Drilled Shaft Foundations in Rock

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Dan Brown and Associates, PLLC
Advances in Drilled Foundations

- Focus on Drilled Shafts (CIDH piles)
  - History & Applications
  - Design Approach with LRFD
  - Measured Axial Resistance in Rock
Why Use Drilled Shafts?

- Up to 13’ dia. available
- Avoids noise & vibration associated with pile driving
- Small footprint: single shaft vs pile group
- Strength: capable of extremely large loads (axial + lateral)
- Most effective where good bearing stratum present
Early “Caisson” Constructions

Chicago Method

Gow Caisson

Texas Drilled Shaft Crew
Drilled Shafts: Foundation Applications

- Heavy Loads
- Over Water Work
- Restricted Access
Applications with Large Lateral Loads

- Single Column Piers with Monoshaft Foundations
- Extreme Event Loads
- Deep Scour
LRFD Design Approach

General Form of Equation:

$$\sum \phi_i R_i \geq \sum \gamma_i Q_i$$

where:
- $\phi_i$ = resistance factor for resistance component $i$
- $R_i$ = nominal value of resistance component $i$
- $\gamma_i$ = load factor for load component $i$
- $Q_i$ = nominal value of load component $i$

For axial resistance to DL + LL:

$$\phi_s R_{sn} + \phi_b R_{bn} \geq \gamma_D Q_{Dn} + \gamma_L Q_{Ln}$$

ASD approach:

$$Q_{all} = \frac{R_n}{FS}$$
Load and Resistance
LRFD Design of Drilled Shafts

- Geotechnical Strength
  - Geotechnical strength limit state
- Serviceability
  - Deformation limit state
- Structural Strength
  - Structural strength limit state
Design for Axial Loading

- Geotechnical Strength Limit State
  - Plunging failure
- Structural Strength Limit State
  - Structural failure
- Servicability Limit State
  - Settlements or Axial Displacement
Generalized Behavior Under Axial Load
Dilation at Rock/Shaft Interface

FIGURE 20 Idealized rock–concrete interface under axial loading (Johnston and Lam 1989).
What does a strain gauge tell you?

Load = (strain)AE

Note: you need to have a good idea of A and E to get load!
Reducing Test Results

Note: 1 ft. = 0.305 m
1 kip = 4.45kN
Example – Tampa, FL
Side & Base Resistance
Improved Design of Drilled Shafts in Rock

- Some Case Histories with Load Test Data
  - Marl or Chalk
  - Limestone
  - Sandstone
  - Shales
  - Metamorphic Rocks
## Marls and Chalks in SE U.S. - Test Data

<table>
<thead>
<tr>
<th>State</th>
<th>Project</th>
<th>Test No.</th>
<th>Reference</th>
<th>Test Type</th>
<th>Material</th>
<th>SPT N values (blf)</th>
<th>$q_s$ (kcf)</th>
<th>Unit Side Shear (kcf)</th>
<th>Unit End Bearing (kcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>US 80 over Mill Creek</td>
<td>AFT-106058</td>
<td>1</td>
<td>Staticm</td>
<td>Demopolis/Mooresville Chalk (hard gray, clayey silt)</td>
<td>N &gt; 100</td>
<td>5.8 - 10.7</td>
<td>41.6</td>
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<tr>
<td>AL</td>
<td>SR 10 Blue Springs</td>
<td>LT-8571</td>
<td>2</td>
<td>O-Cell</td>
<td>Claystone</td>
<td>N &gt; 100</td>
<td>0.9 - 1.7</td>
<td>27.4</td>
<td></td>
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<tr>
<td>AL</td>
<td>Hyundai Motor Manufacturing</td>
<td>LT-8904</td>
<td>2</td>
<td>O-Cell</td>
<td>Demopolis Chalk</td>
<td>42 - 62</td>
<td>3.4 - 9.4</td>
<td>90.9</td>
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<tr>
<td>AL</td>
<td>Andalusia, AL</td>
<td>WRT-1-1</td>
<td>3</td>
<td>Conventional</td>
<td>Claystone</td>
<td>17 - 127</td>
<td>7.0 - 9.6</td>
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<tr>
<td>MS</td>
<td>US 45 over Town Creek</td>
<td>LT-8194</td>
<td>2</td>
<td>O-cell</td>
<td>Mooreville Chalk (hard grey, clayey, silt)</td>
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<td>23.5</td>
<td>5.1</td>
<td>197.0</td>
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<td>MS</td>
<td>SR 25 over Talking Warrior Creek</td>
<td>LT-8373</td>
<td>2</td>
<td>O-cell</td>
<td>Basal Formation (Hard Clayey Silt and Silty Clay)</td>
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<td>6.1 - 27.9</td>
<td>2.2 - 5.9</td>
<td>67.8</td>
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<tr>
<td>MS</td>
<td>US 82 Oktibbeha County</td>
<td>LT-8461-1</td>
<td>2</td>
<td>O-cell</td>
<td>Demopolis Formation (Hard, Argillaceous Chalk)</td>
<td></td>
<td>10.9 - 38.6</td>
<td>3.1 - 7.3</td>
<td>214.0</td>
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<td>MS</td>
<td>US 82 Oktibbeha County</td>
<td>LT-8461-2</td>
<td>2</td>
<td>O-cell</td>
<td>Prairie Bluff Formation (Hard, Silty, Clay) and Ripley Formation (Hard, Sandy, Silt)</td>
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<td>27.1 - 28.8</td>
<td>2.1 - 3.9</td>
<td>108.0</td>
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<td>MS</td>
<td>SR 42 over Thompson Creek</td>
<td>LT-8487</td>
<td>2</td>
<td>O-cell</td>
<td>Very stiff to hard, clayey silt and silty sand</td>
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<td>7.1</td>
<td>1.9 - 5.0</td>
<td>24.8</td>
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<td>MS</td>
<td>I-55 at Old Agency Rd.</td>
<td>LT-8788</td>
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<td>O-cell</td>
<td>Yazoo Formation (Hard, tan, silty clay)</td>
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<td>9.0 - 11.1</td>
<td>0.3 - 1.5</td>
<td>52.3</td>
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<td>MS</td>
<td>SR 9 over SR 6</td>
<td>LT-8912-1</td>
<td>2</td>
<td>O-cell</td>
<td>Clayton Formation (Hard, clayey silt and silty clay)</td>
<td>N &gt; 100</td>
<td>18.0</td>
<td>7.7 - 8.4</td>
<td>202.8</td>
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<tr>
<td>MS</td>
<td>SR 9 over SR 6</td>
<td>LT-8912-2</td>
<td>2</td>
<td>O-cell</td>
<td>Ripley Formation (Hard, very fossiliferous, sandy silt)</td>
<td>N &gt; 100</td>
<td>8.8 - 12.9</td>
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<td>MS</td>
<td>Leake County, MS</td>
<td>WRT-4</td>
<td>3</td>
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<td>Chalk</td>
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<td>12.1</td>
<td>3.2</td>
<td>46.2</td>
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<tr>
<td>SC</td>
<td>Mt. Pleasant, SC</td>
<td>WRT-5-1</td>
<td>3</td>
<td>Conventional</td>
<td>Cooper Marl</td>
<td>9 - 100+</td>
<td>2.9</td>
<td>3.6</td>
<td>28.6</td>
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<tr>
<td>SC</td>
<td>Mt. Pleasant, SC</td>
<td>WRT-5-2</td>
<td>3</td>
<td>Conventional</td>
<td>Cooper Marl</td>
<td>9 - 100+</td>
<td>2.9</td>
<td>3.6</td>
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<tr>
<td>SC</td>
<td>Cooper River Bridge</td>
<td>LT-86500</td>
<td>2</td>
<td>O-cell (10 tests)</td>
<td>Cooper Marl (Clayey sand, sandy clay, sandy silt)</td>
<td>15 - 100+</td>
<td>2.0 - 6.5</td>
<td>43.5 - 80</td>
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<tr>
<td>SC</td>
<td>Breach inlet Bridge</td>
<td>LT-8661</td>
<td>2</td>
<td>O-cell</td>
<td>Cooper Marl (Clayey sand, sandy clay, sandy silt)</td>
<td>15 - 28</td>
<td>4.2 - 5.9</td>
<td>0.2 - 2.8</td>
<td>49.4</td>
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</tbody>
</table>

Reference:
1. AFT-XXXXXX - Staticm test report from AFT, Inc. with permission of owning state DOT
2. LT-XXXXX - O-Cell test report from Loadtest, Inc. with permission of owning state DOT.

Drilling & Sampling

- Conventional Rock Coring Tools
- Pitcher Barrel
Side Resistance

\[ f_s = C \cdot \sqrt{\frac{q_u}{p_u}} \]

- \( f_s \) = Skin friction
- \( C \) = Coefficient
- \( q_u \) = Unit side resistance
- \( p_u \) = Unit weight

Graph showing various data points and a line equation for calculating skin friction.

Legend:
- US 80 Test (est)
- AL Chalk (1 test)
- AL Claystone (Avg)
- AL Claystone (2 tests)
- MS Chalk (Avg)
- MS Chalk (2 tests)
- SC Cooper Marl (Avg)
- SC Cooper Marl (7 tests)

Note: N-SPT = 50/3°
Strong Limestone: Stan Musial Veterans Memorial Bridge, St. Louis
Eads Bridge

Sketch at right from the British Journal Engineering, Feb., 1872
Hard Limestone Bedrock

Unconfined Compressive Strength (psi)

Elevation (ft)

- 16.5ft Socket

Post-Award, Geotechnology
Post-Award, MoDOT
Pre-Award, Geotechnology
Pre-Award on ~1yr Old Samples, MoDOT
Limestone Coring
Load Test Shaft
New World Record Load Test
36,000 tons!

Osterberg Cell Load-Displacement
Test Shaft 1 - I-70 Mississippi River Bridge - St. Louis, MO

Displacement (in)
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25

O-cell Load (kips)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000

Upward Top of O-cell
Downward Base of O-cell
Load Test Results

Mobilized Unit End Bearing
Test Shaft 1 - I-70 Mississippi River Bridge - St. Louis, MO

NOTE: End bearing calculation uses diameter of 119.4 inches. This is based on bottom bearing plate diameter of 108 inches and 2:1 slope with O-cell assembly 11.4 inches above tip of shaft.

\[ E = 3800 \text{ksi} \approx 200q_u \]

\[ E = 900 \text{ksi} \approx 50q_u \]

\[ \rho_s = 0.79 \cdot \frac{qB(1-\nu^2)}{E} \]
Nashville ADSC Research: Test Conditions

Test Shaft 1
Surface 0
Tip of Casing -16.0
Top of Conc -17.5
SG Level 1 -26.0
O-cell -33.25
Tip of Shaft -33.5

Test Shaft 2
Top of Conc -14.0
Tip of Casing -20.0
SG Level 1 -31.4
Base of O-cell -36.9
Tip of Shaft -37.0

Graphs showing:
- Compressive Stress vs. Depth Below Top of Socket
- RQD (%) vs. Depth Below Top of Socket for Test Shafts 1 and 2
Nashville ADSC Research: Test Results

For Test Shaft 1:
- avg $q_u = 8300$ psi
- range = 1660 – 16,110
- %rec = 74% – 100%
- RQD = 9% - 65%

Back-calculated $C = 0.4$

\[ f_s = C \cdot p_a \cdot \sqrt{\frac{q_u}{(p_a)}} \]

\[ \rho_s = 0.79 \cdot \frac{q_B(1-v^2)}{E} \]

$E = 30$ to $50$ (q_u)
Case Studies in Weak Sandstones

- Bryant – Denny Stadium, Tuscaloosa
- MN I-35W Bridge
- St. Crois Bridge, Minnesota/Wisconsin
Shaft drilled under polymer slurry and base cleaned with bucket
For rigid circular footing on elastic half-space:

With ν = ¼:

\[ E = 9,600 \text{ksf} \approx 65 \text{ksi} \]

\[ \rho_s = 0.79 \cdot \frac{qB(1 - \nu^2)}{E} \]

With 48” dia, ρ/B ≈ 0.01 at ρ=0.48”
MN I-35W Replacement
MN I-35W Replacement

78” Dia. Socket
20’ embedment into decomposed sandstone
20’ embedment into soft sandstone ($q_u \approx 40\text{tsf} = 500\text{psi}$)
35W – Side Resistance

Net Unit Side Shear Curves
Test Shaft 2 - I-35 W of Mississippi River - Minneapolis, MN

- Upper O-cells to Lower O-cells (Stage 2A)
- S.G. Level 2 to Upper O-cells (Stage 2B)
- S.G. Level 3 to S.G. Level 2 (Stage 2B)
- Zero Shear to S.G. Level 3 (Stage 2B)
- Zero Shear to Uppers O-cell (Stage 2B)

avg

Upper O-cell Displacement (in)
35W Side Resistance

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

Elev 665-645, 
C \approx 2.5 to 2.8

FIGURE 24  Unit side resistance versus strength (Kulhawy and Phoon 1993).
35W Base Resistance

For rigid circular footing on elastic half-space:

With \( \nu = \frac{1}{4} \):

\[
E = 7,800 \text{ksf} \approx 54 \text{ksi}
\]

\[
\rho_s = 0.79 \cdot \frac{qB(1-\nu^2)}{\rho/B}
\]

With 78” dia, \( \rho/B \approx 0.01 \) at \( \rho=0.78” \)

135 ksf/in
St. Croix Bridge, Minnesota
St. Croix Bridge, Minnesota
St. Croix Foundation Construction
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
1995 Load Test

Recommended Design Values for sandstone:

- $f_s = 6.6 \text{ ksf, top 30ft}$
- $f_s = 9 \text{ ksf, below 30ft}$
- $q_b = 19 \text{ ksf, below 30ft}$
- 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
- SCC concrete, 24” spread
- Integrity testing with CSL to verify concrete quality
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)

$$E = 200 \text{ksi} \approx 100q_u$$

$$\rho_s = 0.79 \cdot \frac{qB(1-v^2)}{E}$$

Mobilized Unit End Bearing
TS 1 - St. Croix River Bridge - Washington Co., MN

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Shale: Some Test Data from KS-MO-KY Area

- Jackson Co., MO Chanute Shale, dry hole
  - $f_s=6\text{ksf}$, weathered shale w/ $q_u=14\text{ksf}$
  - $f_s=9-12\text{ksf}$, unweathered shale w/ $q_u=32\text{ksf}$
- Lexington, MO Gray & Black Shale, water
  - $f_s=15\text{ksf}$, $q_b=144\text{ksf}$, no strength data
- Waverly, MO Clay Shale, polymer slurry
  - $f_s=6-12\text{ksf}$, $q_b=110\text{ksf}$, no failure, no boring
- Topeka, KS, Severy Shale, dry
  - $f_s=4-40\text{ksf}$, $q_b=127\text{ksf}$, no strength data
- Republic Co., KS, Graneros Shale, dry
  - $f_s=3-4\text{ksf}$, $q_b=56\text{ksf}$, no strength data, $RQD > 75%$
- Osborne, KS, Fairport Chalk (gray shale), polymer
  - $f_s=11\text{ksf}$, $q_b=136\text{ksf}$, no strength data
- Des Moine, IA, Soft-Fm Shale, “roughened socket”, polymer
  - $f_s=4.5-7\text{ksf}$, $q_b>40-114\text{ksf}$, $RQD=39-70\%$, $q_u=24-170\text{ksf}$
- Owensboro, KY, 3 tests soft gray shale, polymer
  - $f_s=3-12\text{ksf}$, $q_b=140-300\text{ksf}$, weathered shale w/ $q_u=28-40\text{ksf}$
Bond Bridge, Kansas City

Plan View of Main Pylon Pier

- Test Shaft. Shown for location only, not a structural member in contact

Profile View

- Cap
  - Seal
  - Steel
- Drilled Shafts
- Shale bedrock
- Alluvium
### Polymer Slurry in Shale at Bond Bridge

<table>
<thead>
<tr>
<th>Sample</th>
<th>Natural Moisture Content (%)</th>
<th>Slake Durability Index Type</th>
<th>I_d(2) (%)</th>
<th>Durability Rating Based on Shear Strength Loss Type</th>
<th>DR_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>River Water</td>
<td>8.3</td>
<td>II</td>
<td>72.2</td>
<td>Intermediate</td>
<td>61.9</td>
</tr>
<tr>
<td>Polymer Slurry</td>
<td>8.3</td>
<td>II</td>
<td>98.2</td>
<td>Hard, more durable</td>
<td>78.6</td>
</tr>
</tbody>
</table>

(a) Polymer slurry at 800x
(b) Slurry interacting with Ottowa sand, 100X

*Figure 7.3* PHPA polymer slurry (Photos courtesy of Likos, Loehr, and Alumnari, University of Missouri – Columbia)
Test Data – Bond Memorial Bridge
Test Data – Bond Memorial Bridge

Mobilized Net Unit Side Shear

Pylon Test Shaft - Paseo River Bridge - Kansas City, MO

- S.G. Level 4 to Top of Shale
- S.G. Level 3 to S.G. Level 4
- S.G. Level 2 to S.G. Level 3
- S.G. Level 1 to S.G. Level 2
- O-cell to S.G. Level 1

Mobilized Net Unit Side Shear (ksc)

Upward Average Shear Zone Displacement (in)

TIP OF 78" Ø CASING: 641.83
SG4 (SN: 08–8772...73): 636.16
SG3 (SN: 08–8770...71): 630.16
SG2 (SN: 08–8768...69): 624.16
SG1 (SN: 08–8766...67): 618.16
LWD (SN: 08–6227...28...29...30): 613.33
3x3600 KIP O-cells: 611.40
Bond Bridge - Side Resistance

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

Elev 640-610, 
C ≈ 1

FIGURE 24  Unit side resistance versus strength (Kulhawy and Phoon 1993).
Bond Bridge - Base Resistance

For rigid circular footing on elastic half-space:

With $\nu = \frac{1}{4}$:

$$E = 27,000 \text{ ksf}$$

$$\approx 185 \text{ ksi}$$

$$\approx 100 \text{ } q_u$$

With 72” dia, $\rho/B \approx 0.01$ at $\rho=0.72$”
Metamorphic Rocks: Piedmont Geology

- Mica-Schist
- Gneiss
Macon, Georgia Powerplant

SPT - N

%Recovery or RQD

Elev

%Rec
RQD
SPT

wet
dry

sand
PWR
Rock

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Load Test Results

**Osterberg Cell Load-Movement**
Test Shaft 1 - Georgia Power - Plant Scherer - Juliette, GA

**Osterberg Cell Load-Movement Curves**
Test Shaft 2 - Georgia Power - Plant Scherer - Juliette, GA
Side Resistance

Mobilized Net Unit Side Shear
Test Shaft 1 - Georgia Power - Plant Scherer - Juliette, GA

Mobilized Net Unit Side Shear Curves
Test Shaft 2 - Georgia Power - Plant Scherer - Juliette, GA
Base Resistance

For rigid circular footing on elastic half-space:

\[ E = 9,800 \text{ksf} \]
\[ \approx 68 \text{ksi} \]

\[ \rho_s = 0.79 \cdot \frac{qB(1 - \nu^2)}{E} \]

With 60” dia, \( \rho/B \approx 0.01 \) at \( \rho=0.6” \).
Inter County Connector - MD

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

Elev 275-265, \( C \approx 1.3 \)

FIGURE 24 Unit side resistance versus strength (Kulhawy and Phoon 1993).
Base Resistance

With 48” dia, 
ρ/B ≈ 0.01 at Δρ=0.48”

For rigid circular footing on elastic half-space:

\[ E = 30,000 \text{ksf} \]
\[ ≈ 200 \text{ksi} \]
\[ ≈ 56 \, q_u \]

\[ \rho_s = 0.79 \cdot \frac{q B (1 - \nu^2)}{E} \]
Summary

- Greater performance demands (e.g., bigger loads, shafts, extreme event conditions)
- LRFD approach to design for transportation structures
- Testing of drilled foundations in rock can demonstrate performance
- Resistance in rock affected by rock type, construction methods

- Need for continuing education, training for design professionals!
Thanks for Listening!