DRILLED SHAFT CONSTRUCTION

- Concrete Mix Design Considerations
- Dry Construction Method
- Wet Construction Method
- Casing Construction Method
- Equipment
- Inspection and Testing

West Tower – Arthur Ravenel Jr. Bridge

Photograph courtesy of Marvin Tallent, Palmetto Bridge Constructors
## CONCRETE MIX DESIGN CONSIDERATIONS

SCDOT 712.03 - Class 4000DS (see SCDOT 701)

<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>Min. Cement Content (lbs/CY)</th>
<th>Min. 28 day f'c (psi)</th>
<th>% Fine to Coarse Aggregate Ratio</th>
<th>Max. W/C Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed</td>
<td>625</td>
<td>4000</td>
<td>40:60</td>
<td>0.44</td>
</tr>
<tr>
<td>Stone</td>
<td>625</td>
<td>4000</td>
<td>39:61</td>
<td>0.43</td>
</tr>
</tbody>
</table>

- Type G or Type D w/ Type F Admixture Required
- Slump: 7-9 inches
- Nominal Coarse Aggregate: ¾ inch
6. The minimum clearance between reinforcing bars shall be 1-7/8” and is equal to 5 times the maximum coarse aggregate size (3/8”) for both, the longitudinal bars as well as the spiral confinement reinforcement, to allow for better concrete consolidation during placement. Concrete mix design and workability shall be consistent for tremie or pump placement. In particular, the concrete slump should be 8 inches ± 1 inch for tremie or slurry construction and 7 inches ± 1 inch for all other conditions.
CONCRETE MIX DESIGN CONSIDERATIONS

Figure 1. Concrete Flow Under Tremie Placement (Brown and Schindler, 2007).

Figure 3. Restriction of Lateral Flow (Brown and Schindler, 2007).
CONCRETE MIX DESIGN CONSIDERATIONS

**Figure 5.** Effects of Loss of Workability during Concrete Placement (Brown and Schindler, 2007).

**Figure 9-1.** Free Fall Concrete Placement in a Dry Excavation (FHWA NHI-10-016).
CONCRETE MIX DESIGN CONSIDERATIONS

Self Consolidating Concrete (SSC) Project for SCDOT (S&ME 2005).
DRY METHOD (SCDOT 712.07)

- Less than 6 inches of water per hour
- Sides and Bottom Remain Stable (Engineer can order 4 hours wait period)
- Loose material & water can be satisfactorily removed
- Temporary casing can be used
STABLE vs. UNSTABLE SOILS

Unstable caving soils prevent maintaining hole stability

Stable non-caving soils maintain hole stability

Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
 Generally, soils cave at the water table preventing hole stability.

Water table at or below the shaft tip elevation.

Stable Non-Caving Soils

Cohesive Soils

Water table below shaft tip does not impact hole stability.

Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
DRY METHOD CONSTRUCTION PROCESS

Drill the shaft excavation

Clean shaft by removing the cuttings & seepage water

Position the reinforcing cage

Competent, Non-Caving Soils

Drill
Clean & Inspect
Position
Place

Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
DRY METHOD CONSTRUCTION PROCESS

- Continuous Operation. No delays > 12 hrs.
- No entering non-cased excavations.

DRILL
(SCDOT 712.10)

Photographs courtesy of WPC Inc.
DRY METHOD CONSTRUCTION PROCESS

CLEAN & INSPECT

Photographs courtesy of WPC Inc.
INSPECTION OF EXCAVATION (SCDOT 712.14)

• Need SCDOT Qualified Inspectors

EXCAVATION CLEANLINESS
(SCDOT 712.14D)

• 50% of Base has < ½ inch of sediment
AND
• Maximum depth of sediment < 1 ½ inches
Drilled Shafts Design and Construction

POSITION
(SCDOT 712.16)

- Spacers needed for 5 inch min. annulus.
- Spacer interval < 10 ft.
PLACE (SCDOT 712.17)

- ASAP after reinforcement placement.
- Must be completed in 2 hours (unless approved).
- Tremie preferred. Tremie ID > 6 x Max. Aggregate Size AND > 10 inches.
- Tremie Embedment > 10 ft.
- Concrete flow: Positive pressure and continuous.
DRY METHOD CONSTRUCTION PROCESS

PLACE (SCDOT 712.17)

- Freefall > 75 ft not permitted.
- Freefall Max. Aggregate Size \( \frac{3}{4} \) inch, 7-9 inch slump.
- Freefall still needs chute. Must have tremie onsite.
- SCDOT can always order tremie.

Photograph courtesy of WPC Inc.
WET METHOD CONSTRUCTION PROCESS
USE WHEN A DRY EXCAVATION CANNOT BE MAINTAINED

More than 6in in one hour = Wet

Less than 6in in one hour = Dry

Figure courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
14.528 DRILLED DEEP FOUNDATIONS
Drilled Shafts Design and Construction

WET METHOD CONSTRUCTION PROCESS

WHEN THE SIDES AND BOTTOM OF THE HOLE CANNOT REMAIN STABLE

WHEN LOOSE MATERIAL AND WATER CANNOT BE SATISFACTORILY REMOVED

Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
Drill the shaft excavation
Stabilize the hole (Plain water, slurry)
Clean shaft by removing the cuttings & seepage water
Position the reinforcing cage
Place the concrete
There are two forms of “wet” shaft construction:

- Static Process
- Circulation Process
WET METHOD: STATIC PROCESS

- Drill down to the piezometric level
- Slurry introduced
- Drilling Completed
- Cuttings are lifted from the hole
WET METHOD: CIRCULATION PROCESS

- Hole is drilled
- Slurry level maintained at the ground surface
- Cuttings and sand, is circulated to the surface, where it is cleaned and reintroduced down the hole.

Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
WET METHOD CONSTRUCTION PROCESS

SLURRY
(SCDOT 712.12)

Photographs courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
WET METHOD CONSTRUCTION PROCESS

TYPES OF SLURRY

- Natural mineral clays
- Bentonite, attapulgite and sepiolite
- Bentonite is the most common
- Attapulgite and sepiolite are typically used in saltwater environments
- Must be hydrated
<table>
<thead>
<tr>
<th>Best Application</th>
<th>Mineral</th>
<th>Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixability</td>
<td>Cohesionless</td>
<td>Cohesive &amp; Argillaceous Rock</td>
</tr>
<tr>
<td>Mix Water Sensitivity</td>
<td>Difficult - Must be Hydrated</td>
<td>Easy</td>
</tr>
<tr>
<td>&quot;Caking&quot; Ability</td>
<td>Saltwater Sensitive</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Suspension Ability</td>
<td>Best</td>
<td>OK</td>
</tr>
</tbody>
</table>
Control tests are used to maintain proper slurry condition. Tests are conducted for:

- **Density** - the slurry weight
- **Viscosity** - flow: consistency
- **pH** - acidity: alkalinity
- **Sand Content**
### WET METHOD CONSTRUCTION PROCESS

#### CONTROLLING SLURRY

**SCDOT 712.12 – MINERAL SLURRY ACCEPTABLE RANGES**

<table>
<thead>
<tr>
<th>Property (Units)</th>
<th>Value Range @ Introduction</th>
<th>Value Range @ Concreting</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (pcf)</td>
<td>64.3 – 69.1*</td>
<td>64.3 – 75.0</td>
<td>Density Balance</td>
</tr>
<tr>
<td>Viscosity (sec/qt)</td>
<td>28-45</td>
<td>28-45</td>
<td>Marsh Cone</td>
</tr>
<tr>
<td>pH</td>
<td>8-11</td>
<td>8-11</td>
<td>pH paper, pH meter</td>
</tr>
</tbody>
</table>

* Add 2 pcf in saltwater ** Sand
WET METHOD CONSTRUCTION PROCESS

CONTROLLING SLURRY FOR BOREHOLE STABILITY

- Proper Dosage and Solids Content for Proper Flowability and Cake Properties
- Thorough Mixing / Adequate Time for Hydration (Bentonite / Polymers)
- Maintenance of Head in Borehole
- Maintenance of pH, Hardness, Salts
- Minimize Pressures from Tools
WET METHOD CONSTRUCTION PROCESS

IMPROPER SLURRY CONTROL

• Fails to properly suspend and facilitate the removal of sediments and cuttings

• Does not control caving

• Does not control swelling of soils

• Hinders slurry displacement during concrete placement

• Leads to a dirty hole
WET METHOD CONSTRUCTION PROCESS

“DIRTY HOLE”

(a) Slurry
(b) Granular Soil That Has Settled
(c) Fresh Concrete

WET METHOD CONSTRUCTION PROCESS

SLURRY EXAMPLES

Poor Slurry Job

Excellent Slurry Job

Photographs courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
• Where an open hole cannot be maintained.

• Where soil or rock deformation will occur.

• Where constructing shafts below the water table or caving overburden.

• SCDOT Types:
  Construction (712.11B) & Temporary (712.11C)
CASING CONSTRUCTION METHOD

SCDOT 712.11

- Smooth, clean, watertight, with ample strength
- Oversized must be approved by SCDOT.
- Temporary: Fresh concrete > 5 ft above hydrostatic pressure.
- Construction: Installed as one continuous unit.
- Welds are only approved connection.

Photograph courtesy of WPC Inc.
1. The Designer shall consider the intended method of construction (temporary or permanent casing, slurry drilling, etc.) and the resulting impact on the stiffness and resistance of the shaft.

4. When a drilled shaft is constructed with a permanent casing, the skin friction along the permanently cased portion of the shaft should be neglected.
CASING CONSTRUCTION METHOD

TELESCOPING CASING

Not Permitted by SCDOT (see 712.11C)
CASING METHOD: CONSTRUCTION PROCESS

Drill the shaft excavation
Install casing through caving soils and seal
Clean shaft by removing the cuttings & seepage water
Position the reinforcing cage
CASING CONSTRUCTION METHOD
CONSTRUCTION (a.k.a. PERMANENT) CASING EXAMPLES

- **River Crossing**
  - Permanent Casing

- **Karstic Formation**
  - Cavity
  - Permanent Casing

- **High-Capacity Drilled Shaft to Sound Rock**
  - Effective Length of Socket

CASING CONSTRUCTION METHOD

CONSTRUCTION (a.k.a. PERMANENT) CASING EXAMPLES

FULL-DEPTH CASING PROCESS

Installation of Casing

Drilling ahead of casing

Remove casing

Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course

Figure 1. Concrete Flow Under Tremie Placement.
CASING CONSTRUCTION METHOD
TEMPORARY CASING REMOVAL

\[ z_f \gamma_f \ll z_c \gamma_c \]

\( z_f \) = fluid head outside casing  
\( \gamma_f \) = unit wt of water or slurry  
\( z_c \) = concrete head inside casing  
\( \gamma_c \) = unit wt of concrete

Figure 9-4. Concrete Pressure Head Requirement during Casing Extraction (FHWA NHI-10-016).
DRILLED SHAFT EQUIPMENT TERMINOLOGY

- Kelly
- Table
- Tool
- Power Unit
- Crane

Photograph courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course
Earth augers are generally used in sands and cohesive materials.

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Earth augers are generally used in sands and cohesive materials.
Rock augers are generally used in soft to hard rock formations.

- Tapered Geometry
- Conical (Bullet) Carbide Teeth
This is typical of rock bits designed for drilling in hard to very hard rock.

Circulating bit

Replaceable Roller Bits
DRILLED SHAFT EQUIPMENT

DRILLING BUCKET
This is typical of a cleanout (muck) bucket used to cleanout the cuttings and sediments from the bottom of the shaft.
Deep Foundation Design

Geomaterial Properties Needed

Table 13-1. Geomaterial Properties Required for Drained and Undrained Axial Resistances (FHWA NHI-10-016).

<table>
<thead>
<tr>
<th>Geomaterial</th>
<th>Short-term resistance</th>
<th>Long-term (fully drained) resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesionless soils</td>
<td>SPT N-values, $N_{60}$ and $(N_1)_{60}$</td>
<td>Effective stress cohesion and friction angle, $c'$ and $\phi'$</td>
</tr>
<tr>
<td>(including materials classified previously as cohesionless IGM)</td>
<td>Average vertical effective stress ($\sigma_v'$) for each layer</td>
<td></td>
</tr>
<tr>
<td>Cohesive soils</td>
<td>Undrained shear strength, $s_u$</td>
<td>$q_u$</td>
</tr>
<tr>
<td>Rock</td>
<td>Uniaxial compressive strength, $q_u$</td>
<td>RQD</td>
</tr>
<tr>
<td>Geological Strength Index, GSI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cohesive IGM</td>
<td>Uniaxial compressive strength, $q_u$</td>
<td>$q_u$</td>
</tr>
<tr>
<td></td>
<td>RQD</td>
<td></td>
</tr>
</tbody>
</table>

(1) Axial resistance of drilled shafts in cohesive soils or IGM for long-term fully-drained loading is not considered in AASHTO (2007) LRFD Specifications under the assumption that design for undrained loading is adequate for routine practice.
Deep Foundation Design

Axial Capacity

\[ Q_{\text{total}} = \sum Q_{\text{skin}} + Q_{\text{tip}} \]

Where:

- \( Q_{\text{total}} \) = Ultimate Pile Capacity
- \( Q_{\text{skin}} \) = Skin Friction (i.e. Side) Capacity
- \( Q_{\text{tip}} \) = Tip (i.e. Toe) Capacity
DEEP FOUNDATION DESIGN

AXIAL CAPACITY

\[ Q_{\text{skin}} = f_s A_{\text{skin}} \]

Where:
\[ f_s = \text{Unit Skin Friction} \]
\[ A_{\text{skin}} = \text{Pile Skin Area} \]

\[ Q_{\text{toe}} = q_p A_{\text{toe}} \]

Where:
\[ q_p = \text{Unit End Bearing} \]
\[ A_{\text{toe}} = \text{Pile Toe (i.e. Tip) Area} \]
DEEP FOUNDATION DESIGN

GENERALIZED LOAD TRANSFER BEHAVIOR

\[ Q_{\text{skin}} = R_s \]

\[ Q_{\text{toe}} = R_b \]

Figure 13-1
(FHWA NHI-10-016).
REFERENCES

• SCDOT Foundation Certification Program Notes.
• FHWA IF-99-025 Drilled Shafts: Construction Procedures and Design Methods.
• FHWA NHI-10-016 Drilled Shafts: Construction Procedures and LRFD Design Methods
• NHI Course 132070 - Drilled Shaft Foundation Inspection.