Axial Design of Drilled Shafts in Rock

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

\[
\sum \gamma_i Q_i \leq \sum \phi_i R_i
\]

\[
\sum \phi_i R_i = \sum_{i=1}^{n} \phi_{S,i} R_{SN,i} + \phi_B R_{BN}
\]
Unit Side Resistance in Rock

\[ \frac{f_{SN}}{P_a} = C \sqrt{\frac{q_u}{P_a}} \]

Most recent analysis of existing data shows that for design of “normal” rock sockets:

- \( C = 1.0 \) mean value
- \( C = 0.63 \) lower bound, encompasses 90% of data
- \( C = 0.50 \) absolute lower bound to encompass 100% of data
“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
Reduce side resistance on the basis of RQD:

<table>
<thead>
<tr>
<th>RQD%</th>
<th>Closed Joints</th>
<th>Open or Gouge-Filled Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.00</td>
<td>0.85</td>
</tr>
<tr>
<td>70</td>
<td>0.85</td>
<td>0.55</td>
</tr>
<tr>
<td>50</td>
<td>0.60</td>
<td>0.55</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>20</td>
<td>0.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Experience suggests the above is applicable only when a rock socket cannot be excavated without support
in terms of uniaxial compressive strength:

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

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

For design in “competent” rock:

\[ q_{BN} = 2.5 \ q_u \]
Strength of fractured rock mass, and bearing resistance, can be characterized using the *Hoek-Brown* strength criterion.
‘Strain Compatibility’ between side and base resistance of rock sockets

• *often cited as a reason to neglect one or the other*

• *Is it real?*
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 shear deformation along the shaft sides is greater than the peak rock shear deformation, i.e., once the rock shear strength begins to drop to a residual value.”
C10.8.3.5.4d – Commentary (revised in 2017)

. . 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. 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.
Illustrative Case 1: Goethals Bridge

Elizabeth, NJ to Staten Island, NY
Reddish brown shale, siltstone, and sandstone
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

Osterberg Cell Load-Displacement
NJ9TS - Goethals Bridge - Elizabeth, NJ
## Results of O-Cell Test, NJ 9-ft Shaft

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socket Diameter</td>
<td>8.5 ft</td>
</tr>
<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 $q_u \approx 8,000$ 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: $q_u \approx 8,000$ psi > design $f_c' = 5,000$ psi

Based on ACI design eq. for nominal strength of R/C, $q_{BN}$ would be limited to $\approx 550$ ksf (factored $q_b \approx 415$ ksf)

Compared to 335 ksf mobilized at .60 inches (0.6% diameter)

Design $q_{BN} = 300$ ksf
Illustrative Case 2: Fore River Bridge

Quincy to Weymouth, MA

Weymouth Formation
Argillite (Cambrian)
Quincy Test Shaft

C1:  
R = 0, RQD = 0

C3:  
R = 90, RQD = 69

C4:  
R = 95, RQD = 23

C5:  
R = 79, RQD = 63

C6:  
R = 100, RQD = 32

Top of Weathered Bedrock

Weathered Bedrock

Quincy Test Shaft Rock Socket L = 24.5 ft

66-inch dia permanent casing

O-cell assembly

Intact Bedrock

begin coring:

8 ft

5 ft

5 ft

5 ft

5 ft

2 ft

5 ft

Quincy Test Shaft
Load Test at Fore River Bridge
5.5-ft Diameter Socket

Osterberg Cell Load vs. Displacement
Fore River Bridge, MA - Quincy Test Shaft

Movement (inches)

O-Cell Load (kips)
Results of Quincy O-Cell Test at FRB

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Diameter</td>
<td>5.5 ft</td>
</tr>
<tr>
<td>Socket length</td>
<td>24.5 ft</td>
</tr>
<tr>
<td>Avg side resistance above O-cell</td>
<td>53 ksf @ .27 inch</td>
</tr>
<tr>
<td>Base resistance</td>
<td>296 ksf @ .30 inch</td>
</tr>
<tr>
<td>Design concrete $f'_c$</td>
<td>4,000 psi</td>
</tr>
</tbody>
</table>

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

Bearing zone: $q_u \approx 6,000$ psi > design $f'_c = 4,000$ psi
Based on ACI design eq. for nominal strength of R/C, $q_{BN}$ would be limited to $\approx 460$ ksf (factored $q_b \approx 343$ ksf)

$q_{BN} = 0.4 \times (6,000 \text{ psi}) = 2,400 \text{ psi} = 345 \text{ ksf}$
Compared to 296 ksf mobilized at .30 inches (0.5% of diameter)
Two Test Shafts
Biaxial Load Test

1. Rock Socketed
   • 48-in DIA to top of PWR at 29 ft
   • 42-in DIA; augered through 9 ft of PWR
   • 40.5-in DIA rock socket, 15 ft long, rock auger/core barrel

2. Tip Bearing on Rock
   • 72-in DIA to PWR
   • 66-in DIA to top of rock
Wolf Creek Formation

Late Proterozoic to Early Ordovician(?) sheared schists, gneisses, and amphibolites

Described in Core Logs as Hornblende Gneiss
Test Shaft 1 Profile

- 48 in Earth Auger
- SOIL Dia = 48 in
- 29
- 40.5 in Rock Auger
- PWR Dia = 42 in
- 38
- 40.5 in Core
- ROCK Dia = 40.5 in
- 41
- 40.5 in Rock Auger
- 53

= Strain Gauge Levels
= Ocell

[Image of construction site with equipment and materials]
Rock Properties

Uniaxial Compressive Strength:

- 4 Core specimens tested
- \( q_u = 7,000 \) to 11,300 psi
Load Test at Lawrenceville
Test Shaft 1, 40 ½ inch DIA Socket

Unit Side Resistance vs. Normalized Upward Displacement

- ROCK - Shaft 1 - Nominal Dia = 40.5"
- PWR - Shaft 1 - Nominal Dia = 42"
- PWR - Shaft 2 (35-42.5) - Nominal Dia = 66"
- PWR - Shaft 2 (19-35ft) - Nominal Dia = 66"

≈ 0.6 in

52 ksf

15 ksf
Load Test at Lawrenceville
Test Shaft 1, 40 ½ inch DIA Socket

Unit Base Resistance vs. Normalized Downward Displacement

Shaft 1 - Nominal Dia = 40.5in
Shaft 2 - Effective Dia = 24in
E=35ksi
E=110ksi

850 ksf @ ≈ 1.6 in
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
Bridge at Pitkins Curve, Big Sur, CA  
Antlers Bridge, I-5 North of Redding  
KC ICON Missouri River (Bond Bridge)  
Mississippi River Bridge (Stan Musial Bridge)  
Dulles Metro Phase II  
Nashville (ADSC SE Chapter)  
Burma Road Overpass, WY  

... and others
Typical side load transfer behavior in rock

Mobilized Net Unit Side Shear
TS 1 - Burma Road Overpass - Gillette, WY

no evidence of strain softening

US 36 over Republican River, KS; grey thinly laminated shale
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.
Test shaft w/ tip in C4: \( q_b = 319 \text{ ksf} @ \delta = 0.21 \text{ inch} \)
\( f_s = 31 \text{ ksf} \)

**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
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Questions?

Thank you