at Antlers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>6.5 ft</td>
</tr>
<tr>
<td>Socket length</td>
<td>35 ft</td>
</tr>
<tr>
<td>Avg side resistance above O-cell</td>
<td>33 ksf @ .11 inch</td>
</tr>
<tr>
<td>Base resistance</td>
<td>532 ksf @ .53 inch</td>
</tr>
<tr>
<td>Design concrete $f'_c$</td>
<td>4,000 psi</td>
</tr>
</tbody>
</table>

Over test shaft, average $q_u = 8,500$ psi > design $f'_c = 4,000$ psi

by GEC 10: $f_{SN} = 35$ ksf, with $C = 1$ and using concrete strength

Compared to mobilized $f_{SN} = 33$ ksf at approximately .1 inch

Bearing zone: $q_u = 9,700$ psi > design $f'_c = 4,000$ psi

Based on ACI design eq. for nominal strength of R/C, $R_{EN}$ would be limited to $= 420$ ksf

Compared to $532$ ksf mobilized at .53 inches (0.7% of diameter)

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### Load Test at Pitkins Curve Bridge

3.5-ft Diameter Socket

<table>
<thead>
<tr>
<th>Movement (inches)</th>
<th>O-Cell Load (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>2.0</td>
<td>4</td>
</tr>
<tr>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>3.0</td>
<td>6</td>
</tr>
</tbody>
</table>

Franciscan mélange and BIM-rocks consists of alternating layers of:

1. JRms: Jurassic/Cretaceous metasediments
   - sandstones and mudstones exhibiting low-grade metamorphism; tectonically deformed
     resulting in shear zones and variable fracturing.

2. JRmb: Jurassic/Cretaceous metabasalt
   - low-grade metamorphosed (greenstone) blocks embedded in the JRms

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### Results of O-Cell Test at Pitkins Curve

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>3.5 ft</td>
</tr>
<tr>
<td>Socket length</td>
<td>35 ft</td>
</tr>
<tr>
<td>Avg side resistance in rock</td>
<td>28 ksf</td>
</tr>
<tr>
<td>Base resistance</td>
<td>396 ksf</td>
</tr>
<tr>
<td>Concrete $f'_c$</td>
<td>4,000 psi</td>
</tr>
</tbody>
</table>

*Sidewall rock was caving during construction of test shaft; used 'plug-ahead' method in order to complete excavation

Over test shaft, average $q_u = 7,300$ psi > design $f'_c = 4,000$ psi

Average RQD over socket length $= 25$

by GEC 10: with $C = 1$ and using concrete strength, with reduction factor for fractured (and caving) rock of $.47$, $f_{SN} = 16.5$ ksf,

Compared to mobilized $f_{SN} = 28$ ksf with no strain softening

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### O-Cell Test at Pitkins Curve

Bearing zone: $q_u = 4,700$ psi > design $f'_c = 4,000$ psi

Based on ACI design eq. for nominal strength of R/C, $R_{EN}$ would be limited to $= 420$ ksf

Based on analysis for fractured rock (Hoek Brown), estimated $q_{EN} = 0.7$, $q_u = 470$ ksf

Compared to $396$ ksf mobilized at .75 inches downward displacement (1.8% of diameter)
The New Mississippi River Bridge (MRB)
Saint Louis

High strength competent limestone
Test shaft socket diameter same as production shaft diameter = 11 ft

O-Cell Test on 11-ft Diameter Socket at New MRB

- Nominal Diameter: 11 ft as-built 11.5 ft
- Socket length: 23.3 ft
- Avg unit side resistance: 44 ksf @ .14 in
- Base resistance: 460 ksf @ .14 in

Along test shaft, average $q_s = 24,000$ psi > $f_c' = 5,000$ psi
by GEC 10: $f_{sh} = 39$ ksf, with $C = 1$ and using concrete strength
Compared to mobilized $f_{sh} = 44$ ksf
Bearing zone: $q_u = 12,000$ psi > $f_c' = 5,000$ psi
Based on ACI design eq. for nominal strength of R/C $q_{nom}$ would be limited to ≈ 520 ksf
Compared to 460 ksf mobilized at .14 inches (0.1% of diameter)

Reference: Axtell and Brown, DFI Journal, Dec 2011

... and others

- KC ICON Missouri River (Bond Bridge) shale
- Nashville (ADSC SE Chapter) limestone
- Lawrenceville, GA (ADSC SE Chapter) Piedmont PWR and gneiss
- Burma Road Overpass, WY weak sandstone

Typical side load transfer behavior in rock

- US 36 over Republican River, KS; grey thinly laminated shale
  - no evidence of strain softening

Are There Exceptions?

Geomaterials in which side and/or base resistance mobilization is either very sensitive to construction or is otherwise unreliable?

YES

Some examples
- Argillaceous clay shales prone to sidewall smearing, e.g., Denver, Dallas
- Franciscan Complex rocks in CA referred to as mélange, BIM rocks: base resistance is all over the map

However, socket behavior and design in these environments should not be generalized to all rock sockets. Experience is telling us these are exceptions, not the rule.

RQD and Rock Sockets: Be Careful

From Deere and Deere (1988) “The Rock Quality Designation (RQD) Index in Practice”.

ABSTRACT: The Rock Quality Designation (RQD) index was introduced 20 years ago at a time when rock quality information was usually available only from geologists’ descriptions and percent of core recovery. The RQD is a modified core recovery percentage in which unrecovered core, fragments and small pieces of rock, and altered rock are not counted so as to downgrade the quality designation of rock containing these features. Although originally developed for predicting tunneling conditions and support requirements, its application was extended to correlations with in situ rock mechanical properties and, in the 1970’s, to forming a basic element of several classification systems. Its greatest value, however, remains as an exploratory tool where it serves as a red flag to identify low-RQD zones which deserve greater scrutiny and which may require additional borings or other exploratory work. Case history experience shows that the RQD red flag and subsequent investigations often have resulted in the deepening of foundation levels and the reorientation or complete relocations of proposed engineering structures, including dam foundations, tunnel portals, underground caverns, and power facilities.
Example: Low RQD, High Socket Resistances

Test shaft w/ tip in C4: \( q_b = 319 \text{ ksf} @ \delta = .21 \text{ inch} \)
\( f_s = 31 \text{ ksf} \)

*RQD does not account for orientation of discontinuities, in this case horizontal*

What Does it Take to Obtain and Count on Mobilization of Base Resistance?

A clean base and some means to measure it, i.e. Quality Control and Quality Assurance

QC Tools:
- Contractors' Means
- cleanout buckets
- airlift
- Specifications
- Installation Plan

Verifying Base Resistance (cont)

QA Tools:
- Shaft Inspection Device (SID)
- Weighted tape
- Sonic caliper
- Competent inspection

Summary of Key Points

- Reliable analytical tools for selecting design values of side and base resistances for rock sockets have evolved and are supported by results of load tests
- Side and base resistances can be combined
- Design rock sockets to be as large as needed . . . . . . and not larger
- Keys to successful design and construction are:
  - site characterization
  - construction means and methods that allow the contractor to control quality (QC) and permit verification of quality (QA)

Questions?

Thank you