14.528 Drilled Deep Foundations
Spring 2014

LECTURE 3 – DRILLED SHAFTS CONSTRUCTION AND DESIGN

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PART I – CONSTRUCTION

References

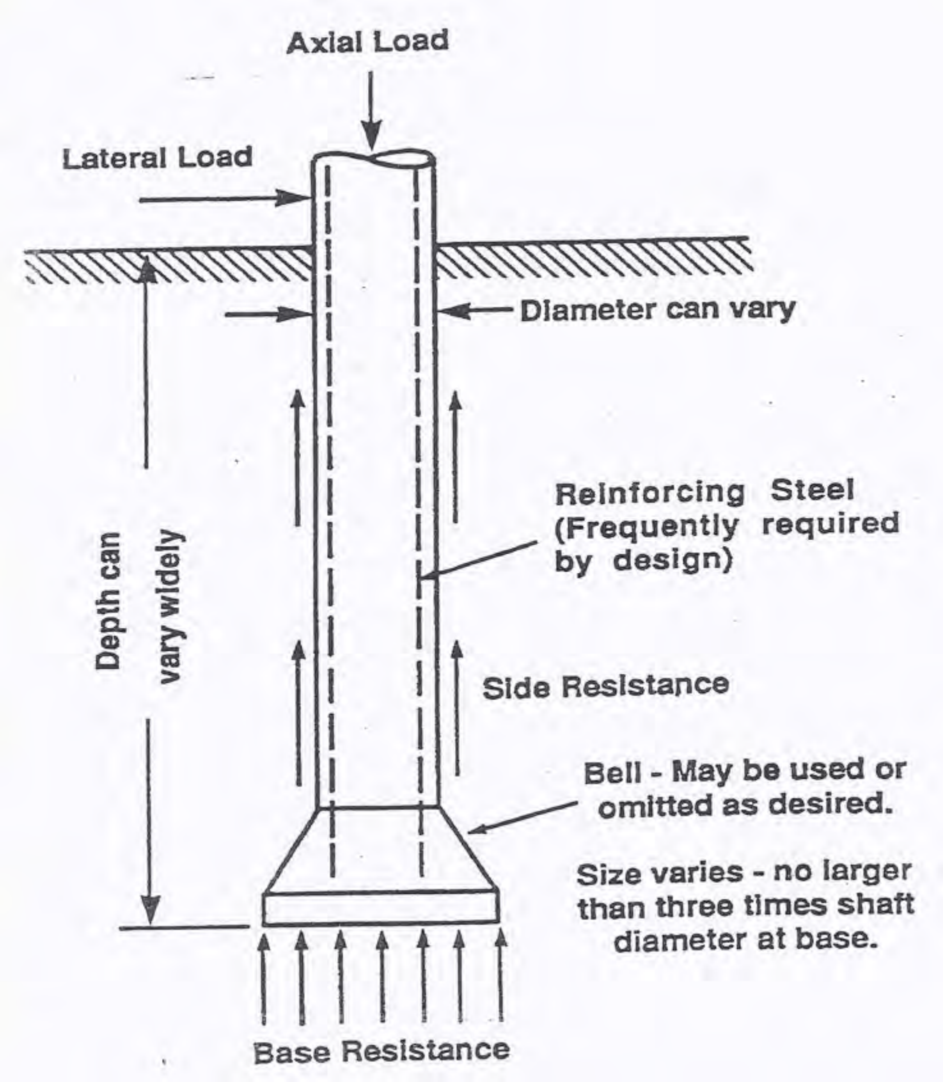
- O'Neill M.W. and Reese L.R. FHWA Publication FHWA-IF-99-025, "Drilled Shafts: Construction Procedures and design Methods", Vol's I&II
- O'Neill M.W. "Drilled Shafts: Effects of Construction on Performance and Design Criteria" FHWA Conf. December 1994, Vol. I, pp. 137-187.
- Bowles Foundations Analysis and Design, Ch. 19, pp. 863-886
- Foundation Engineering handbook, Ch. 14, pp. 537-551
- FHWA NHI-10-016 - *Drilled Shafts: Construction Procedures and LRFD Design Methods* (Geotechnical Engineering Circular No. 10), May 2010

Definitions and Use (refresher)

Lecture 3 concentrates on drilled shafts distinguished from the generic deep drilled foundations that includes CFA, mini-piles, etc.

Definitions and Use (cont'd.)

A drilled shaft is a deep foundation that is constructed by placing fluid concrete in a drilled hole, typically with reinforcing steel installed in the excavation prior to the placement of the concrete. Most common construction in the US is done by rotary drilling equipment with the borehole unsupported in soils with cohesion or rock but can be kept open by using drilling slurry or casing in granular or bouldery soils, or any other unstable underwater conditions.



Terminology (refresher)

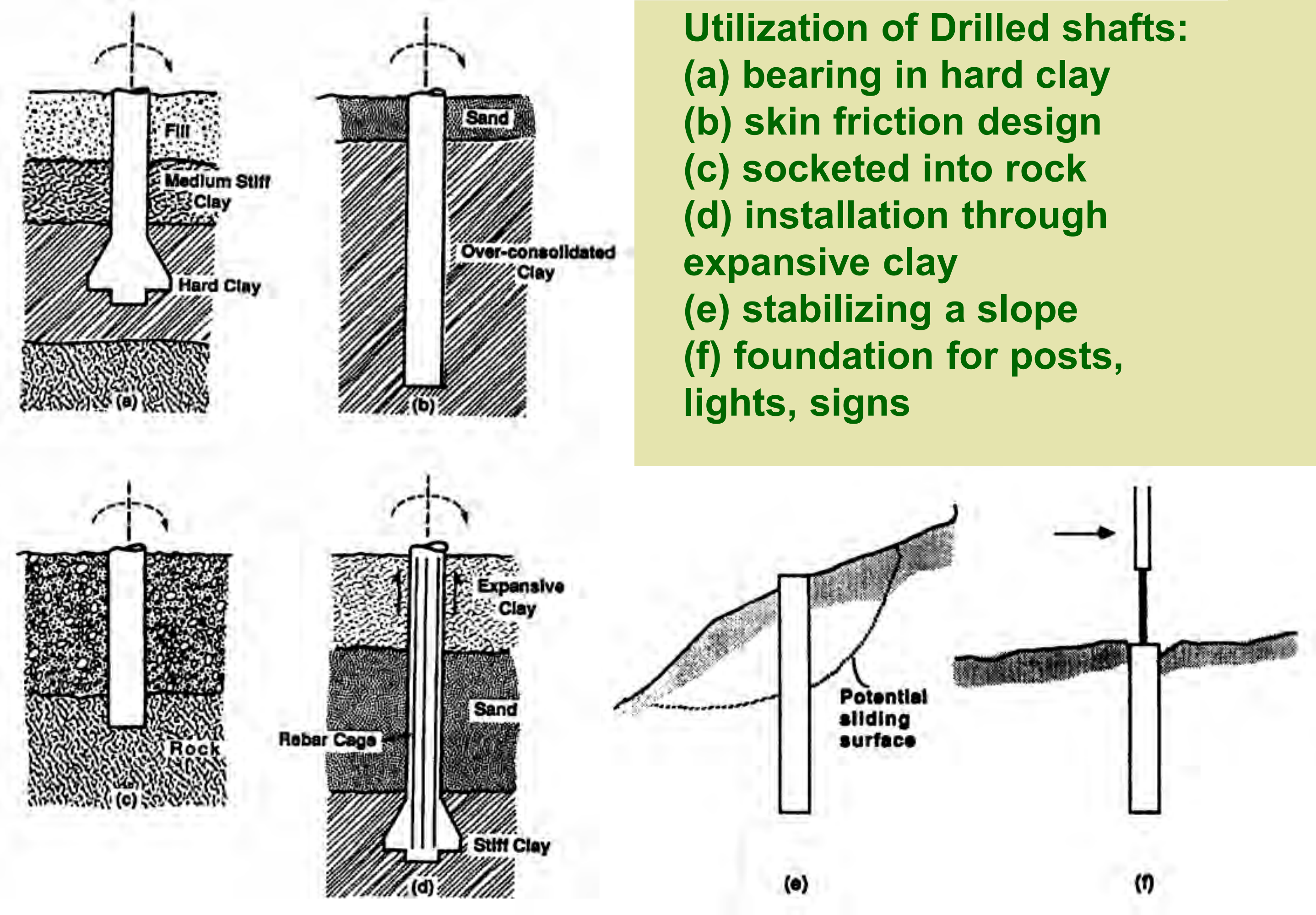
- Drilled shafts' development progressed by and large independently worldwide and even in the US. Different names are therefore associated with different construction methods or different geographical zones. All the names relate essentially to deep foundation elements constructed in place, differing from the prefabricated piles used in driving.
- (Drilled) Shafts (Texas), Bored Piles (outside the US) Excavated under slurry.
- (Drilled) Caissons (Drilled Piers) (Midwestern US) Excavated in the dry (the above differentiation is not always kept when talking about shafts or caissons).
- Cast in Drilled Hole Pile (California by Caltrans).

Terminology (refresher)

- Rock Sockets When the caissons/shafts are embedded in the rock
- Other types of constructed in place deep foundations: CFA (Continuous Flight Auger), Geojet, soil-cement mix, mini or micro-piles, Barrette Foundations - Different shaped cast in place elements (e.g., rectangle, round, H, etc.) usually associated with slurry wall construction.
- PIF (Pressure Injected Footings) are also concrete constructed in place deep foundations but due to the construction method, they also are not considered drilled shafts.

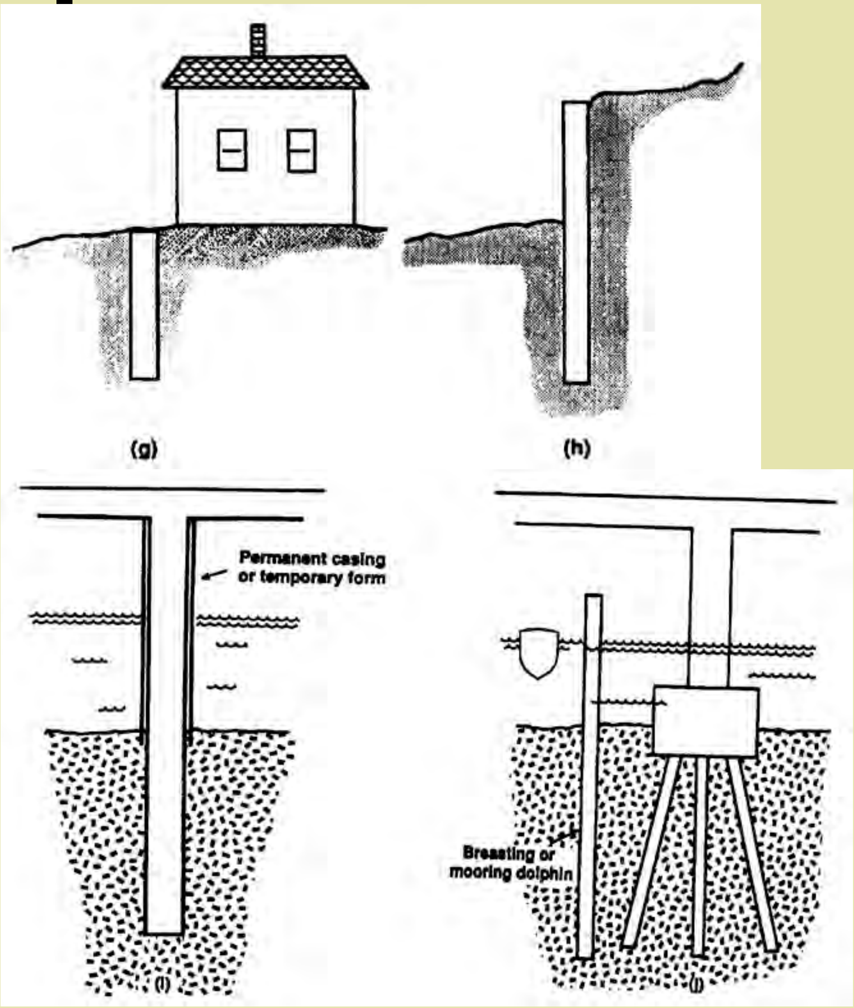
Application (refresher)

All locations where deep foundations are required



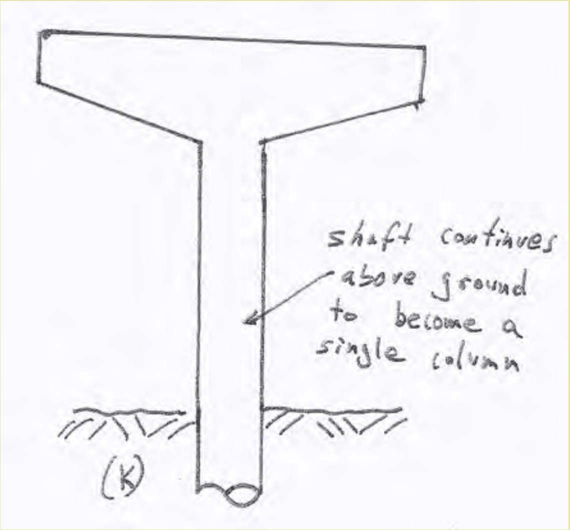
Utilization of Drilled shafts:
(a) bearing in hard clay
(b) skin friction design
(c) socketed into rock
(d) installation through expansive clay
(e) stabilizing a slope
(f) foundation for posts, lights, signs

Application (refresher cont'd.)



Utilization of Drilled shafts:

(g) foundations near existing structures
(h) closely spaced drilled shafts serving as a cantilever or tie-back wall
(i) marine application
(j) pier protection or navigation aid
(k) non-redundant elevated walkway or bridge support



Advantages & Disadvantages of Drilled Shafts

Advantages

- Large sizes are possible
- High capacity
- Elimination of pile groups and pile cap
- Low noise and vibrations
- Can be progressed through difficult conditions
- Does not cause heave

Advantages & Disadvantages of Drilled Shafts (cont’d)

Disadvantages

- High price relative to driven piles, depending on local design and construction practices, typically 8 to 10 piles will be equivalent to one shaft.
- Quality control difficulties
- Ensuring capacity is difficult (i.e., conducting a load test)
- Susceptible to difficult weather conditions for drilling and concreting
- Soil and slurry disposal is required
- Required a relatively sound bearing stratum for either friction and/or end bearing

Advantages & Disadvantages of Drilled Shafts (cont'd)

Economic advantage is the most controlling factor. When compared to driven piles, drilled shafts can be installed to replace groups of driven piles and do not require a pile cap. Issue of redundancy and its importance is only recently being recognized. On the other hand, driven piles are easily and quickly installed and monitored. However, often-conservative design of driven piles (e.g. neglect of friction in deep clay layer, relying on end bearing alone) results in the need of large number of piles, hence making drilled shafts an economical viable option where otherwise maybe questionable.

Advantages & Disadvantages of Drilled Shafts (cont'd)

Two examples from the FHWA manual (1999) by O'Neill and Reese are provided

Example 1. *Foundations for the Interior Bents of the Queens River Bridge, Olympic Peninsula, State of Washington*

This example resulted from the development of alternate designs by the design agency before the project was bid. The construction schedule for the foundations for this bridge was severely constrained by the imposition of a short construction season due to the migration of salmon in the stream that the bridge was to span. One alternate foundation called for the construction of one spread footing and two capped groups of steel H-piles for the three interior bents that were required to be placed in the river. Both the spread footing and driven piles (with pile caps) were to be constructed within cofferdams because of the need to construct footings/caps. The drilled shaft alternate called for the replacement of the spread footing and driven pile groups by three large-diameter drilled shafts. The drilled shafts could be drilled during low water using a crane-mounted drill rig positioned on timber mats within the river and pouring the concrete for the shafts to an elevation above the water level, eliminating the need for cofferdams. Other general data are as follows:

- *Bridge:* Two-lane bridge that was a replacement for an existing bridge.
- *Number of Spans:* 4, with each of the three interior bents consisting of a single column. The abutments were supported on driven piles with either alternate.
- *Span Length:* 76 m (250 ft) for the two spans between the interior bents Shorter spans to the abutments.
- *Year of Construction:* 1986

Advantages & Disadvantages of Drilled Shafts (cont'd)

Two examples from the FHWA manual (1999) by O'Neill and Reese are provided (cont'd)

Example 1

Figure 1.3. Photograph of Queets River Bridge at time of completion (Note old bridge in background and flood debris against the columns)

- *Drilled Shaft Contractor*: DBM Contractors, Inc.
- *Subsurface Conditions*: Siltstone near the surface at one end dipping to a depth of about 6.1 m (20 ft) near the other end of the bridge. Mixed fine sediments above the siltstone.
- *Pile Alternate*: 25 capped H-piles driven into the soft siltstone for each of two interior bents and a spread-footing at the other interior bent. All pile driving, cap construction and spread footing construction were within cofferdams. A single-bent column was formed on the top of the spread footing or pile cap prior to removal of the cofferdams. The need to construct cofferdams prior to installing the foundations required first the construction of a work trestle. Because of the length of time required to construct the trestle and cofferdams, construction of pile groups, caps and footing could not proceed until the following working season, since operations in the river had to be suspended during the salmon runs.
- *Drilled Shaft Alternate*: 3, 3.20-m- (10.5-ft-) diameter drilled shafts socketed about 10 m (30 ft) into the siltstone, with casing extending from the top of the siltstone to high water level. The casing was used as a form, and the drilled shaft concrete was poured directly up to the top of the casing. The single columns for the bents were formed on top of the extended sections of drilled shafts, without the requirement to construct cofferdams.
- *Drilled Shaft Construction*: The casings were installed, the shaft excavations drilled and the reinforcing steel and concrete were placed during the low-water season by operating off timber mats placed on the floor of the river, which was less than 1.5 m (5 ft) deep during low water. All of the construction in the river took place within the low water season, during which salmon did not migrate in the river. The elimination of the need to operate in the river over two seasons greatly enhanced the cost-effectiveness of the drilled shaft alternate.
- *Estimated Foundation Cost of the Pile-Footing Alternate*: $842,000
- *Actual Foundation Cost of the Drilled Shaft Alternate*: $420,000
- *Cost Savings Realized by Using Drilled Shafts*: $422,000 (50.1%)

A photo of the completed Queets River Bridge is shown in Figure 1.3.

UMASS LOWELL

Advantages & Disadvantages of Drilled Shafts (cont'd)

Two examples from the FHWA manual (1999) by O'Neill and Reese are provided (cont'd)

Example 2

Example 2. *Foundations for Central Spans for State Route 34 over the Great Pee Dee River, South Carolina*

This example resulted from a value-engineering proposal to replace groups of capped driven steel H-piles, as originally designed, with single drilled shafts. The approach spans and abutments were founded on driven, prestressed concrete piles. The issue for the value engineering proposal was the interior bents. Two of the six interior bents on this bridge were in the river, which was 3 - 6 m (10 - 20 ft) deep; the remaining four were on land. The pile foundations originally designed for the bents in the river were to be installed within sheet-piled cofferdams. The drilled shafts within the river were installed off barges. Other general data are as follows:

- *Bridge:* Two-lane bridge that was a replacement for an existing bridge
- *Number of Spans:* 5 (excluding approach spans)
- *Span Length:* 58 - 73 m (190 - 240 ft)
- *Year of Construction:* 1994

Advantages & Disadvantages of Drilled Shafts (cont'd)

Two examples from the FHWA manual (1999) by O'Neill and Reese are provided (cont'd)

Example 2

- *Drilled Shaft Contractor:* Long Foundation Drilling Company
- *Subsurface Conditions:* Soft to stiff clays interbedded with layers of generally dense, waterbearing sand and silt. No rock formation. No boulders.
- *Pile Design:* 234 steel HP 14 X 73 piles driven in six capped groups, 33 to 44 piles per group, with multiple bent columns formed on top of each pile cap. Approximate minimum penetration of the piles below cofferdam seal elevation = 12.2 m (40 ft). Cofferdam seal elevation was about 6.1 m (20 ft) below the soil surface within the river. The seal elevations were approximately at the predicted scour depth.
- *Drilled Shaft Design:* 14 drilled shafts (one per bent column) with diameters of 1.53 m to 1.83 m (5 to 6 ft), with one bent column formed on the top of each drilled shaft. Approximate penetration of drilled shafts below soil surface = 21.3 m (70 ft).
- *Drilled Shaft Construction:* Permanent steel casing was set from the scour line elevation to the water level within the river for the river bents or to finsihed ground level for land bents. The scour elevation was estimated to be approximately 4.5 - 6.1 m (15 to 20 ft) below the soil surface at all bents. Polymer drilling slurry was used to maintain borehole stability. [Note: Permanent steel casing is expensive. Temporary casing or removable forms should be used where possible.]
- *Cost of Driven Pile Foundation as Bid (including cofferdams and caps):* $1,709,400.00
- *Actual Cost of Drilled Shaft Foundation Option:* $1,567,500.00
- *Cost Savings Realized by Using Drilled Shafts:* $141,900 (8.3% of cost of piles)
- *General Note:* An axial loading test was conducted on a full-sized drilled shaft to evaluate drilled shaft performance prior to implementation of the drilled shaft proposal. The cost of this test ($175,000) was included in the cost of drilled shaft option.

A photo of the construction operations for the Great Pee Dee River project, in which the drilled shaft contractor is placing casings off a barge within the river, is shown in Figure 1.4.

Advantages & Disadvantages of Drilled Shafts (cont'd)

Two examples from the FHWA manual (1999) by O'Neill and Reese are provided (cont'd)

Example 2

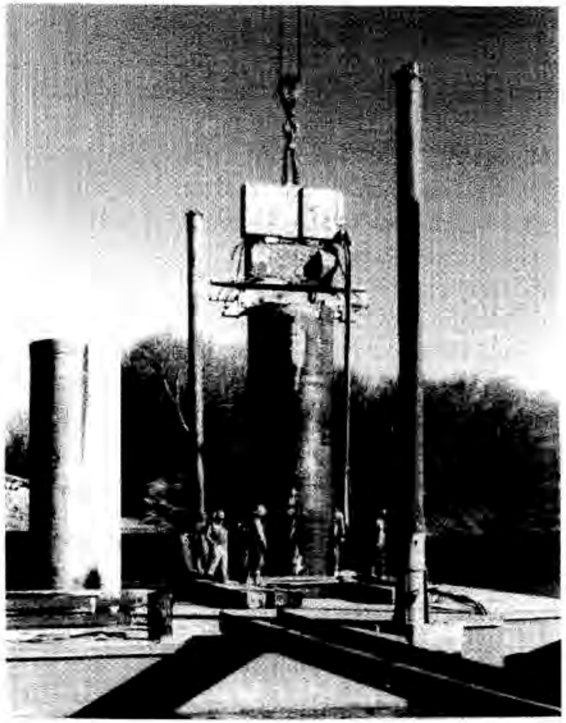


Figure 1.4. Construction of drilled shafts from barge in the Great Pee Dee River

There may also be situations in which drilled shafts are not economically suited to a particular project. For example, where soft clays and/or loose, waterbearing sands to large depths are encountered, the resistance advantage and relative ease of construction afforded by driven piles or other alternates may sometimes make them more economical than drilled shafts. For small, single-span, bridges in which the designer requires batter piles in the abutments, driven piles are often more economical than drilled shafts. However, in most other instances drilled shafts are cost-competitive with driven piles when both systems are designed appropriately. It is advisable that, where feasible, alternate designs, one including drilled shafts, be made and bids solicited on each alternate. Some guidance on the estimation of costs of drilled shafts is provided in Chapter 19.

Drilled Shaft Construction

West Tower – Arthur Ravenel Jr. Bridge

Photograph courtesy of Marvin Tallent, Palmetto Bridge Constructors

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

Concrete Mix Design Considerations

SCDOT 712.03 - Class 4000DS (see SCDOT 701)

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

- Type G or Type D w/ Type F Admixture Required
- Slump: 7-9 inches
- Nominal Coarse Aggregate: ¾ inch

Concrete Mix Design Considerations

MassDOT LRFD Design Manual (2009) Section 3.2.3.2

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

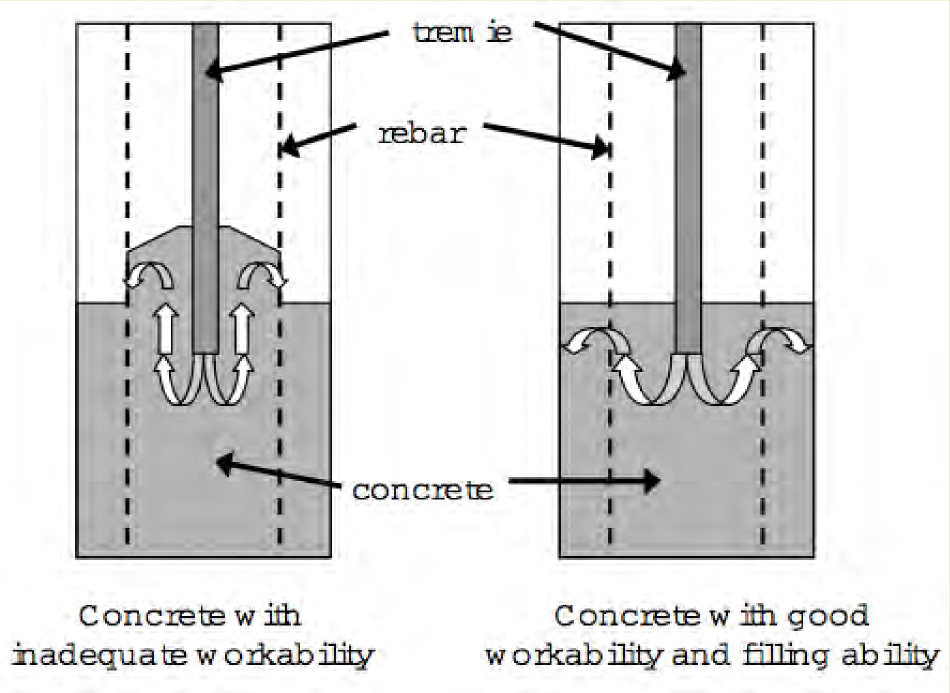


Figure 1. Concrete Flow Under Tremie Placement (Brown and Schindler, 2007).

Figure 3. Restriction of Lateral Flow (Brown and Schindler, 2007).

Concrete Mix Design Considerations

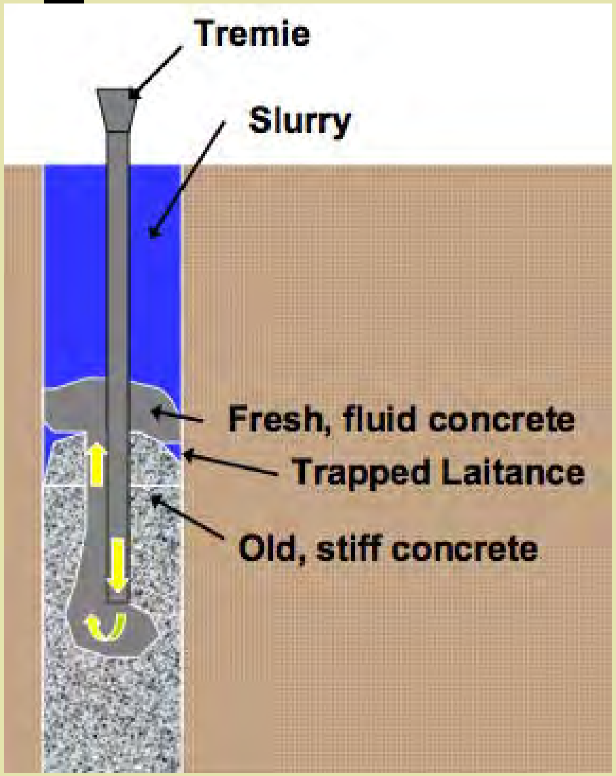


Figure 5. Effects of Loss of Workability during Concrete Placement (Brown and Schindler, 2007).

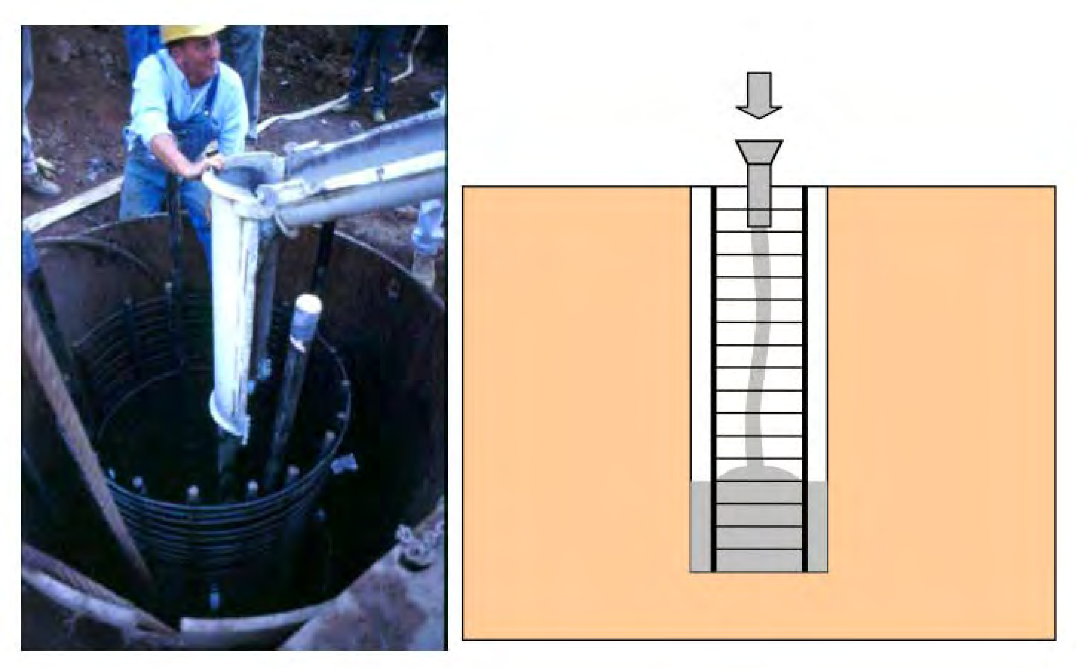


Figure 9-1. Free Fall Concrete Placement in a Dry Excavation (FHWA NHI-10-016).

Concrete Mix Design Considerations

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

Construction Methods

Rotary drilling is the most common method used in the US. Rotary drilling drilled shaft construction can be classified into three broad categories:

(a) dry method, (b) wet method, and (c) casing method

The selected method depends on the subsurface. As the design depends on the construction method, it becomes part of the design process. In spite of the fact that the DS's performance depends to some extend on the method of construction; normal practices leave the responsibility of the construction method with the contractor, (cost effective consideration).

The designer need to be familiar with the construction methods in order to be able to develop construction specifications, evaluate alternative construction methods and to develop preliminary cost estimates.

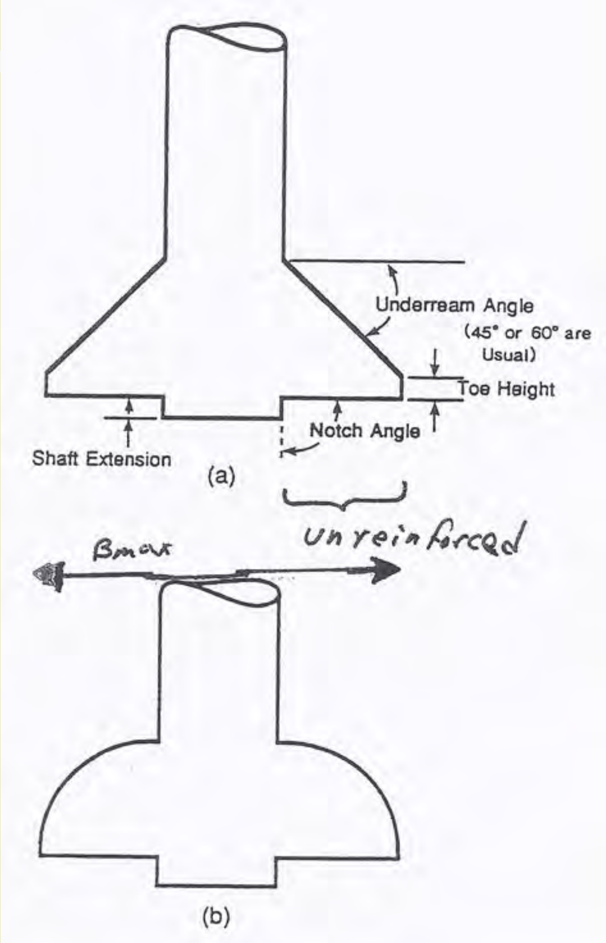
Construction Methods

Underreams (Bells)

Construction – hinged arms that are pushed outwards (downward force on the Kelly), causing soil to be cut away.

Advantages – increased end bearing B_{max}= 3 B (shaft diameter) (A_{tip}x10)

Limitations – quality control of a stable excavation and tip clean up.



Shapes of typical underreams:
(a) cut with "standard" conical reamer, and
(b) cut with a "bucket" or hemispherical reamer.

Construction Methods

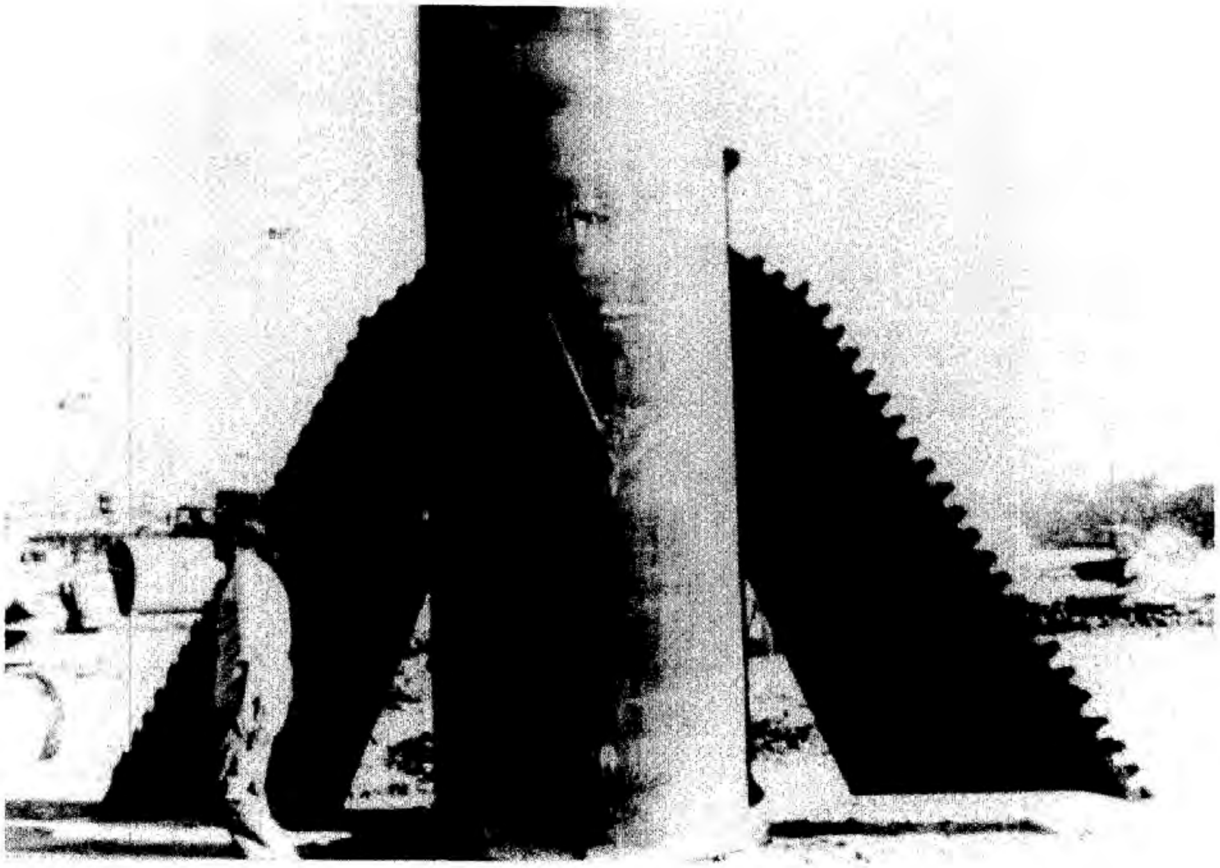


Figure 4.15. A typical belling bucket in drilling position

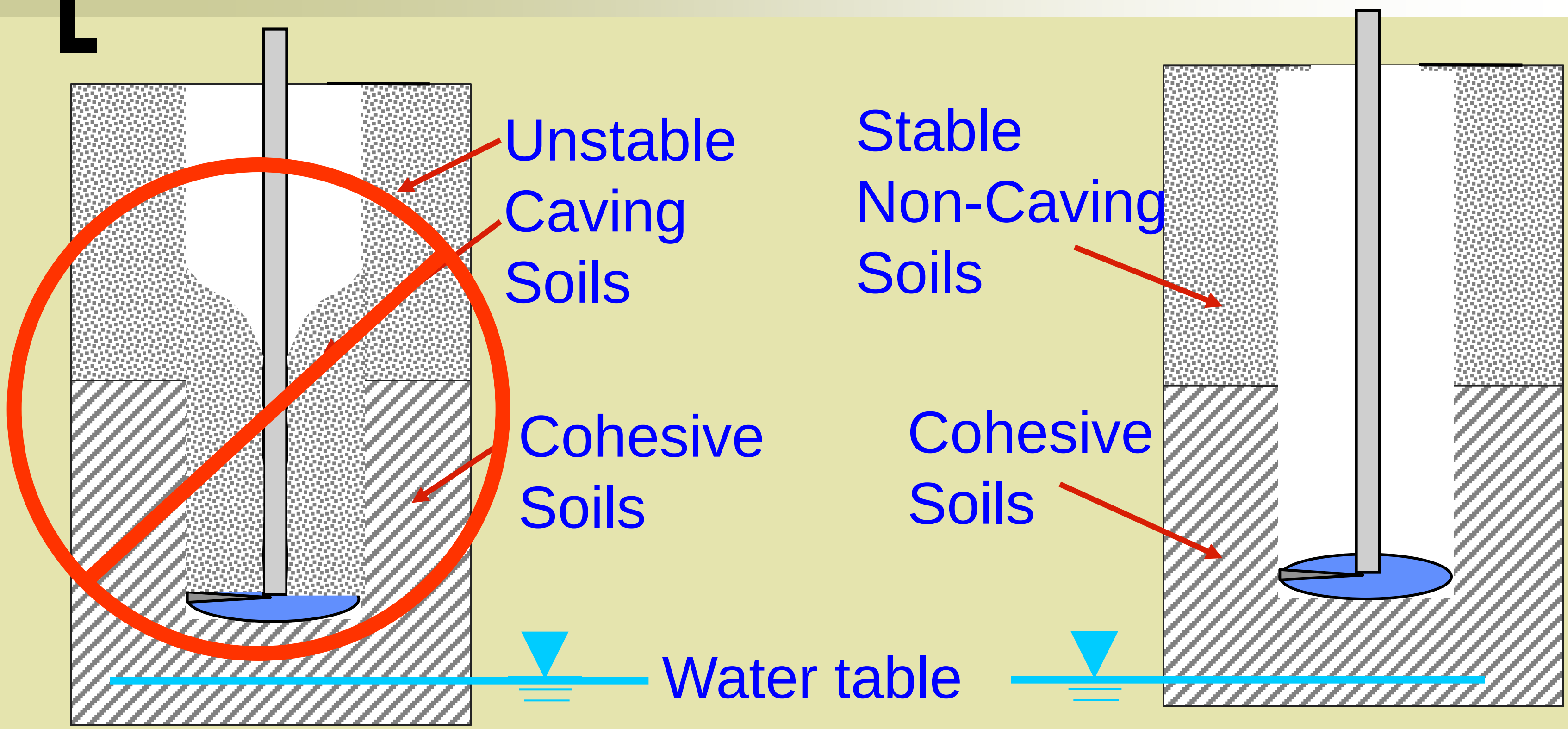
Dry Method (Scdot 712.07)

Photograph courtesy of GPE Inc.

- 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

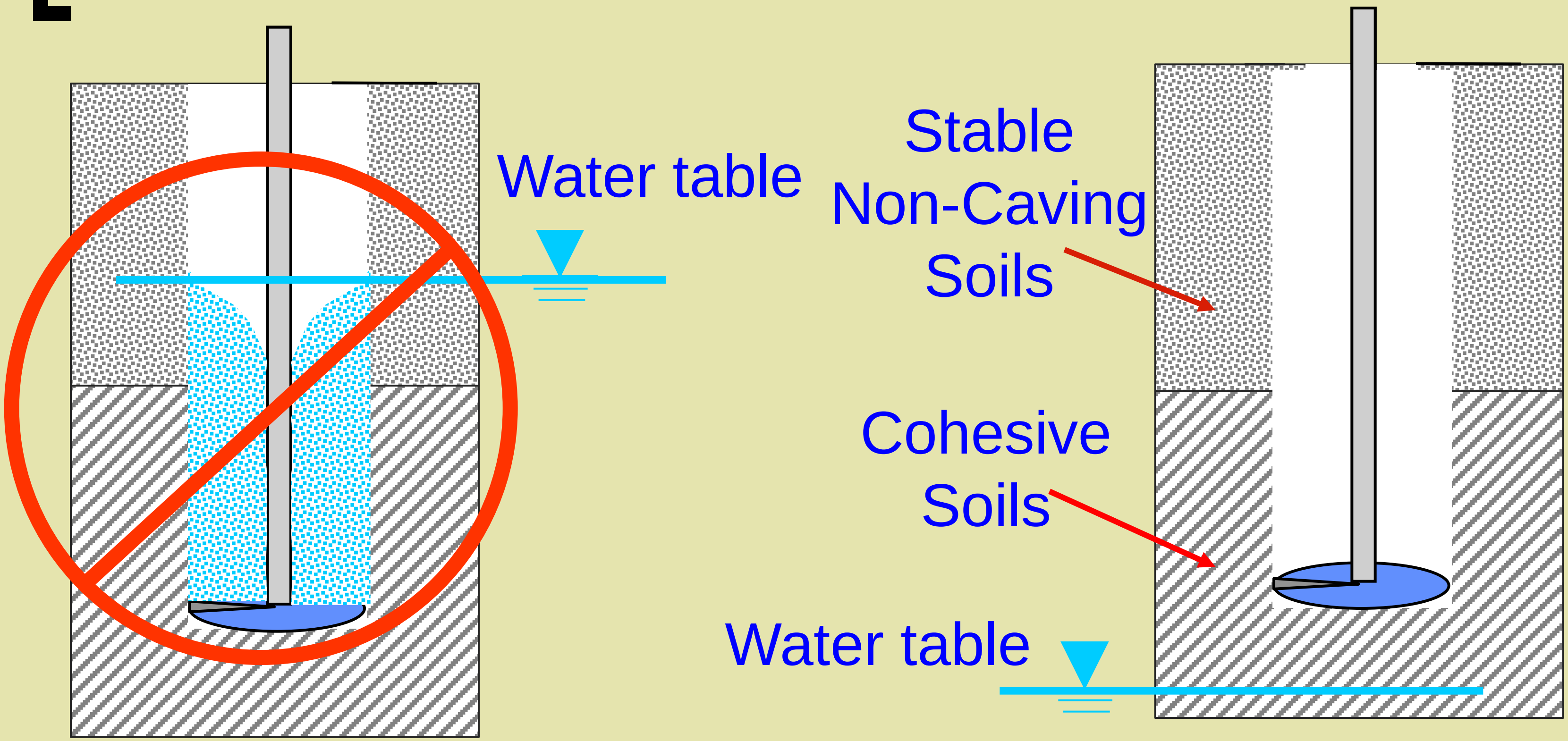


Unstable caving soils prevent maintaining hole stability

Stable non-caving soils maintain hole stability

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

Water Table at or Below the Shaft Tip Elevation



Generally, soils cave at the water table preventing hole stability

Water table below shaft tip does not impact hole stability

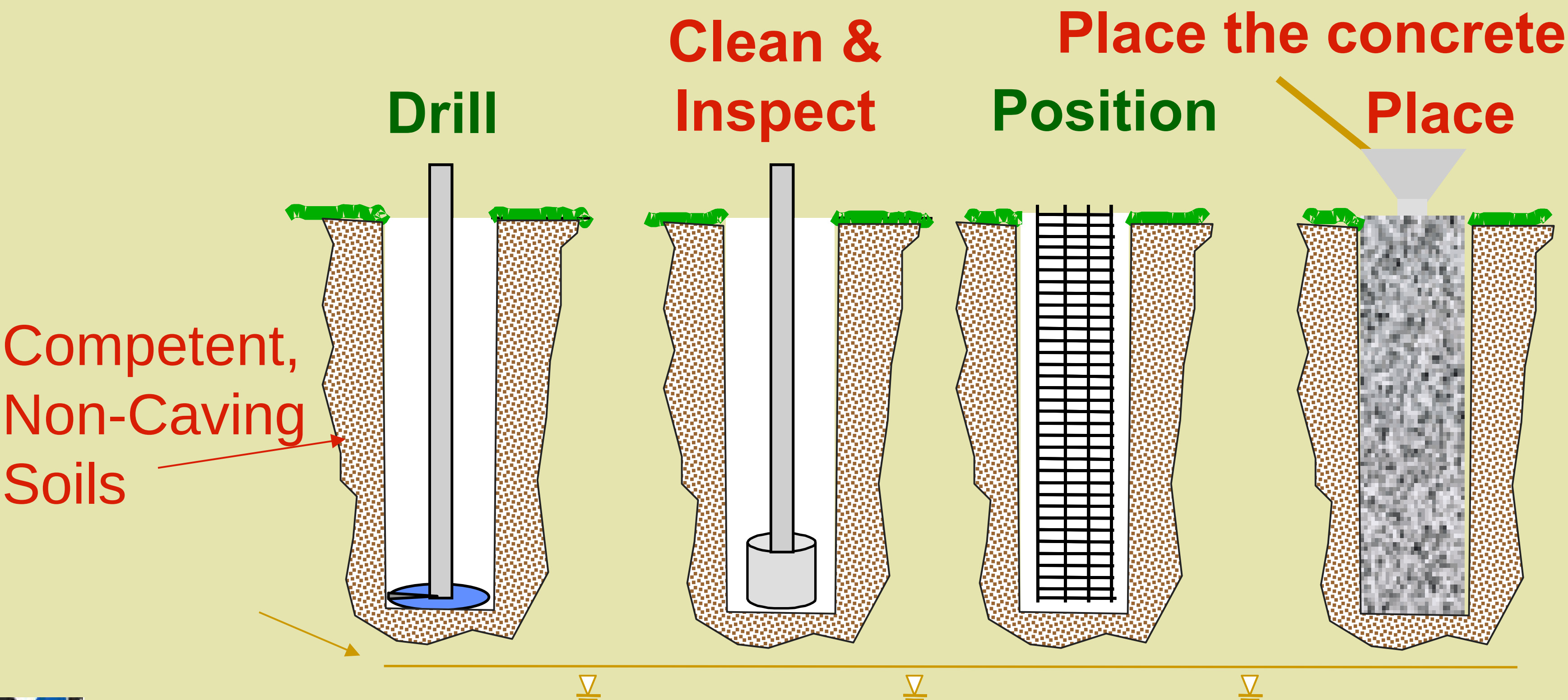
Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course

Dry Method of Construction Process

Drill the shaft excavation

Clean shaft by removing the cuttings & seepage water

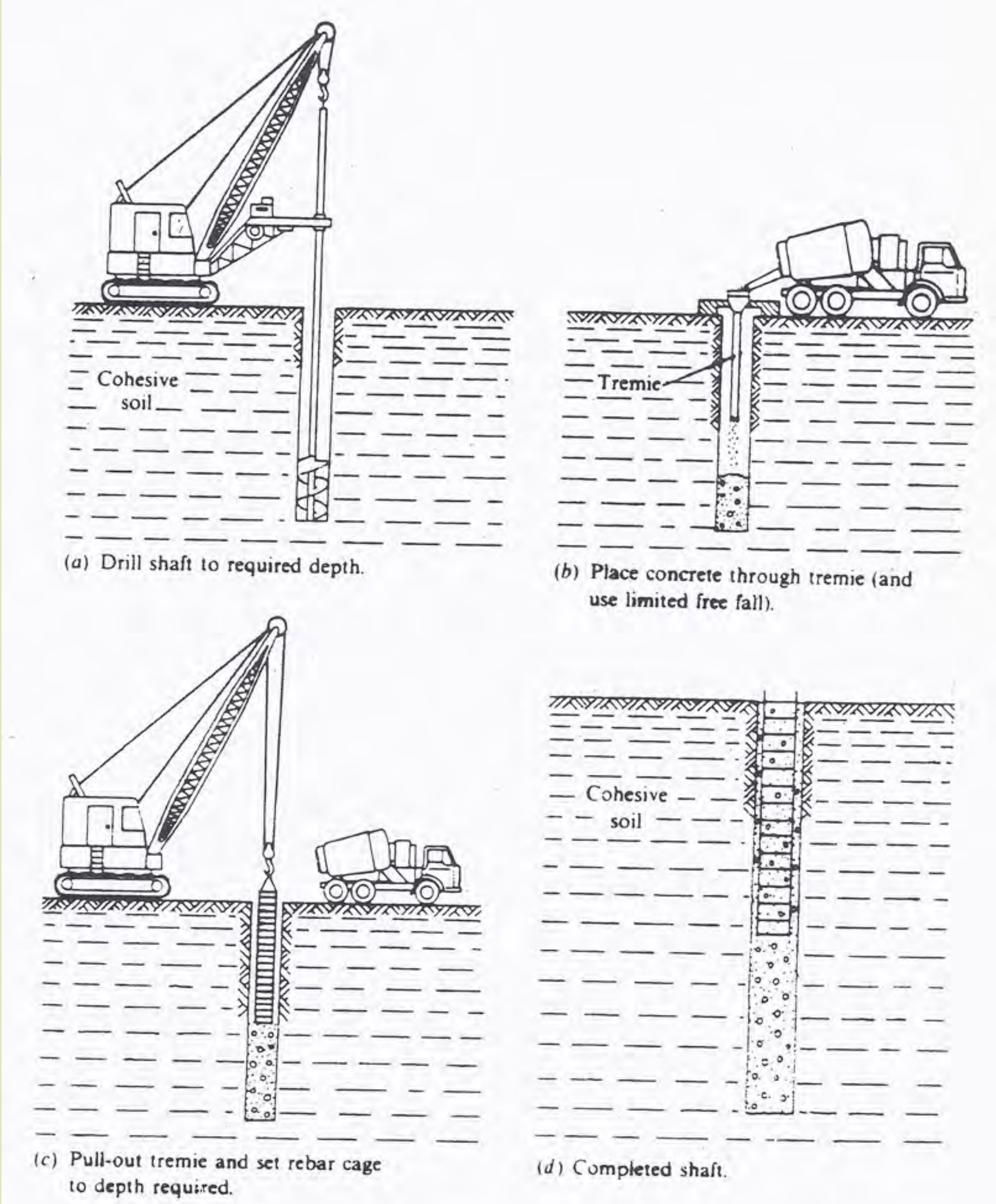
Position the reinforcing cage



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

Dry Method of Construction Process

Dry method of Drilled Pier Construction (Bowles)



(a) Drill shaft to required depth.

(b) Place concrete through tremie (and use limited free fall).

(c) Pull-out tremie and set rebar cage to depth required.

(d) Completed shaft.

Dry Method of Construction Process

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

DRILL (SCDOT 712.10)

Photographs courtesy of WPC Inc.

Dry Method of Construction Process

CLEAN

& INSPECT

Photographs courtesy of WPC Inc.

Dry Method of Construction Process

INSPECTION OF EXCAVATION (SCDOT 712.14)

- Need SCDOT Qualified Inspectors

EXCAVATION CLEANLINESS (SCDOT 712.14D)

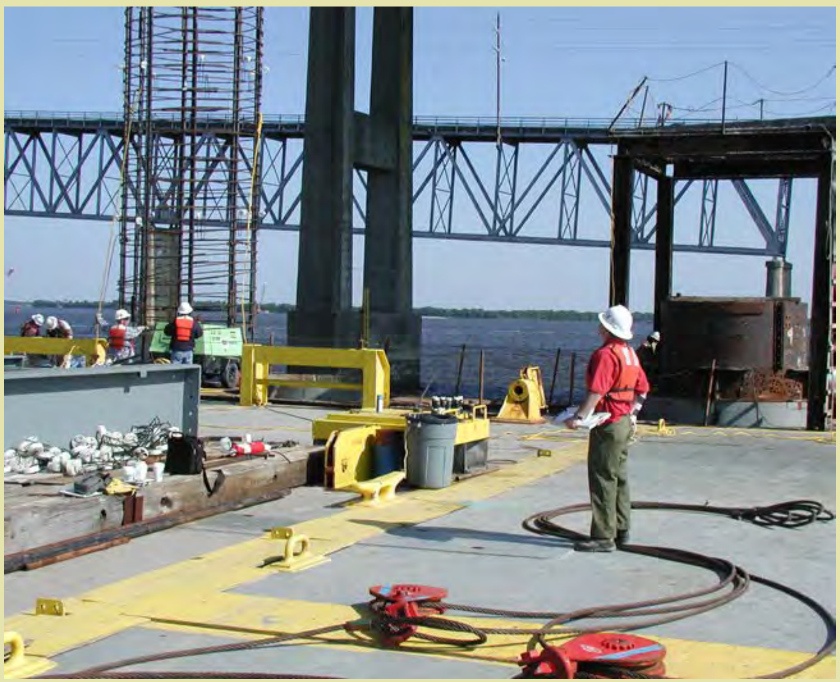
- **50% of Base has < ½ inch of sediment**

AND

- **Maximum depth of sediment < 1 ½ inches**

Dry Method of Construction Process

POSITION (SCDOT 712.16)



- Spacers needed for 5 inch min. annulus.
- Spacer interval < 10 ft.

Photographs courtesy of WPC Inc.

Dry Method of Construction Process

Photograph courtesy of WPC Inc.

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 of Construction Process

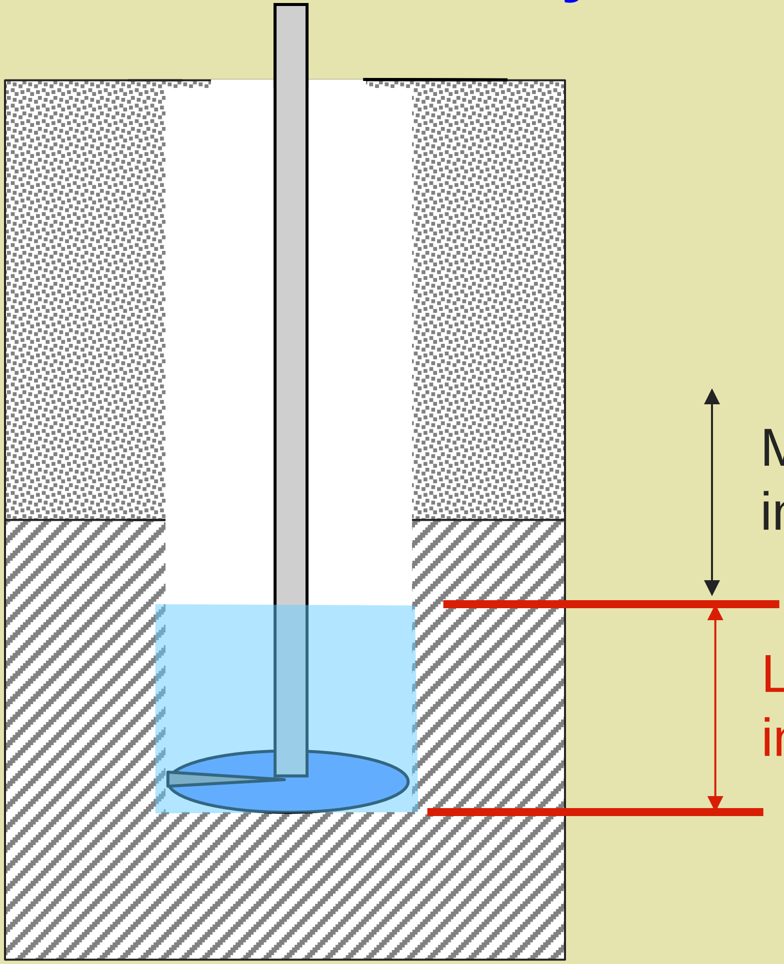
PLACE (SCDOT 712.17)

Photograph courtesy of WPC Inc.

- Freefall > 75 ft not permitted.
- Freefall Max. Aggregate Size ¾ inch, 7-9 inch slump.
- Freefall still needs chute. Must have tremie onsite.
- SCDOT can always order tremie.

Wet Method of Construction Process

Use When A Dry Excavation Cannot Be Maintained



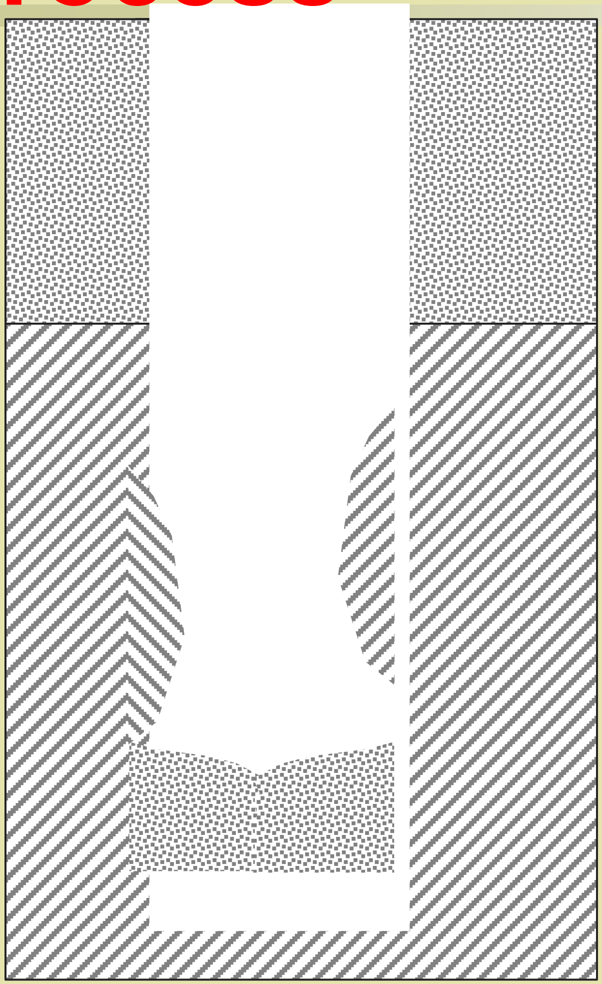
SCDOT 712.08

More than 6in in one hour **= Wet**

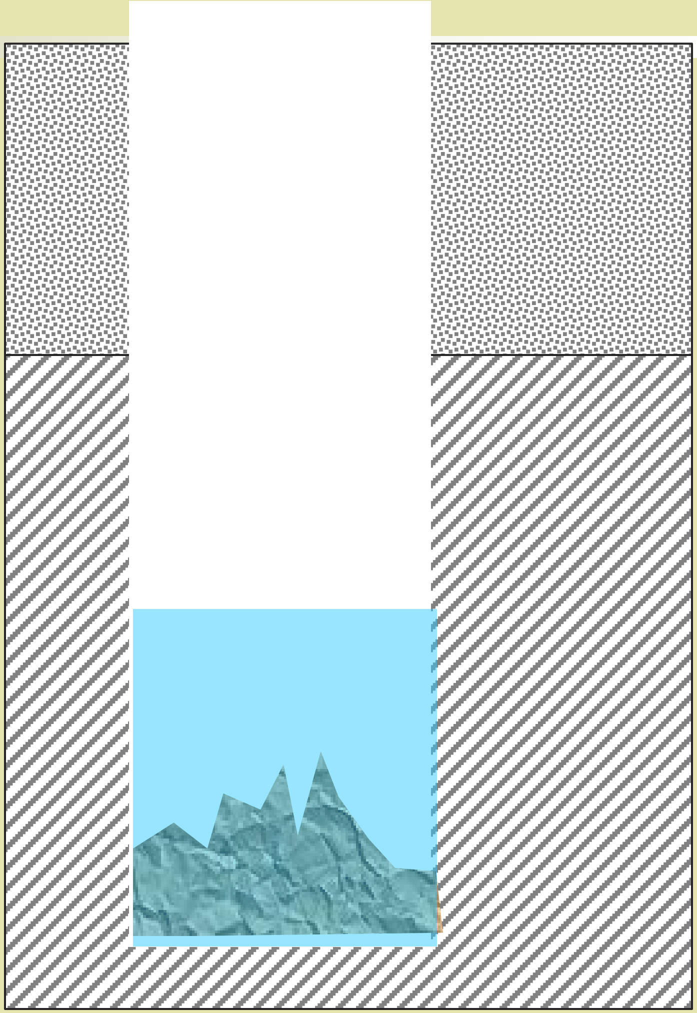
Less than 6in in one hour **= Dry**

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

Wet Method of 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

Wet Method of Construction Process

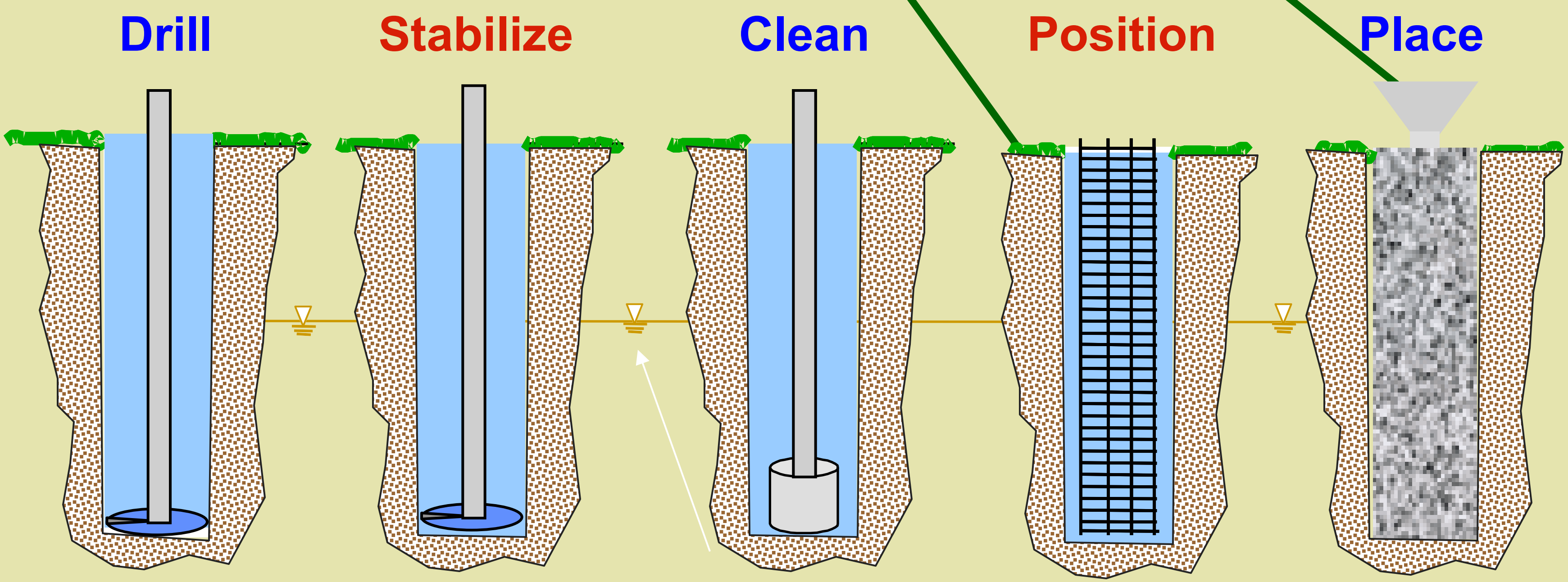
Drill the shaft excavation

Stabilize the hole (Plain water, slurry)

Clean shaft by removing the cuttings & seepage water

Position the reinforcing cage

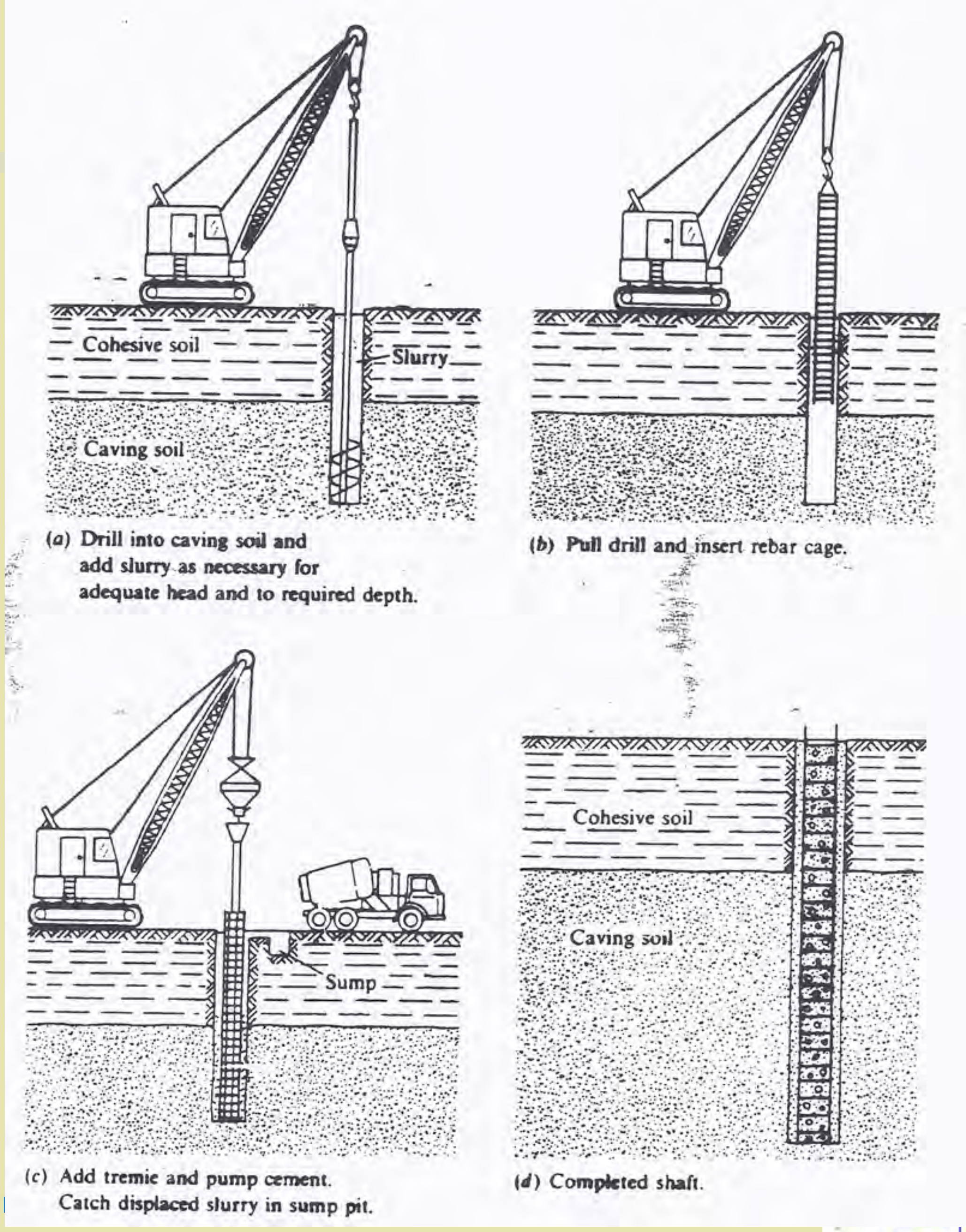
Place the concrete



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

Wet Method of Construction Process

Slurry method of Drilled Shaft Construction (Bowles)



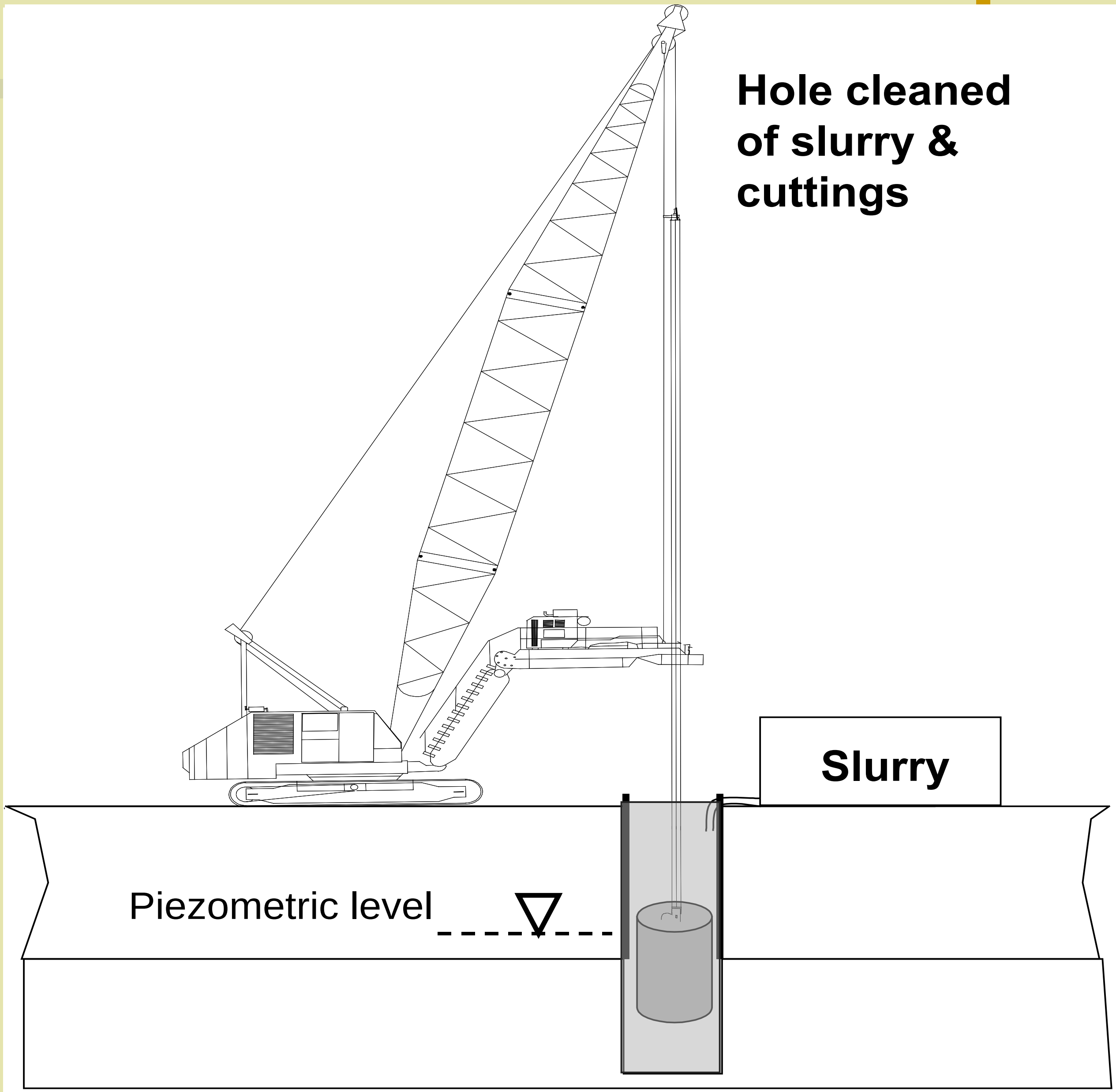
Wet Method of Construction Process

There are two forms of "wet" shaft construction:

- **Static Process**
- **Circulation Process**

Wet Method: Static Process

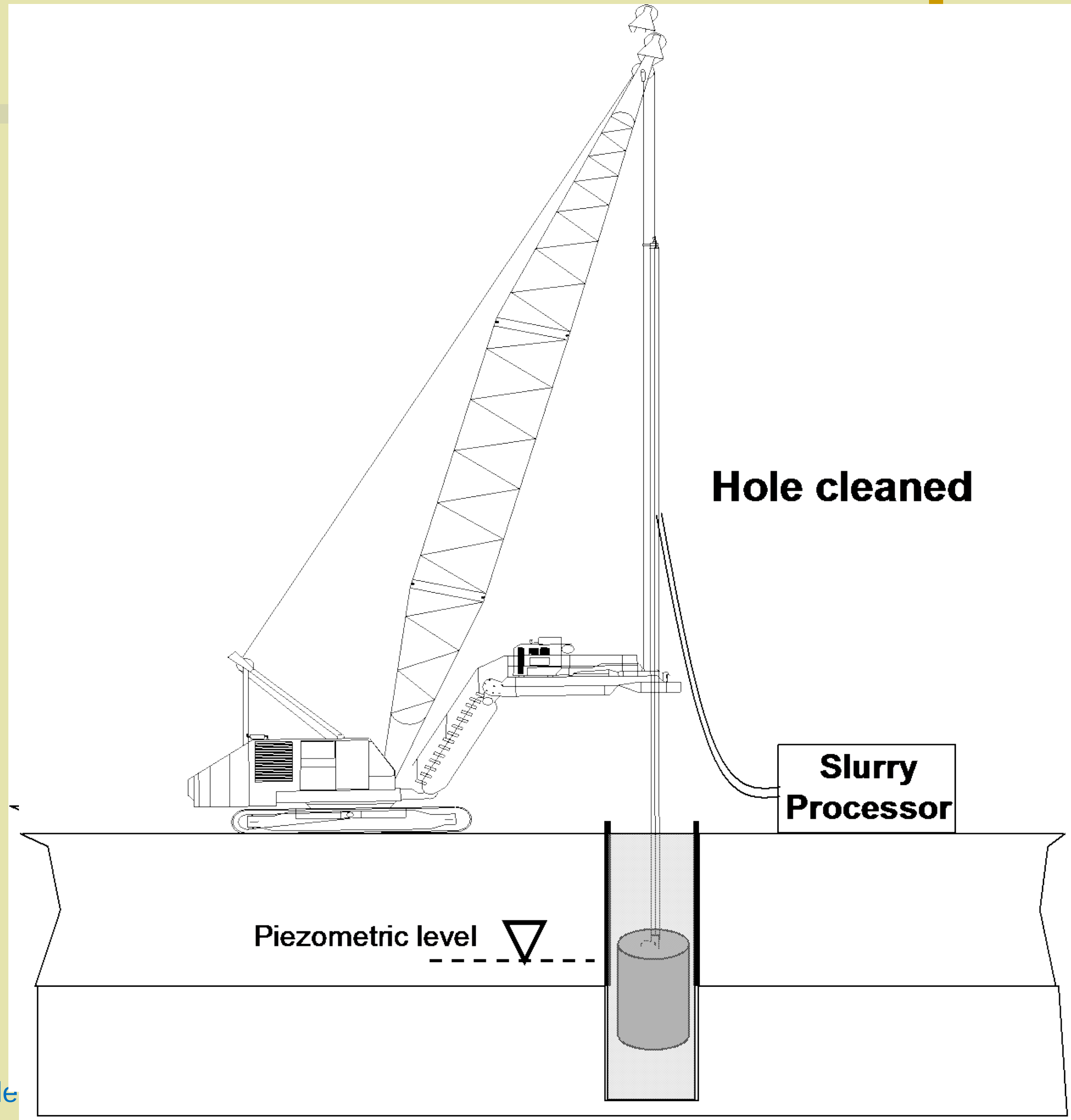
- Drill down to the piezometric level
- Slurry introduced
- Drilling Completed
- Cuttings are lifted from the hole



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

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 of Construction Process

SLURRY (SCDOT 712.12)

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

Drilling Slurry

Overview

Slurry is needed in soils that can potentially cave. Filing the excavation with drilling slurry stabilizes the hole and allows completing the excavation. Drilling slurry is used in two construction methods and hence two procedures are possible using slurry. With the casing construction method; a casing is installed and sealed into impermeable soil or rock, the slurry is bailed or pumped and the concrete is placed. With the wet construction method; the slurry is left in the excavation and the concrete is placed with the use of a tremie.

- **Water alone can be used as a drilling fluid if the formation does not slough or erode, e.g. cemented sand. Water is kept above the piezometric surface to prevent inflow.**
- **1950's and 1960's – make of slurry by mixing on-site clay. Not a recommended procedure as the slurry properties are difficult to control and particles continuously fall out of suspension. As such, the cleaning of the borehole is difficult and soil settles in the concrete (wet method).**

Drilling Slurry

Overview (cont'd)

- **Bentonite – processed powder clay (mostly montmorelonite) have been commonly used in drilled shafts construction since the 1960's (US). Cross and Harth (1929) patented the use of Bentonite as an agent that could gel and suspend cuttings. The technology of drilling fluids was extensively developed in the petroleum industry. Early Civil Engineering applications for slurry walls described by Veder (1953).**
- **Bentonite hydrates by water and therefore flocculates in saline environment. Attapulgite and Sepiolite are other minerals that do not hydrate and are suitable for saline environment.**

Drilling Slurry

Overview (cont'd)

- Environmental concerns of slurries with minerals containing solid particles are that they suffocate aquatic life. This and other concerns resulted with a need for an approved disposal at the end of a job (not allowed in sewer or a body of water). This requirement forced contractors to handle mineral slurries in a closed loop.
- The use of synthetic polymer slurries has recently increased because these slurries are subject to environmental control less stringent than that of the mineral slurries.

Drilling Slurry

Principles of Slurry Operations

- Betonite and other clay minerals form a suspension when mixed properly with water.
- Preparation depends on mixing effort – shearing and time for hydration. In case of Bentonite – several hours are required before final mixing and introduction into the borehole.
- After mixing mineral slurries have unit weights of 1.03 to 1.05 that of water. As drilling progresses, the slurry picks up more soil, the unit weights and viscosity increases and eventually are corrected by the contractor when reused.
- If the fluid pressure within the slurry column in the borehole exceeds the ground water pressure in a permeable formation, the slurry penetrates the formation and deposits the suspended clay plates on the surface of the borehole, (termed “filtration”) in effect forming a membrane or “mud cake” that assists in keeping the borehole stable.

Drilling Slurry

Principles of Slurry Operations (cont’d)

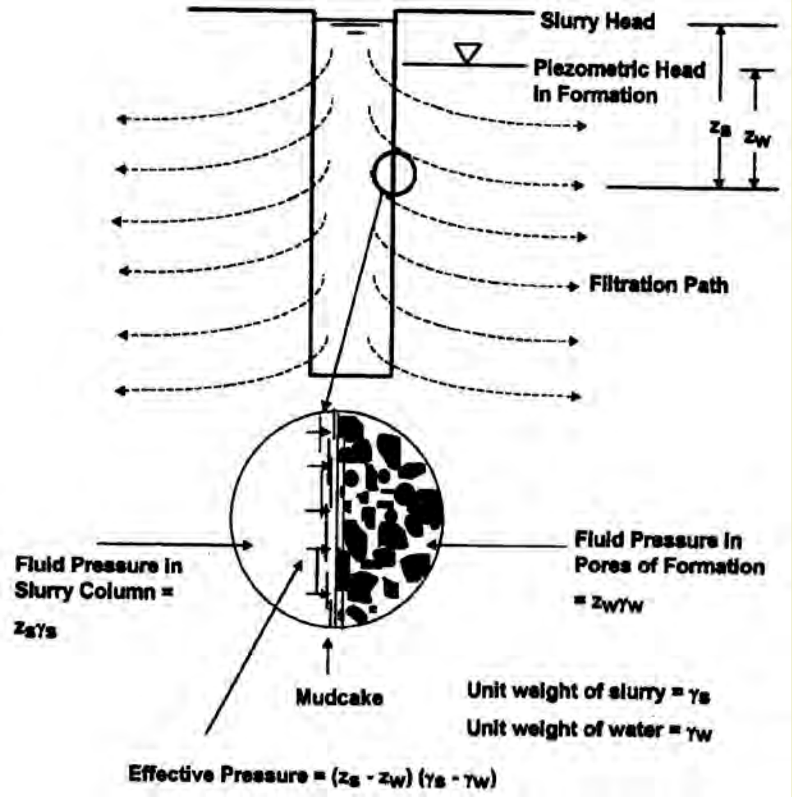


Figure 6.1 Formation of mudcake and positive effective pressure in a mineral slurry in sand formation (O’Neill and Reese, 1999)

Drilling Slurry

Principles of Slurry Operations (cont'd)

- **When the pore sizes in the formation are large (e.g. gravely soils), the mud-cake may be replaced by a deep zone of clay plate deposition within the pores that may or may not be effective in producing a stable borehole.**
- **Bentonite should not be used when the clay will diminish the adhesion, for example smooth drilling rock socket.**

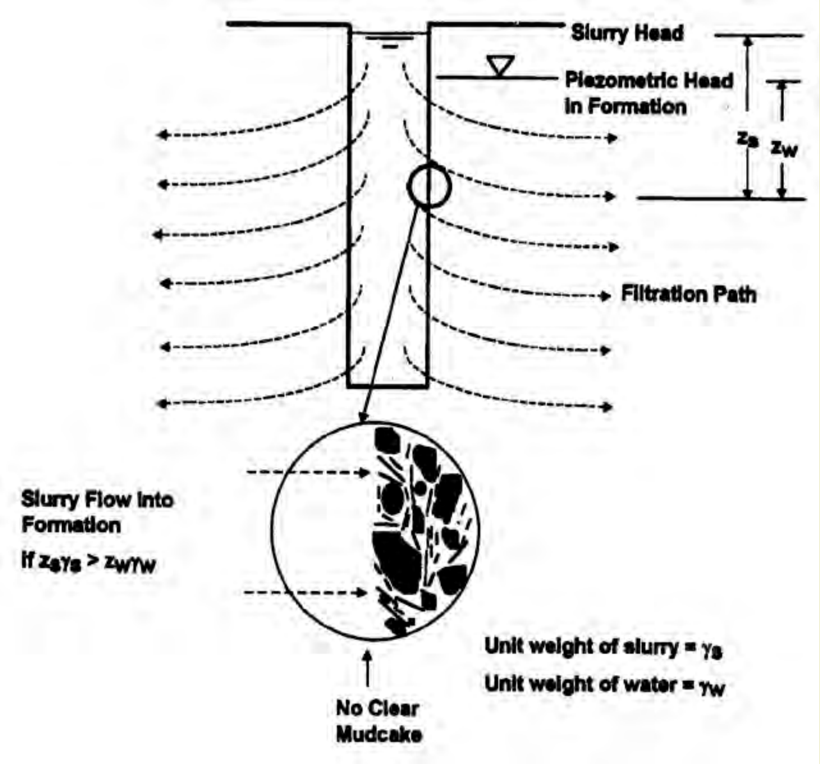


Figure 6.2 Mineral slurry plates in pores of open-pored formation (modified after Fleming and Silvinski, 1977) (O'Neill and Reese, 1999)

Drilling Slurry

Influence of Slurry on Axial Capacity of Drilled Shafts

- Major concern – loss of side resistance because of the development of a thick membrane of weak material at the side of the borehole.
- A thick mud cake (or filter cake) will reduce the roughness of the contact and the interfacial friction.
- Load tests and close examination of “wet” constructed drilled shafts did not show any evidence of a thick, weak layer of Bentonite.
- Laboratory investigations show that when left in place, the filter cake thickness increases with time. Slurry should be left less than 24 hours and a maximum of four hours holding time for mineral slurry in the borehole is recommended.
- Lab and field tests did not show any influence of the slurry on the bond between the concrete and the reinforcing steel.

Drilling Slurry

Influence of Slurry on Axial Capacity of Drilled Shafts (cont;d)

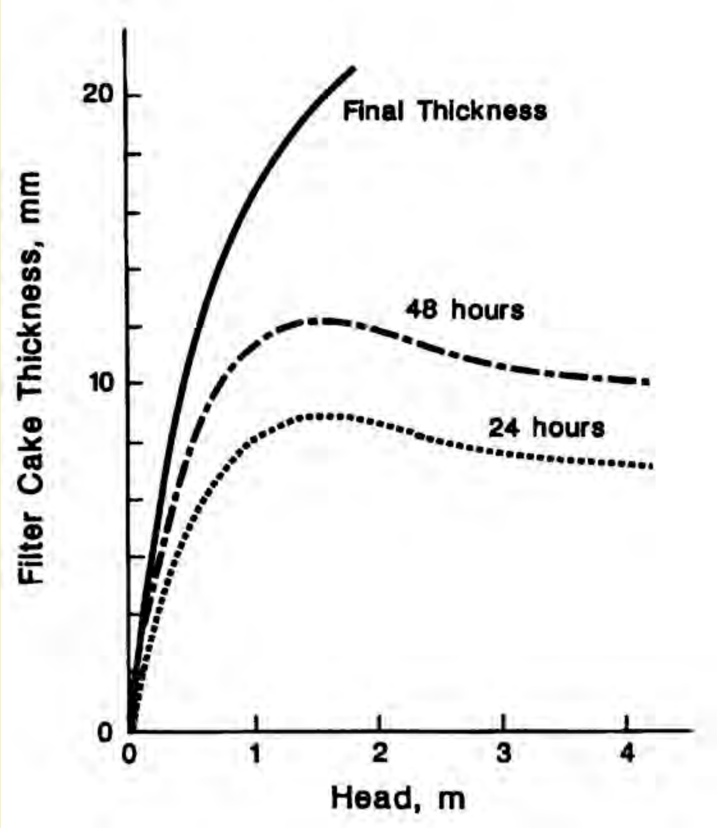


Figure 6.14 The buildup of bentonite filter cake in a model apparatus in response to different pressure heads (after Wates and Knight, 1975) (O'Neill & Reese, 1999)

Drilling Slurry

Principles of Polymers Slurry Operation

- **Polymers have the following advantages: better in soil formations containing clay minerals (including rocks) that produce enlargements and instabilities (when using Bentonite), require less conditioning and are easier and cheaper to dispose of.**
- **The polymers used are chain-like hydrocarbon molecules, which act like clay minerals. The molecules are hair-shaped (not plate-shaped), they do not form a mud-cake and the borehole stability is produced through continual filtration keeping the soil particles in place. The viscous drag effect in the soil near the borehole produces eventually an effective seal, much like the Bentonite mud-cake.**
- **Slurry continuously being lost and a maintenance of a positive head (at least 2m above piezometric head as a rule of thumb) demands adding continuously slurry stock to the column.**

Drilling Slurry

Principles of Polymers Slurry Operation (cont'd)

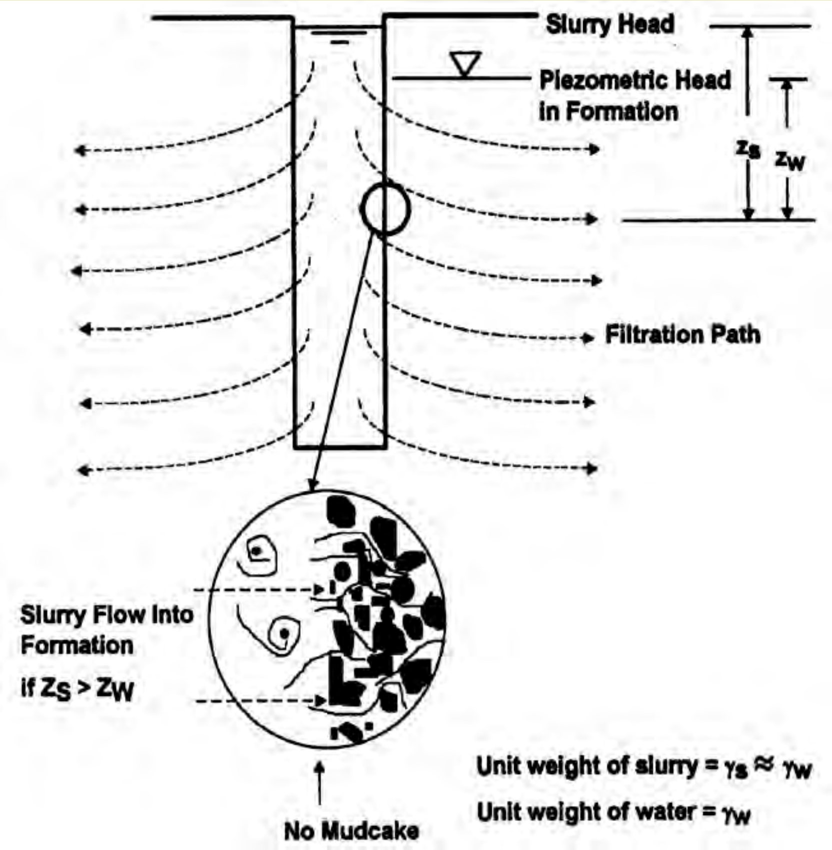


Figure 6.3 Stabilization of borehole by the use of polymer drilling slurries (O'Neill & Reese, 1999)

Drilling Slurry

Examples of Problems with Slurry Construction

- Continuous inspection by the contractor and the inspector are required, visualizing what is happening in the ground.
- A wet excavation through soils into disintegrated rock. The slurry contains more sand than it can hold in suspension, but due to neglect or wrong slurry sampling, the slurry is not cleaned prior to the installation of the concrete, (a). A quantity of granular material settles on the top of the concrete column as the pour progresses, (b). Large frictional resistance is built up between the sand and the walls, the flowing concrete breaks through and folds the layer of granular material into the concrete, creating necking. This type of defect often occurs at the water table elevation where the granular material loses its buoyancy and settles to the top of the concrete column.

Drilling Slurry

Examples of Problems with Slurry Construction (cont'd)

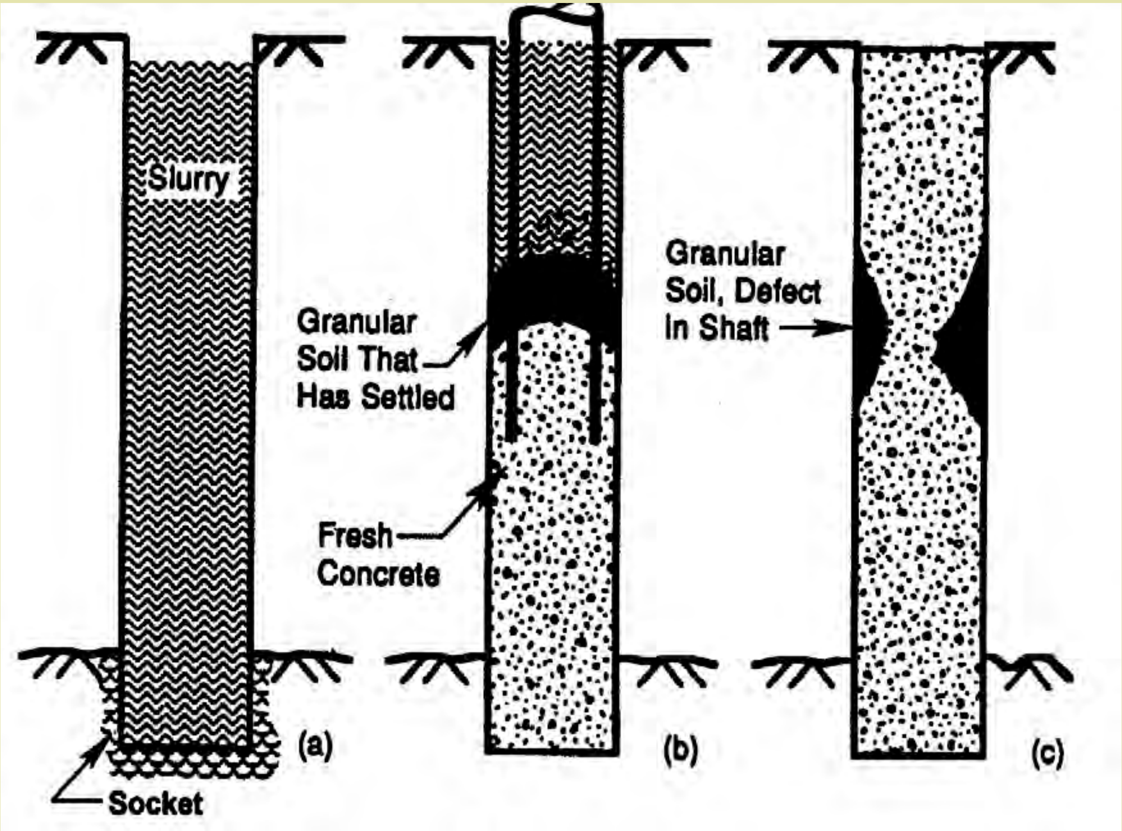


Figure 6.15 Placing concrete through heavily-contaminated slurry (O'Neill & Reese, 1999)

Drilling Slurry

Examples of Problems with Slurry Construction (cont'd)

- **A tremie defect can arise if during the placement of the concrete, the bottom of the tremie is lifted above the top of the column of fresh concrete, allowing the concrete to fall through the slurry and become leached. The elevations of both, the top of the concrete and the bottom of the tremie need to be monitored continuously and simultaneously. The top of the concrete, using weighted tape and the tremie by marks.**
- **Plugged tremie during pour, requires the tremie withdrawal, potentially producing a tremie defect. Proper tremie cleaning and proper design of concrete mix -- are the solution.**

Drilling Slurry

Examples of Problems with Slurry Construction (cont'd)

- Problems that can develop at the base of a DS when using the wet method and assuming high end bearing value.
  a) Stopping the excavation in a disintegrated area → require a good site investigation with sufficient detail.
  b) Loose sediment settled to the bottom of the excavation (after cleaning) and is capsulated in the concrete → good sampling and testing the slurry, recleaning if necessary.
  c) Weak concrete at the bottom of the DS (e.g. concrete passes through the slurry) → monitor the concrete level and the tremie location.

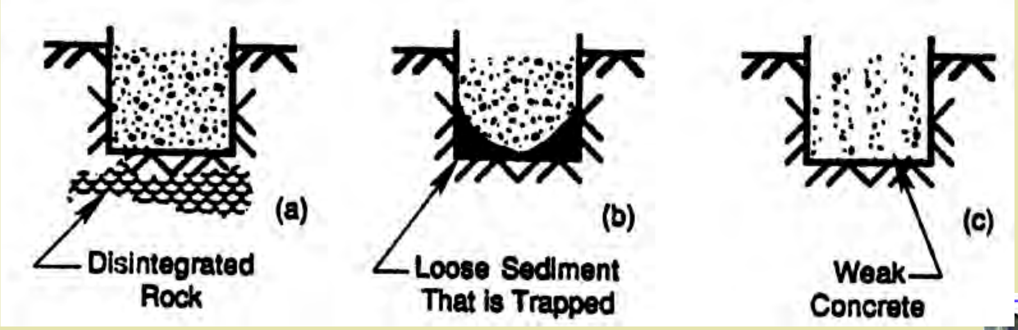


Figure 6.16 Factors causing weakened resistance at base of a drilled shaft (O'Neill & Reese, 1999)

Drilling Slurry

Examples of Problems with Slurry Construction (cont'd)

- If the cut-off elevation is below the ground surface → Concrete is continued to be placed until a good quality concrete is well above the cut-off level. The excess concrete is then chipped away.

Drilling Slurry

Examples of Problems with Slurry Construction (cont'd)

- (a) Proper casing construction with a sealed casing in an impermeable formation. (b) The casing has been pulled with an insufficient amount of concrete in the casing so that the hydrostatic pressure in the slurry invaded the concrete and produced a neck in the drilled shaft. → The casing need to be pulled only after it is filled with concrete of good flow characteristics so that the hydrostatic pressure in the concrete is always greater than that in the slurry.

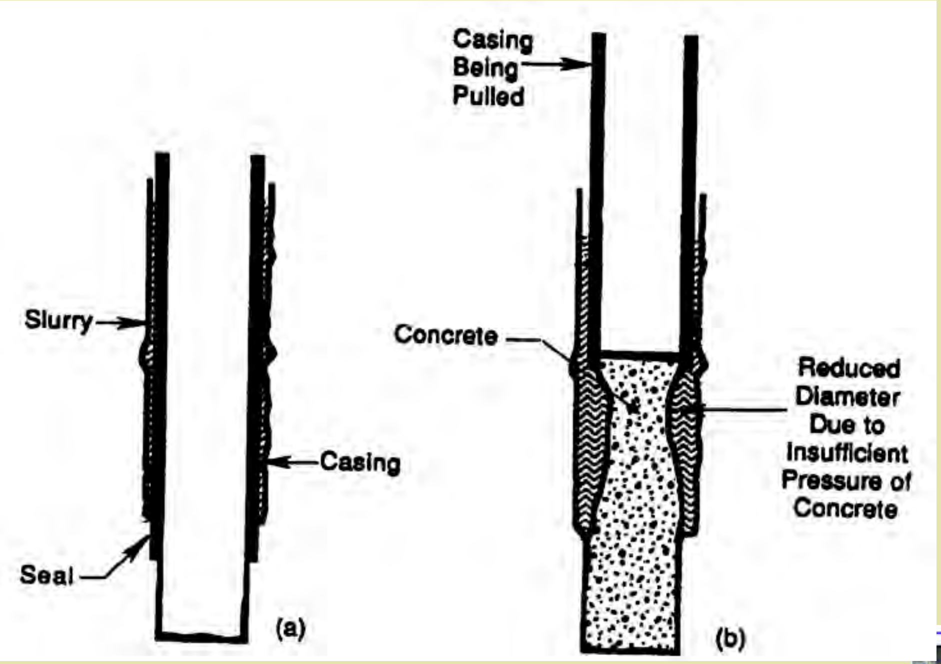


Figure 6.18 Pulling casing with insufficient head of concrete (O'Neill & Reese, 1999)

Drilling Slurry

Examples of Problems with Slurry Construction (cont'd)

- (a) Proper casing construction with a sealed casing in an impermeable formation. (b) The casing has been pulled with an insufficient amount of concrete in the casing so that the hydrostatic pressure in the slurry invaded the concrete and produced a neck in the drilled shaft. → The casing need to be pulled only after it is filled with concrete of good flow characteristics so that the hydrostatic pressure in the concrete is always greater than that in the slurry.

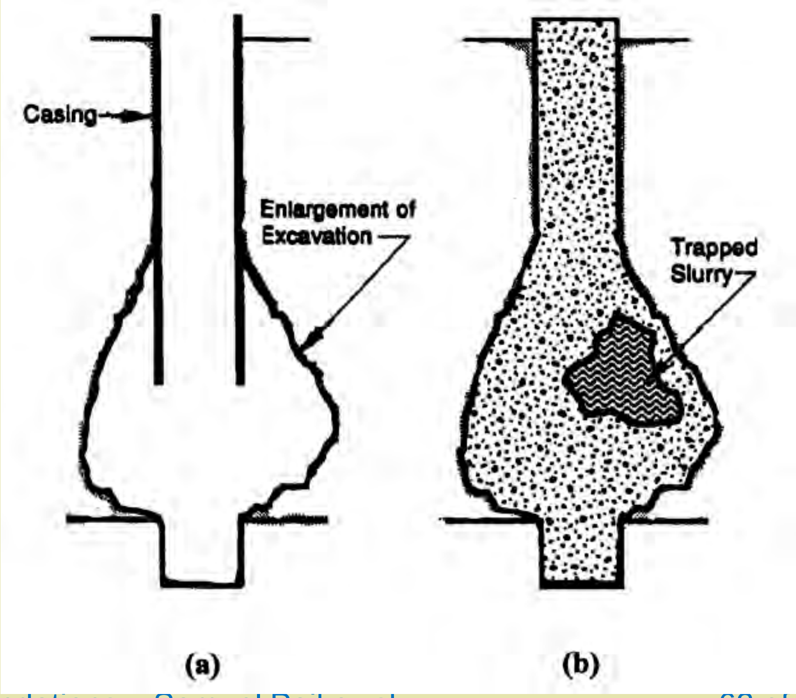


Figure 6.19 Placing concrete where casing was improperly sealed (O'Neill & Reese, 1999)

Wet Method Construction Process

Slurry Examples

Poor Slurry Job

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

Excellent Slurry Job

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**

WET METHOD CONSTRUCTION PROCESS
SLURRY COMPARISONS

	Mineral	Polymer
Best Application	Cohesionless	Cohesive & Argillaceous Rock
Mixability	Difficult - Must be Hydrated	Easy
Mix Water Sensitivity	Saltwater Sensitive	Yes/No
"Caking" Ability	Best	OK
Suspension Ability	Best	OK

WET METHOD CONSTRUCTION PROCESS
CONTROLLING SLURRY

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

Property (Units)	Value Range @ Introduction	Value Range @ Concreting	Test Method
Density (pcf)	64.3 – 69.1*	64.3 – 75.0	Density Balance
Viscosity (sec/qt)	28-45	28-45	Marsh Cone
pH	8-11	8-11	pH paper pH meter

*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

Casing Construction Method

SCDOT 712.09 & 712.11

- 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)

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

Casing Construction Method

SCDOT 712.11

Photograph courtesy of WPC Inc.

- Smooth, clean, watertight, w/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.

Casing Construction Method

MassDOT LRFD Design Manual (2009) Section 3.2.3.2

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)

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

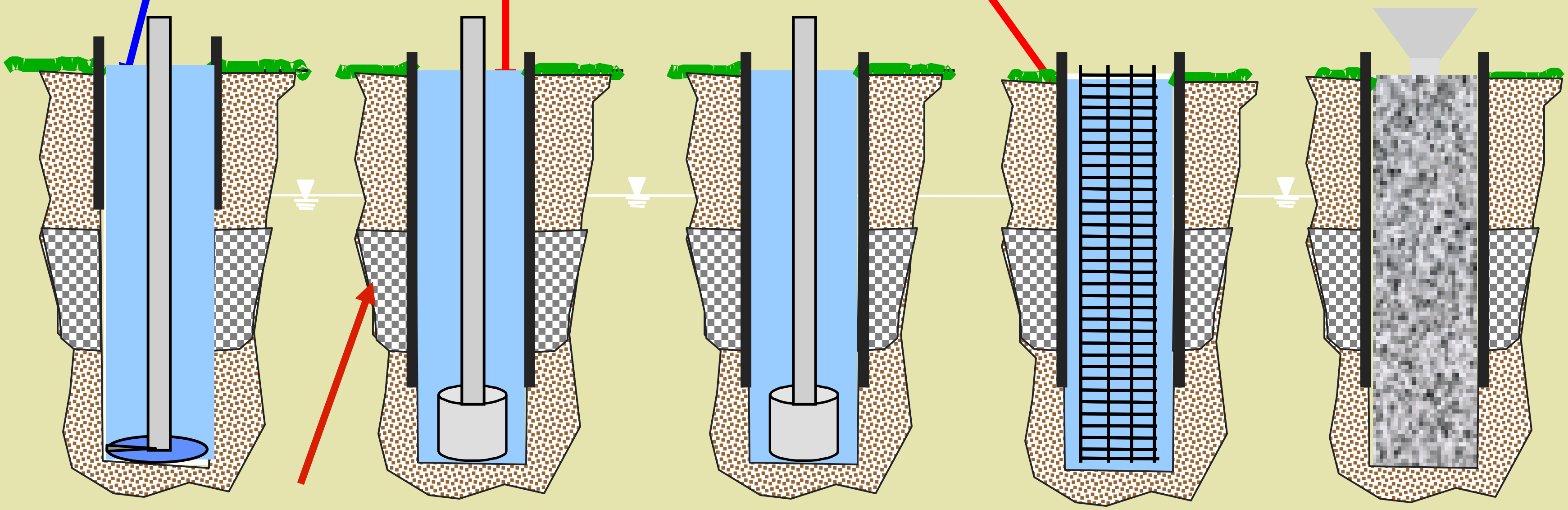
CASING METHOD: CONSTRUCTION PROCESS

Drill the shaft excavation

Install casing through caving soils and seal

Clean shaft by removing the cuttings & seepage water

Position the reinforcing cage



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

Casing Method: Construction Process

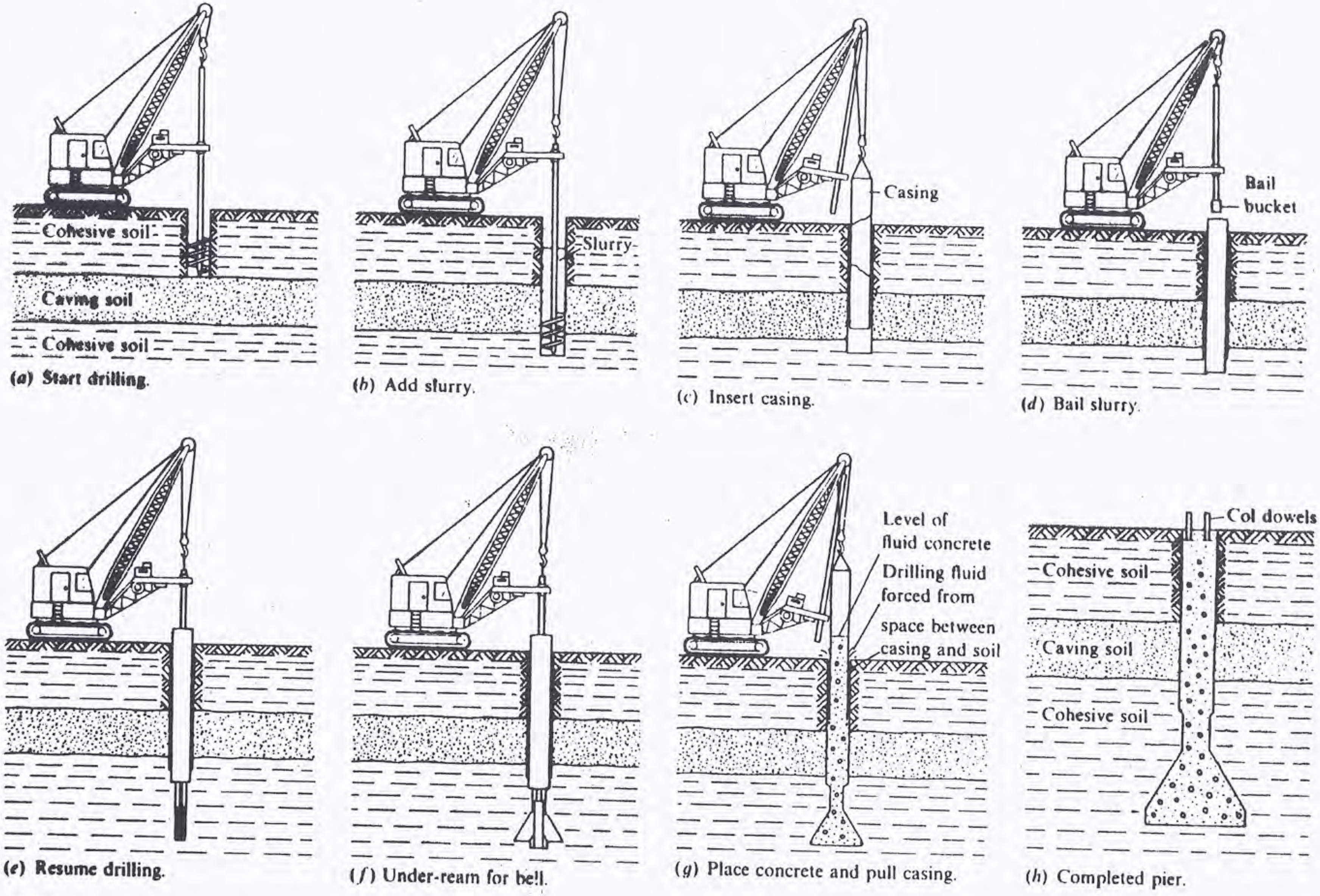


FIGURE 19-4
Casing method of drilled pier construction.

Casing Method: Construction Process

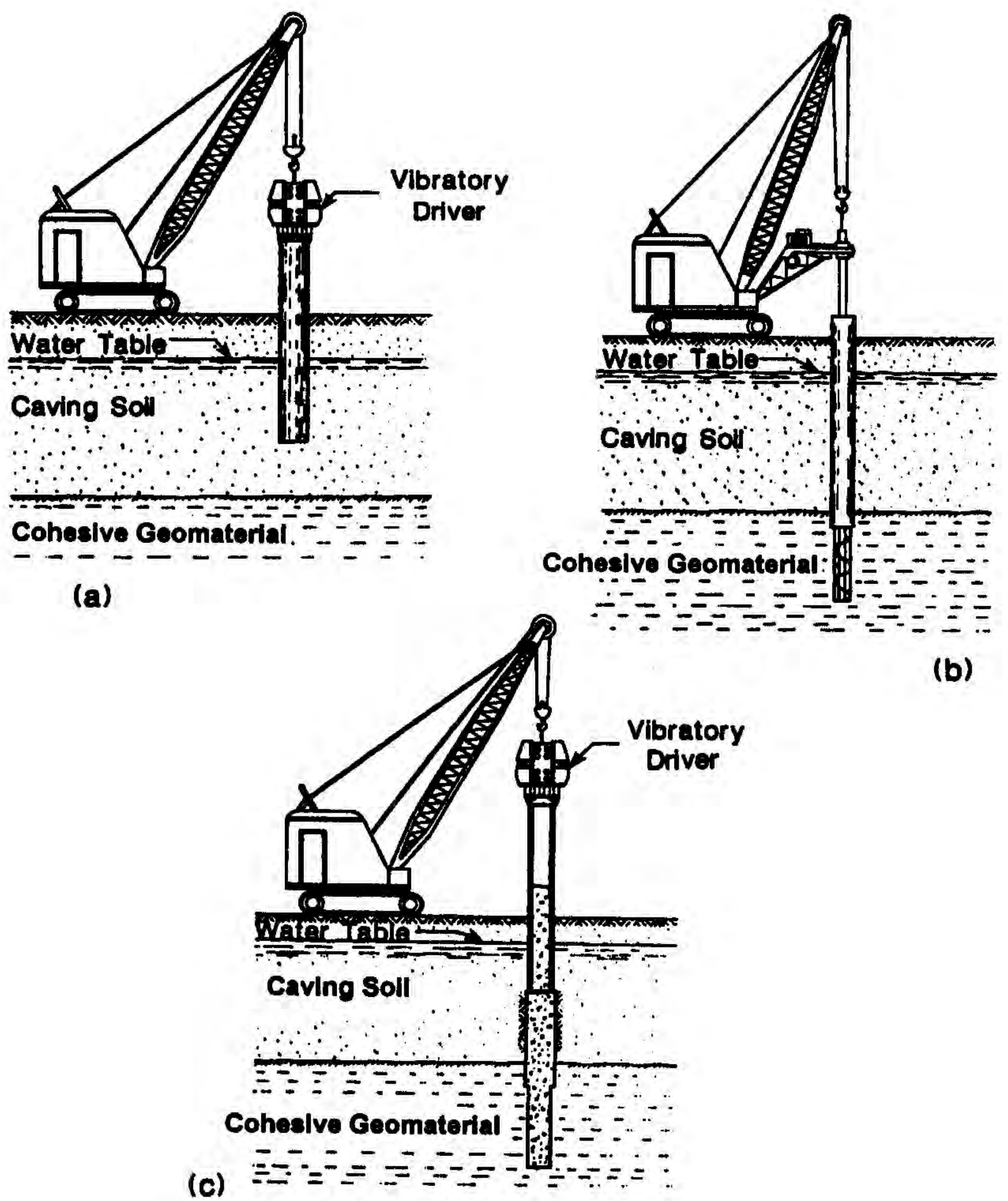
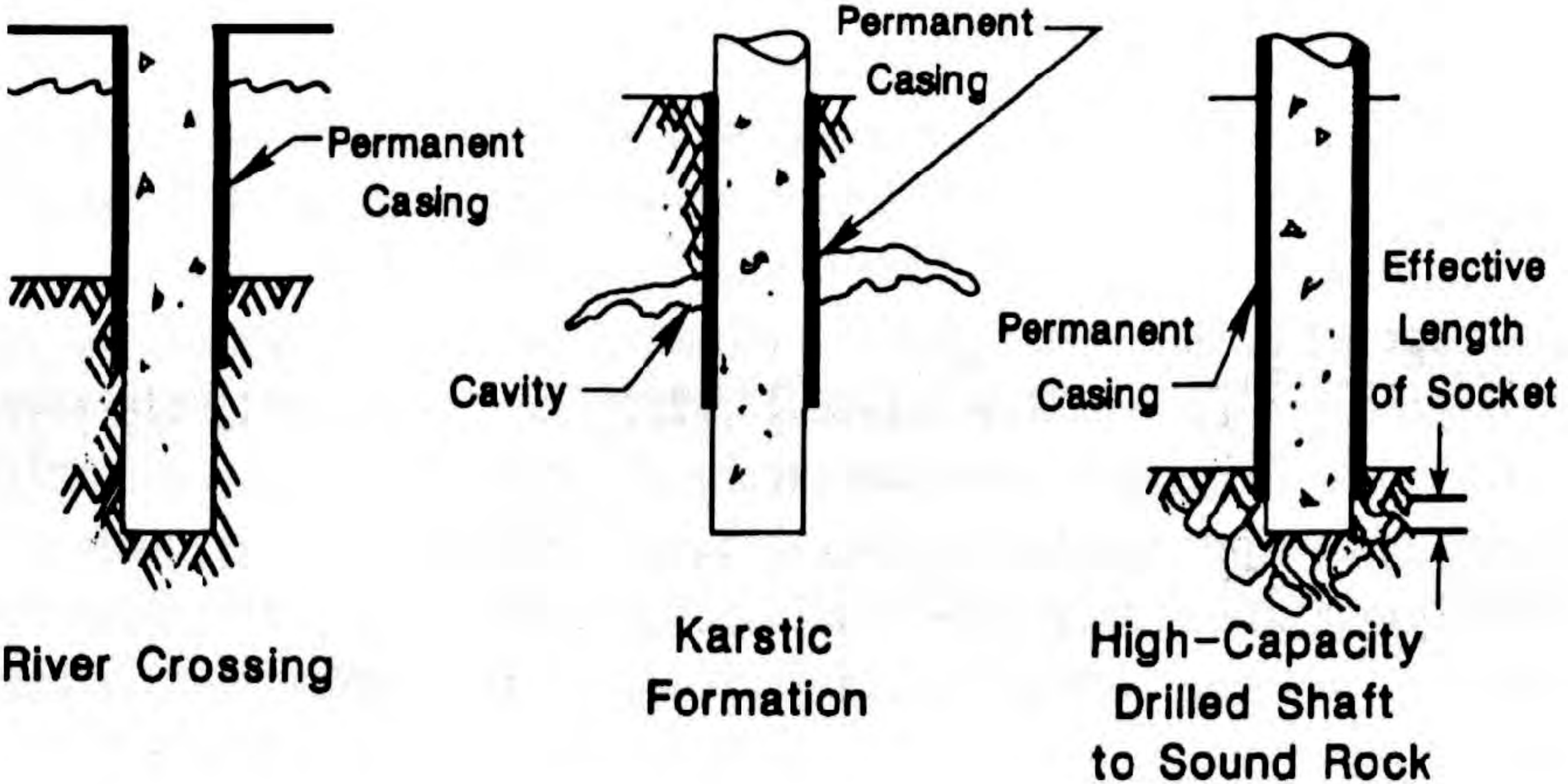


Figure 3.4 Alternate method of construction with casing: (a) installation of casing, (b) drilling ahead of casing, (c) removing casing with vibratory driver (O'Neill & Reese, 1999)

Casing Construction Method

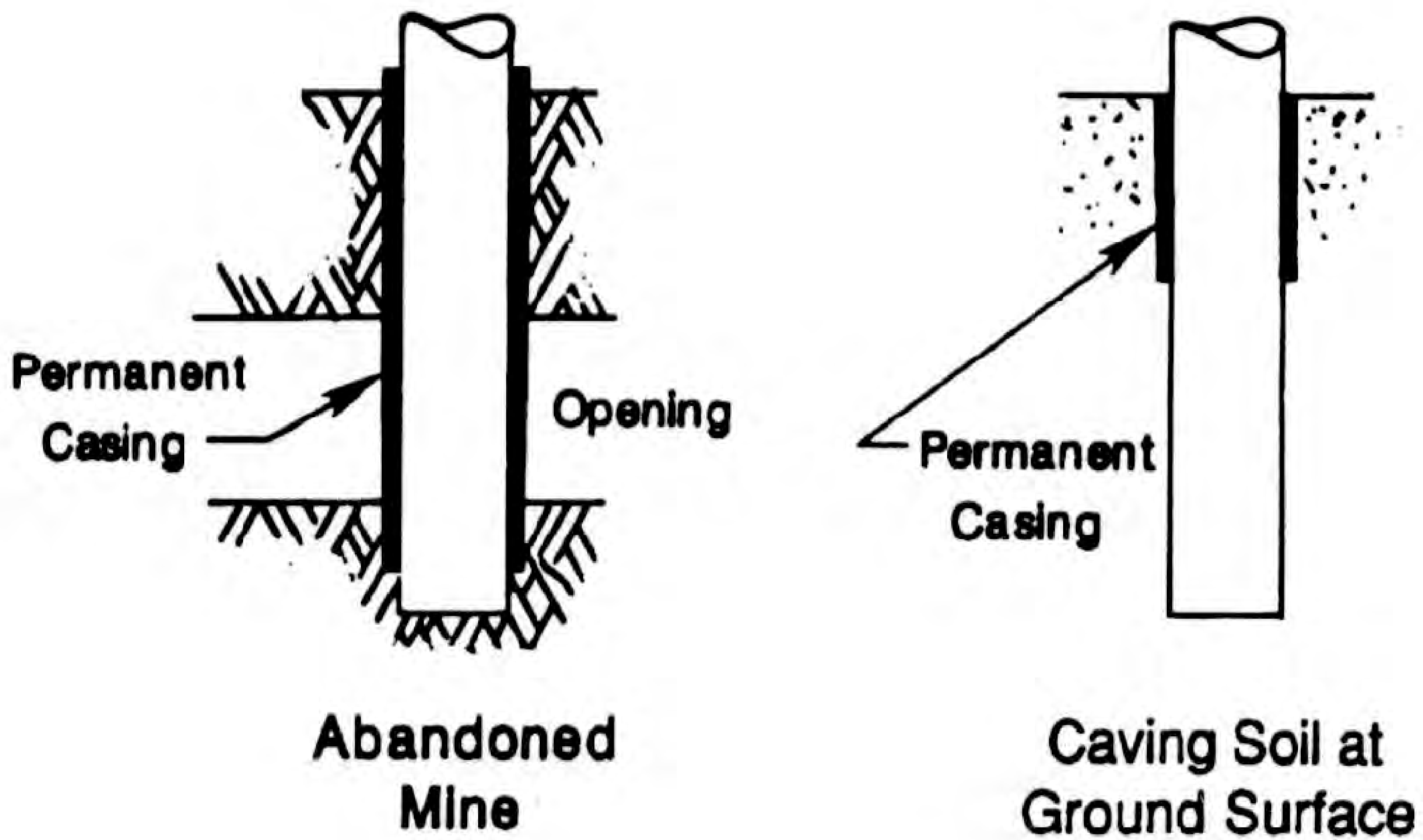
CONSTRUCTION (a.k.a. PERMANENT) CASING EXAMPLES



Figures courtesy of FHWA IF-99-025 Drilled Shafts: Construction Procedures and Design Methods.

Casing Construction Method

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



Figures courtesy of FHWA IF-99-025 Drilled Shafts: Construction Procedures and Design Methods.

Full-depth Casing Process

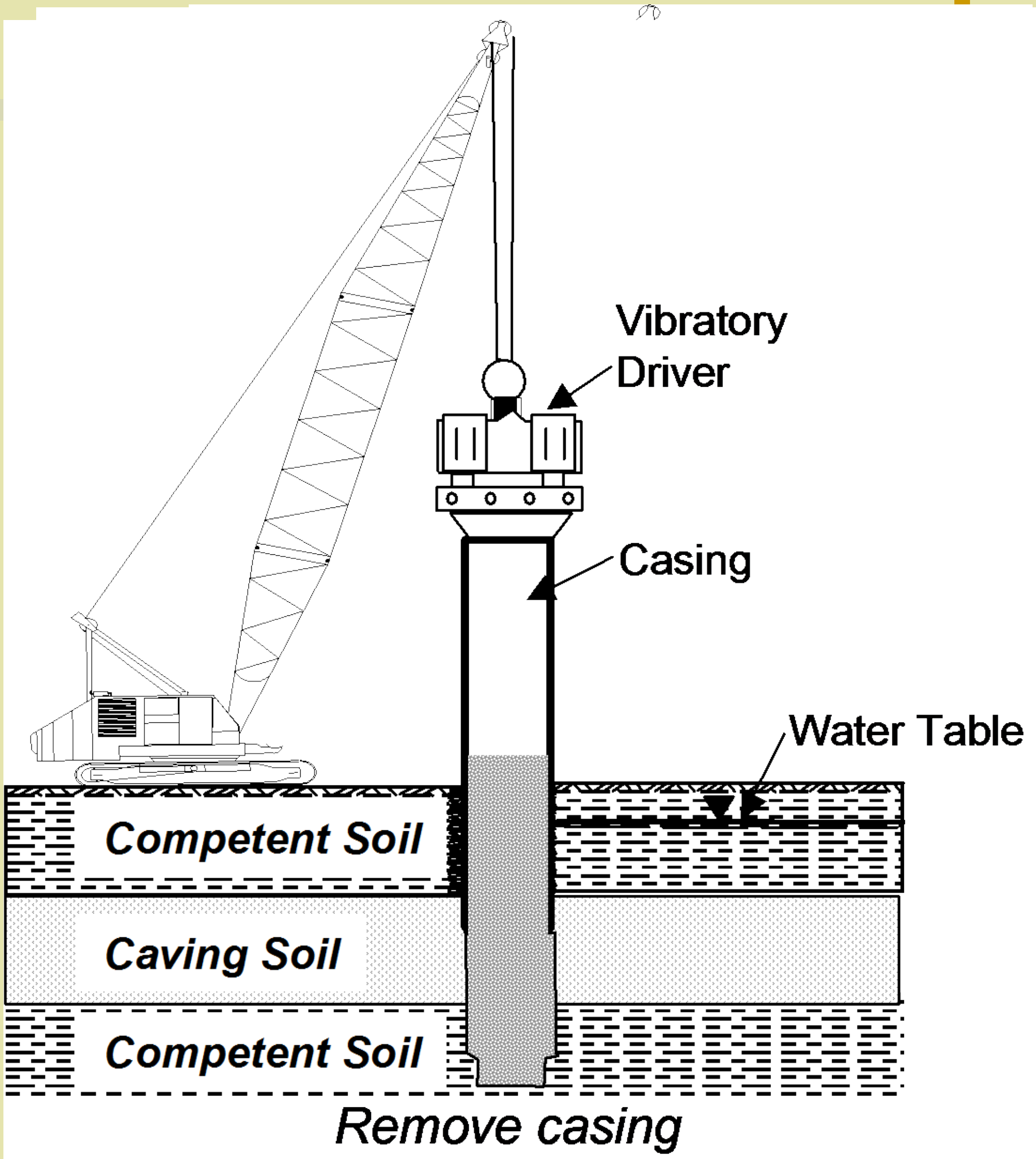
Installation of Casing

Drilling ahead of casing

Remove casing

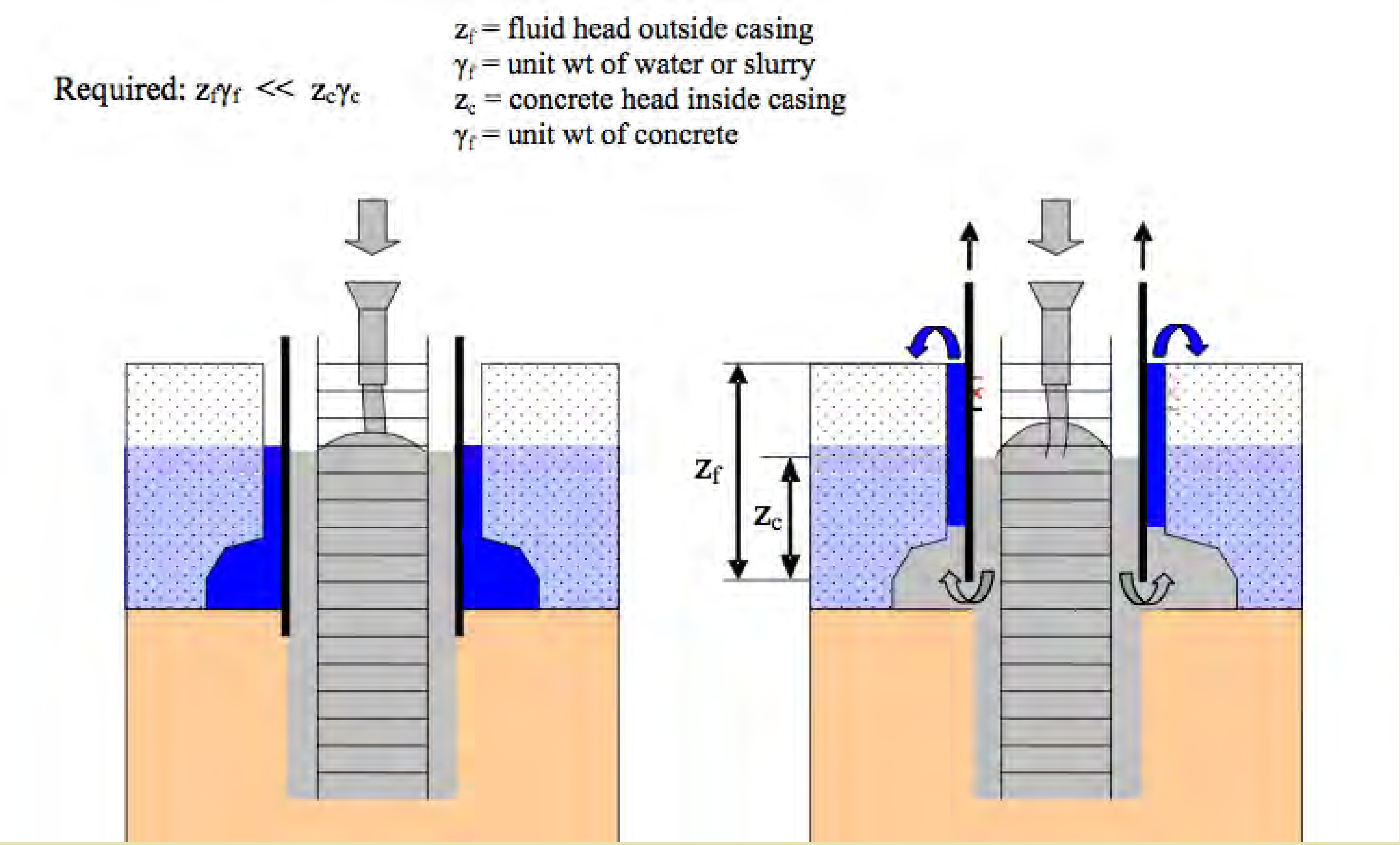
Figures courtesy of FHWA NHI-132070 Drilled Shaft Foundation Inspection Course

Figure 1. Concrete Flow Under Tremie Placement.



Casing Construction Method

Temporary Casing Removal



(a) Prior to lifting casing

(b) As Casing is Lifted.

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

Construction Equipment (Drilling Machines and Tools)

Drilling units (rigs) are mounted on trucks, cranes or crawler tractors. The major two parameters that express the capacity of the rig are; maximum torque that can be delivered to the drilling tool and the "crowd", the downward force that can be applied. The efficiency of the excavation depends to a great extent on the drilling tool. The result of a good (or poor) combination of torque, crowd and drilling tool determines the drilling rate.

Construction Equipment (Drilling Machines and Tools) (cont'd)

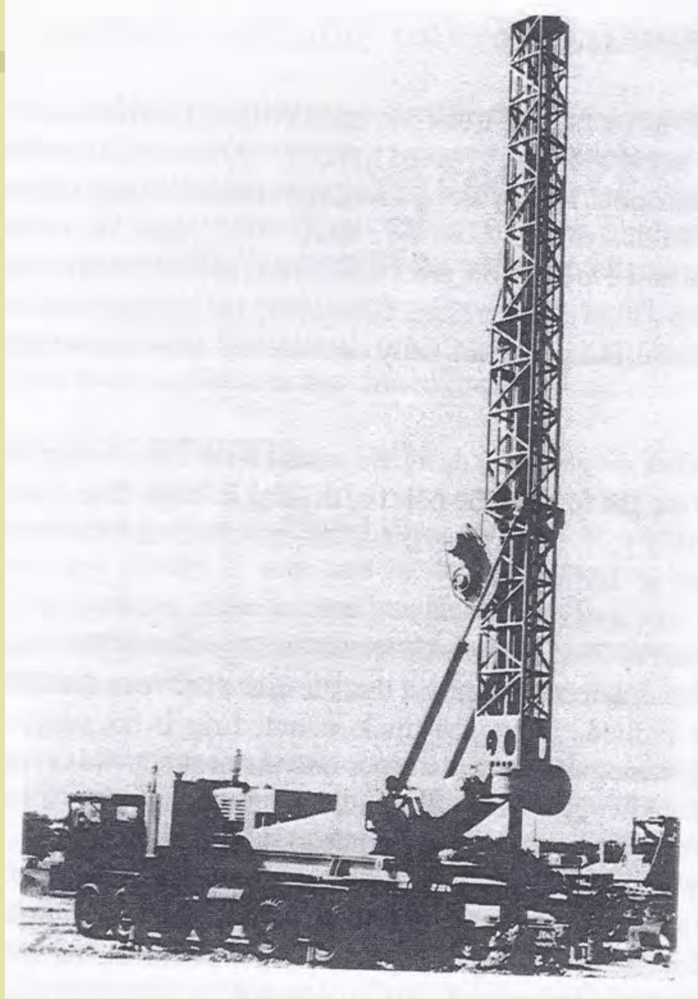


Figure 4.1 A typical truck-mounted drilling machine (O'Neill & Reese, 1999)

Figure 4.2 A typical crane-mounted drilling machine (Photograph courtesy of Farmer Foundation Company, Inc.) (O'Neill & Reese, 1999)

Drilled Shaft Equipment Terminology

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

Drilling Shaft Equipment Terminology (cont'd)

Table 4.1 Brief listing of characteristics of some drilling machines (O'Neill & Reese, 1999)

Model	Mount	Max. torque (kN-m)	Crowd (kN)*	Approx. max. hole diam. (m)	Approx. max. hole depth (m)	Kelly size (mm on side)**
Watson						
5000CA	Crane	135	Variable***	3.05	43	203
EDT-7	Crawler (low h'roon)	68	89	1.37	28.7	Varies
3100	Truck or Crawler	136	223	2.75	36.5	203
2500	Truck or Crawler	110	169	2.44	27	152
1500	Truck or Crawler	76	107	1.93	27	152
Hain						
8V71/754	Crane	509 (stall)	Variable***	3.66	45	343
4-71/3531-3	Crane	227 (stall)	Variable***	3.05	36.5	279
Atlantic						
Hughes LDH	Truck	68	164	2.44	30.5	152
Hughes LLDH	Truck	136	267	3.05	36.6	275
Calweld						
155	Crane	204	160	2.44	61	Round kelly
ADL	Truck	87	178	1.83	20	152
Texoma						
700 II	Truck or Crawler	73	100	1.83	18	140
TAURUS	Truck	114	228	2.44	30.5	178

* Crowd is limited by rig weight.
** Outside dimension of outer kelly. Inner sections will have smaller diameters.
*** Crowd depends on weight of kelly plus drilling tool used.

Note 1: The values given in this table represent approximate limiting economic capabilities and not continuous operating capacities. Deeper and larger diameter boreholes can often be drilled by using special tools and longer kelly bars.

Note 2: 1kN-m = 737ft-lb; 1kN = 224.7lb; 1m = 3.28ft; 1mm = 0.0394in

Note 3: Common good equipment in our area Bauer (Germany) www.bauer.de, Casagrande (Italy) www.casagrandegroup.com, Soil Mech (Italy) www.soilmec.com (Trevi Group)

Drilled Shaft Equip Terminology

Flight Augers (Open Helix) – Good for a variety of soils (mostly cohesive) and relatively soft rocks (shale, sandstone, soft limestone, decomposed rock). The cutting edge of the auger breaks the soil or rips the rock, after which it travels up the flights. The auger is then withdrawn and the cuttings are emptied by spinning.

Figure 4.7. A single-flight auger

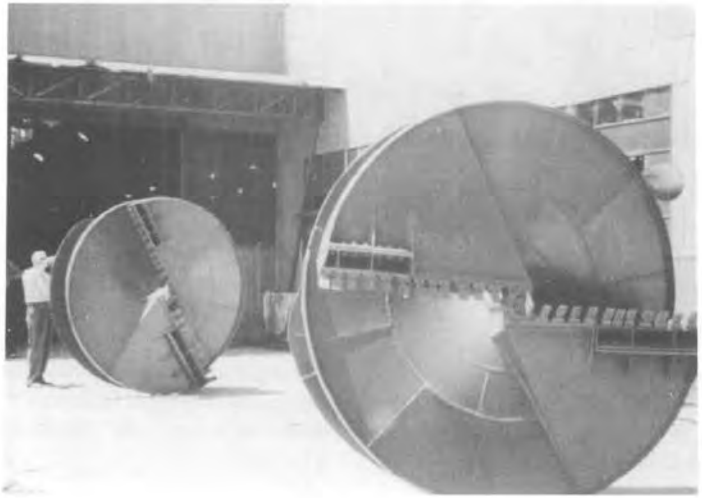
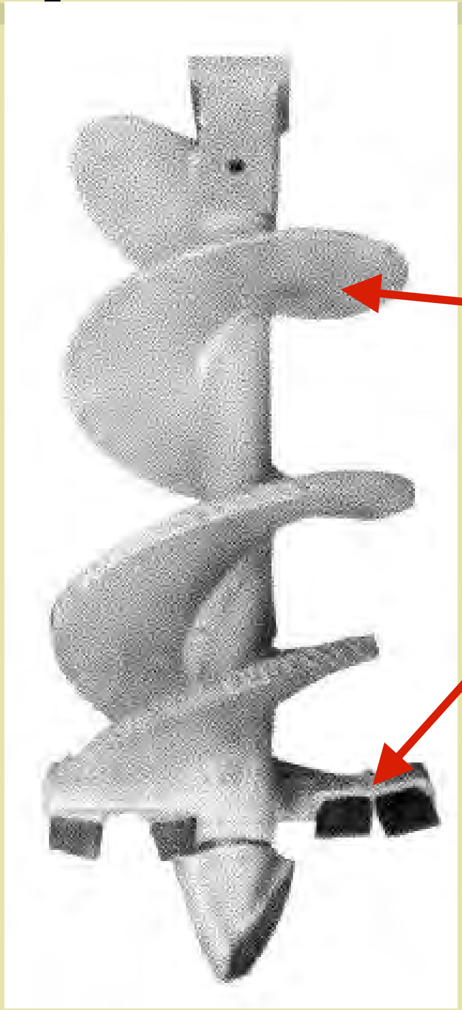


Figure 4.8. A typical double-flight auger

Drilled Shaft Equipment
Earth Augers

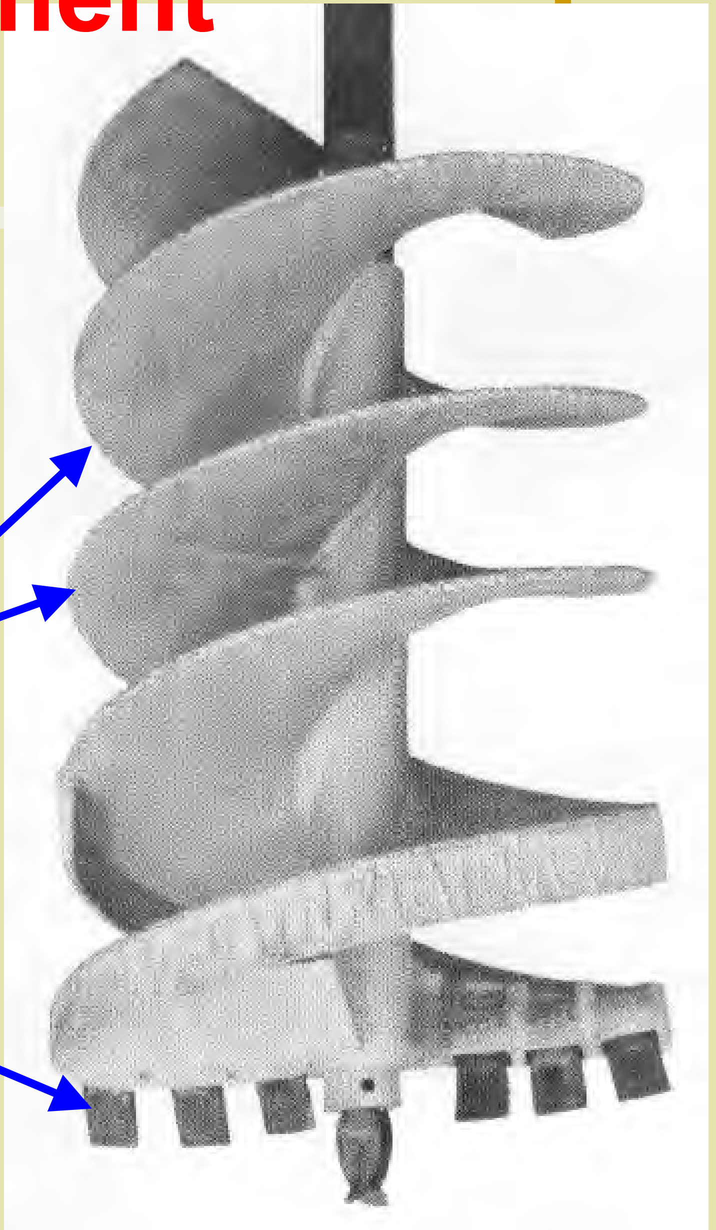


Single Flight

Double Flight

Double Cut

Triple Cut



Earth augers are generally used in sands and cohesive materials.

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

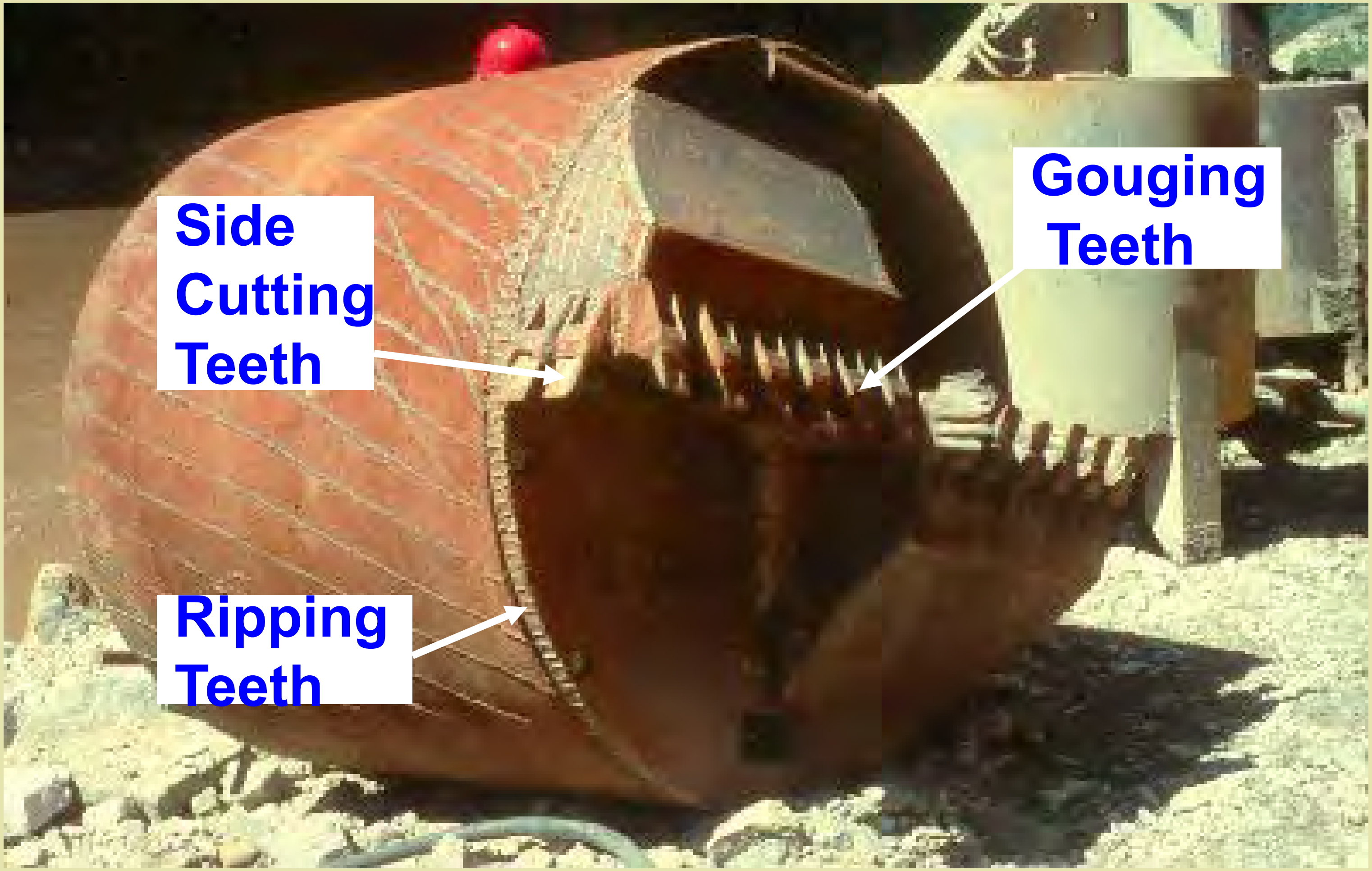
Drilled Shaft Equip Terminology

Drilling Buckets – Used in soils, particularly granular soils where open-helix auger cannot bring the soil up. Soil is forced by the rotary digging to enter the bucket and flaps inside prevent the soil from falling out. Good for dry or wet rotary drilling. Some buckets are designed to clean the base and are known as “muck buckets” or “clean-out buckets”.
After obtaining a load of soil, the tool is withdrawn and the hinged bottom of the bucket is opened to empty the spoil.

Figure 4.5 A typical drilling bucket (O’Neill & Reese, 1999)

Figure 4.6 A typical “muck bucket” or “clean-out bucket” (O’Neill & Reese, 1999)

Drilled Shaft Equipment
Drilling Bucket



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

Drilled Shaft Equipment Cleanout (Muck) Bucket

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

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

Drilled Shaft Equipment Rock Augers

Rock Augers – Mostly the double helix type with hard-surfaced conical teeth, usually made of tungsten carbide.

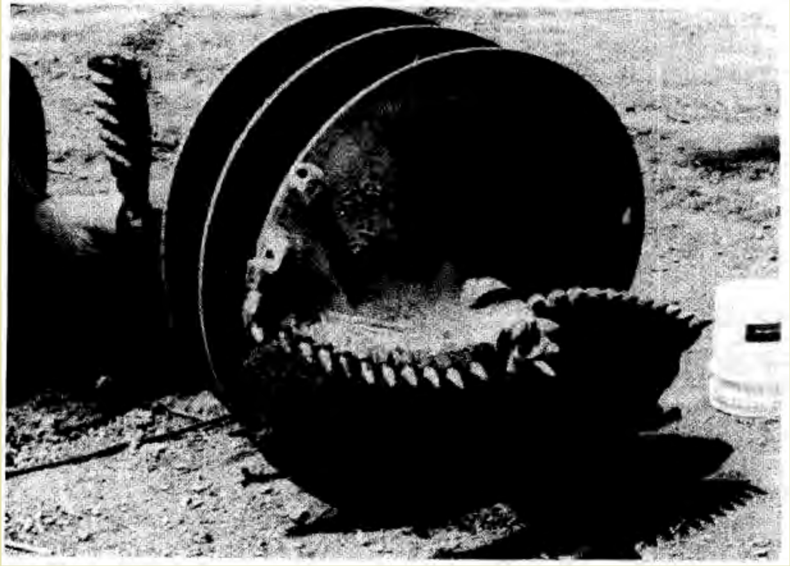


Figure 4.9 A typical rock auger (O'Neill & Reese, 1999)

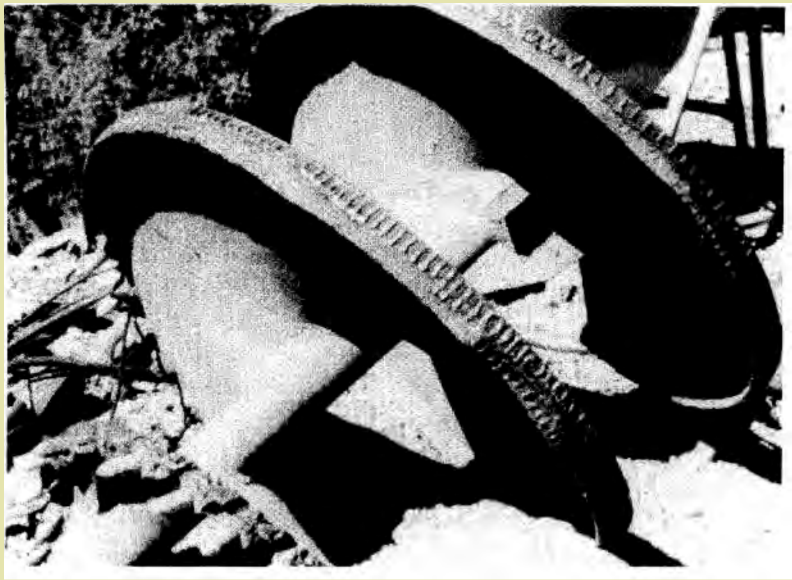
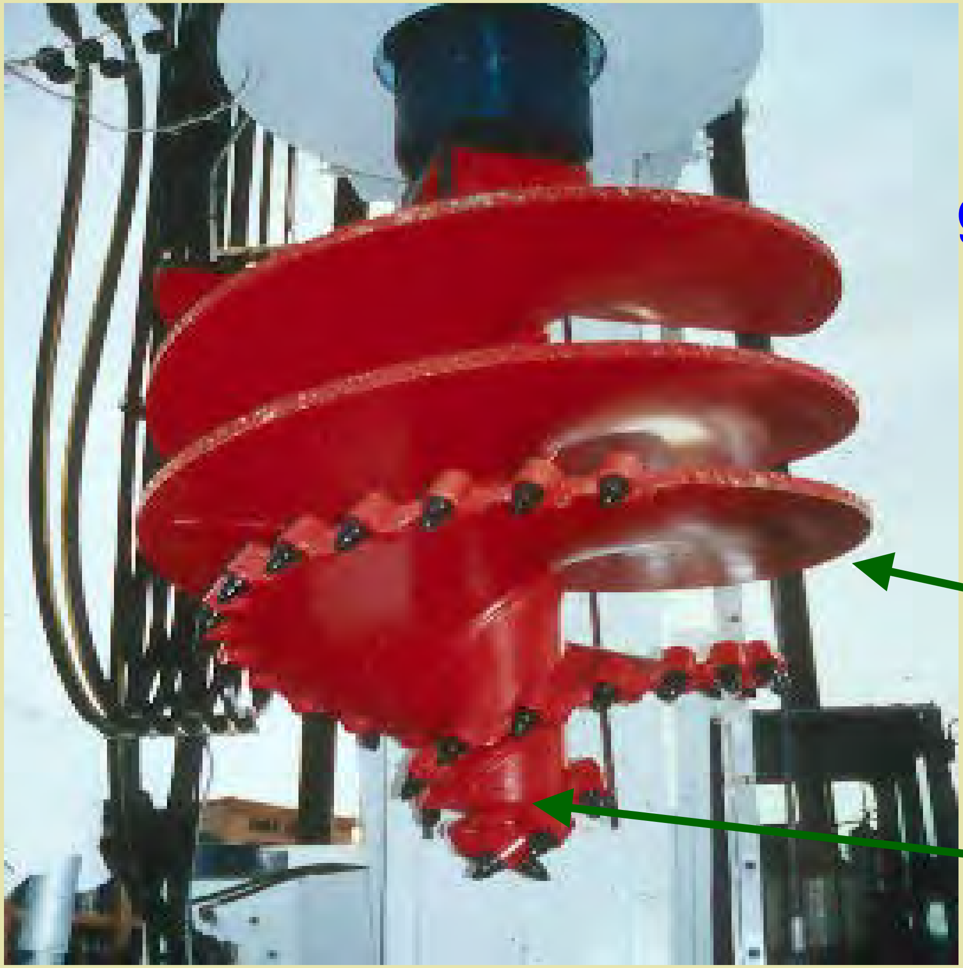


Figure 4.10 Tapered rock auger for loosening fragmented rock (Photograph courtesy of John Turner) (O'Neill & Reese, 1999)

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

Drilled Shaft Equipment
Rock Augers



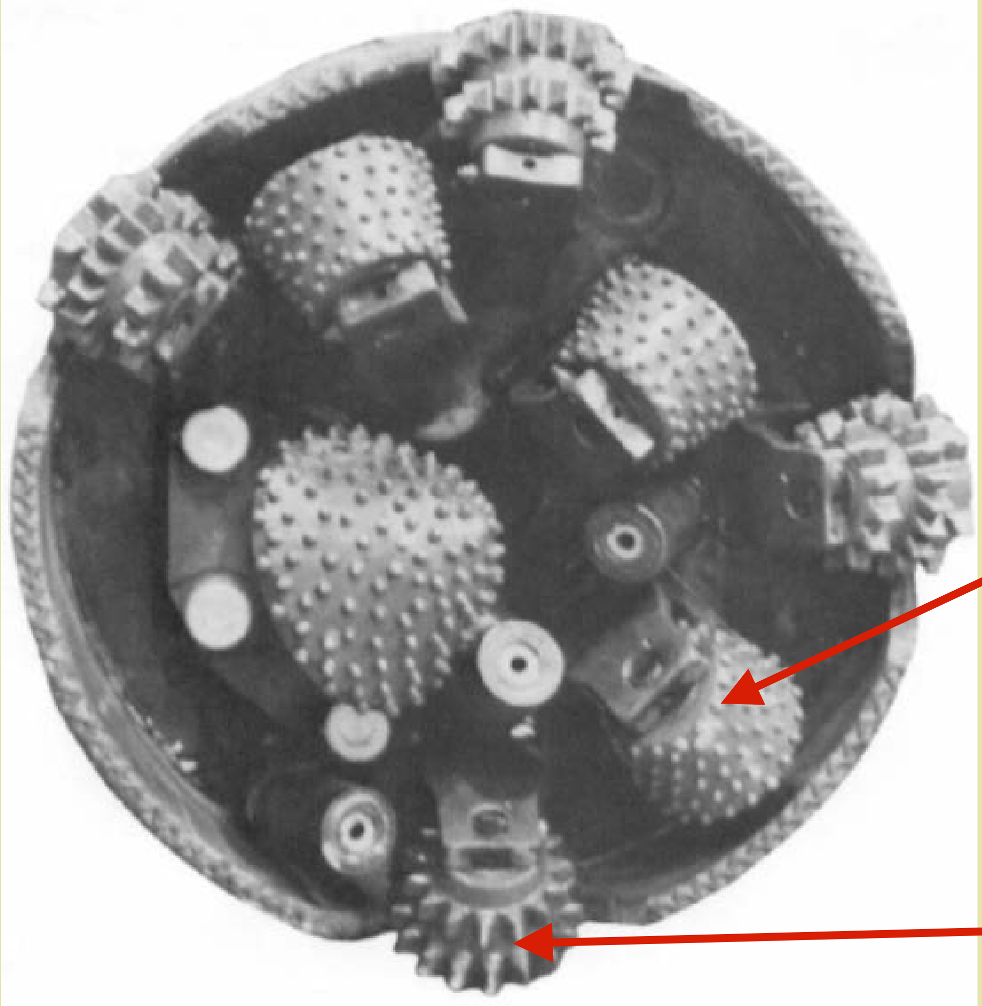
Rock augers are generally used in soft to hard rock formations.

Tapered Geometry

Conical (Bullet) Carbide Teeth

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

Drilled Shaft Equipment
Rock Bits



This is typical of rock bits designed for drilling in hard to very hard rock.

Circulating bit

Replaceable Roller Bits

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

Drilled Shaft Equipment Terminology

Core Barrel – For hard rocks when augers become ineffective. A single cylindrical steel tube with hard metal teeth at the bottom cutting edge. Also available with double walls (double –wall core barrel), the outer wall, contains roller bits at the end, rotates but does not have a contact with the rock core, hence allows to recover larger length of rock.

Figure 4.11 A typical single-walled core barrel (O'Neill & Reese, 1999)

Figure 4.12 A double-wall core barrel (Photography courtesy of W.F.J. Drilling Tools, Inc.) (O'Neill & Reese, 1999)

Drilled Shaft Equipment Terminology

Excavation by Percussion – Instead of rotary drilling, the rock is broken by impact and is being lifted by a clamshell-type bucket.

Figure 4.17 A typical grab bucket (Photograph courtesy of John Turner) (O'Neill & Reese, 1999)

Figure 4.18 An example of a churn drill (Photography courtesy of John Turner) (O'Neill & Reese, 1999)

Drilled Shaft Equipment Terminology

Hammergrabs are percussion tools that both break and lift the rock.

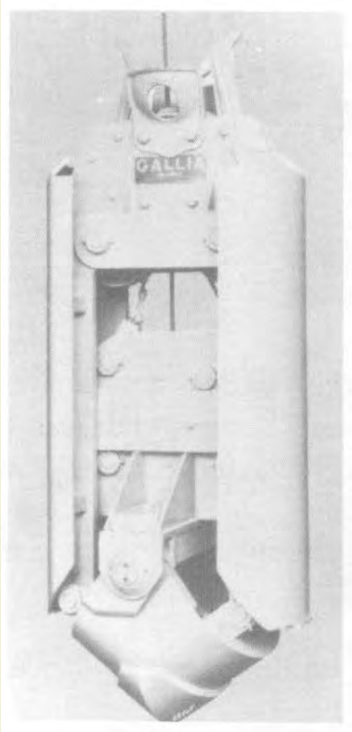


Figure 4.19 An example of a hammergrab (from LCPC, 1986) (O'Neill & Reese, 1999)

Rodless drills that have down-the-hole motors that drive excavating cutters that rotates in the bentonite. The cutters push the soil into the center of the excavation where it is sucked with the slurry through a flexible return line.

Figure 4.20 An example of a rodless soil drill (Photography courtesy of Tone Boring Corp., Ltd.) (O'Neill & Reese, 1999)

General Practical Considerations Related to DS Construction

- **Shaft Alignment - difficult to achieve**

  Location (plan) misalignment up to 5 to 6 inches (150 mm)
  Vertical (elevation) misalignment depends on the shaft type -

  - **Unreinforced - Max 1/8 diameter**
  - **Unreinforced under lateral resistance - max 0.015 diameter**
  - **Reinforced - determine on site**

- **Slurry disposal**

General Practical Considerations Related to DS Construction

- **Concrete quality control**

  28 to 35 Mpa range, 5 to 6 inch slump and plasticizers to improve flowability. Continuity through the monitoring small strain, large strain, gamma, echo, etc.)of volumes (soil and concrete) as well as testing (coring,

- **Underreaming (belling) - enlarge base (up to 3B) and increase capacity**

- **Ground loss, "squeeze in"**

  $Rs = \sigma'_{v0}/Su$ **$Rs < 6$ possible, but slow**
  $Rs > 6$ certain and for $Rs > 8$ to 9 will be very rapid

  Solutions: fast construction, slurry, caissing