

CHAPTER 3 GENERAL CONSTRUCTION METHODS

3.1 INTRODUCTION

The effective use and design of drilled shafts requires a knowledge of drilled shaft construction methods, and an understanding that the construction techniques, magnitude of effort and related cost for drilled shaft installation are closely tied to the existing ground conditions at a project site. For successful performance of the completed drilled shafts, the construction technique used must preserve the integrity of the bearing materials and ensure the structural integrity of the cast-in-place reinforced concrete foundation.

In principle, construction of drilled shafts is a very simple matter and follows these basic steps:

1. Excavate the hole, maintaining stability,
2. Clean the hole and prepare for concrete,
3. Place the reinforcement and the concrete, and
4. Finish the top of the drilled shaft for the connection to the rest of the structure.

These steps are simple, but each present a unique set of challenges due to the many variations in ground conditions and design requirements. This chapter provides an overview of the typical methods used to complete the steps outlined above, with more detailed descriptions of the many variations of techniques provided in the following chapters.

In normal contracting practice for transportation projects in the U.S., it is the contractor's responsibility to choose an appropriate method for installing drilled shafts at a given site, and details of the general methods used for construction on a given project can vary with project-specific ground conditions as well as the capabilities, experience, and equipment of an individual constructor. The efficiency and cost-effectiveness of the means and methods chosen for specific circumstances are the contractor's burden, subject to the constraints of the design. Unwarranted interference affecting the contractor's ability to prosecute the work can lead to claims and additional costs.

A good understanding of construction methods is necessary to:

1. identify conditions suitable for drilled shaft foundations, and to estimate costs and schedule,
2. develop constructible designs,
3. execute a site investigation plan to document geotechnical conditions that are important for drilled shaft construction, as discussed in Chapter 2,
4. understand limitations which may be imposed on construction because of potential impacts on foundation performance or nearby structures,
5. develop specifications and inspection procedures that are suitable for the conditions, as discussed in Chapters 14 and 15,
6. develop contract provisions that are appropriate for payment for the work and include appropriate provisions to handle subsurface risks inherent in the work, as discussed in Chapter 14.

For these reasons, designers and other project professionals must be familiar with construction methods. A constructability review by knowledgeable construction professionals during the design phase of the project can often be helpful in improving constructability and cost effectiveness of a design as well as

mitigating potential impacts of construction risks. Drilled shaft construction planning always starts with a thorough understanding of subsurface conditions (as discussed in Chapter 2).

The most important considerations for construction are the ground conditions and the techniques that will be required to maintain stability of the drilled shaft excavation. A stable excavation is necessary to avoid loosening the ground or even collapse of the excavation, which could undermine stability of the worksite and impair the performance of the completed foundation. The size and depth of the hole, the soil or rock to be excavated, and the groundwater conditions all affect the equipment and tooling to be used for the project.

3.2 OVERVIEW OF GENERAL CONSTRUCTION OF A DRILLED SHAFT IN DRY STABLE GROUND CONDITIONS

Under some circumstances, the ground conditions permit an open hole to be excavated without external support. Stable conditions may exist when an excavation is made in strong clays (Figure 3-1) or cemented soils where the groundwater is low and/or the soils have very low permeability. Where ground conditions permit open hole construction techniques to be employed, drilled shafts can be built very quickly and economically. An example is provided by the recent construction of a very large manufacturing facility in central Alabama. At this site 3-ft diameter drilled shafts were installed to a depth of about 45 ft through stiff clay soils into the Selma Chalk formation, a cemented calcareous material with a compressive strength of around 100 to 300 psi. The contractor was able to install 15 to 20 drilled shafts each day, providing a very cost-effective foundation solution for the owner. Another example is the T-Rex project in the Denver, Colorado area, a major interstate project where many areas within this project were suitable for dry open-hole construction of drilled shaft foundations for bridges and retaining walls.



Figure 3-1 Excavation of a Drilled Shaft in Naturally Stable Soils

As the excavation advances, it is important that records (usually in the form of a construction log) be maintained of the soil and rock materials that are encountered, with notes of any obstructions or conditions that might differ from expectations. Where elevations of founding strata vary, the as-built length of the drilled shaft may be adjusted as needed. This log serves as a valuable record of the as-built foundation to confirm that the design intent has been accomplished, and the records often document contract pay items.



Figure 3-2 Visual Inspection of Excavated Materials for Construction Records

Note that the dry stable hole in Figure 3-2 includes a short surface casing which is commonly employed for stability near the ground surface, a guide for the tools, and may serve as a safety barrier if left high enough (Figure 3-2 has a separate safety barrier).

With a dry stable hole, the placement of reinforcement and concrete is relatively straightforward. After any loose material is cleaned from the base of the excavation, the reinforcing cage is lifted and placed into position (Figure 3-3). Consideration of the need for pre-assembly and lifting is required in the design and fabrication of the reinforcement. Concrete used for drilled shaft construction is a special mix with high workability (typically 6 to 8 inch slump for use in a dry hole) which is designed to readily flow through the reinforcement and self-compact with no external vibration. In a dry hole, the concrete can be placed by free-fall techniques provided that a centering device is used to direct the concrete down through the center of the reinforcement to prevent concrete from hitting the rebar or sides of the hole (Figure 3-4).

Completion of the drilled shaft includes some finish work at the top to prepare the connection to the structure. There is typically some contaminated concrete at the top to be removed; even with dry placement of concrete some laitance due to bleed water is normal. In some cases the reinforcement is left extending from the top of the completed drilled shaft and then the splice to the column or footing cage is formed above the top of shaft. For a transmission tower or sign foundation, as shown in Figure 3-5, a pattern of anchor bolts may form this connection, and these may sometimes be installed at the end of concrete placement while the drilled shaft concrete is still fluid. In other cases a short permanent casing or form is left in place so that the splice to the structure is formed below grade.

Where the ground is not inherently stable, drilling fluids and/or casing may be used to support the excavation during construction. The following sections provide an overview of these techniques and how they are used to maintain stability of the excavation during drilled shaft construction. A more detailed discussion is provided in Chapter 5.



Figure 3-3 Lifting and Placing the Reinforcement



Figure 3-4 Free-fall Concrete Placement in a Dry Hole



Figure 3-5 Finishing the Top Includes the Connection to the Structure

3.3 USE OF CASING IN DRILLED SHAFT CONSTRUCTION

A steel casing may be installed to provide support against caving or collapse of the excavation, especially if or when more aggressive excavation tools are employed to advance the excavation into rock or hard materials. The casing can be used to provide temporary support during construction, in which case it is extracted as concrete placement occurs, or it can be installed as a permanent part of the foundation when the drilled shaft must extend through open water or extremely soft and unstable soil layers.

Unless the bearing formation into which the casing is sealed is stable and dry, it will not be possible to use the casing method alone without the addition of drilling fluid.

Installation of casing is generally accomplished in one of three ways.

1. Excavate an oversized hole using the dry method, then place the casing into the hole. This method is suitable only for construction in soils that are generally dry or have slow seepage and that will remain stable for the period of time required to advance the hole to the more stable bearing stratum. The work shown in Figure 3-6 includes excavation through overburden soils to rock in the dry, and then a casing was placed through the soils to rock to prevent caving while the rock socket was drilled.
2. Excavate an oversized hole through the shallow permeable strata using a drilling fluid, then place and advance the casing into the bearing stratum. After the casing is sealed into the underlying more stable stratum, the drilling fluid can be removed from inside the casing and the hole advanced to the final tip elevation by dry methods. A schematic diagram of this approach is provided in Figure 3-7. Note that since the drilling fluid must be flushed out later by the fluid concrete, it must meet all of the requirements for slurry used in the wet method described in Section 3.5.
3. Advance the casing through the shallow permeable strata and into the bearing formation ahead of the shaft excavation, and then excavate within the casing in the dry. With this approach, casing may be driven using impact or vibratory hammers or using a casing oscillator or rotator with sufficient torque and downward force to advance the casing through the soil ahead of the excavation. Even larger upward force may be required to pull the casing during concrete placement. A schematic diagram of this approach is provided in Figure 3-8.

Most steel casing is recovered as the concrete is being placed. In some circumstances, permanent casing may be used and left in place as a form or as a structural element required in the design of the drilled shaft. Instances requiring the use of permanent casing are discussed in Chapter 5, as are other characteristics of temporary and permanent casings.



Figure 3-6 Drilling into Rock through a Cased Hole

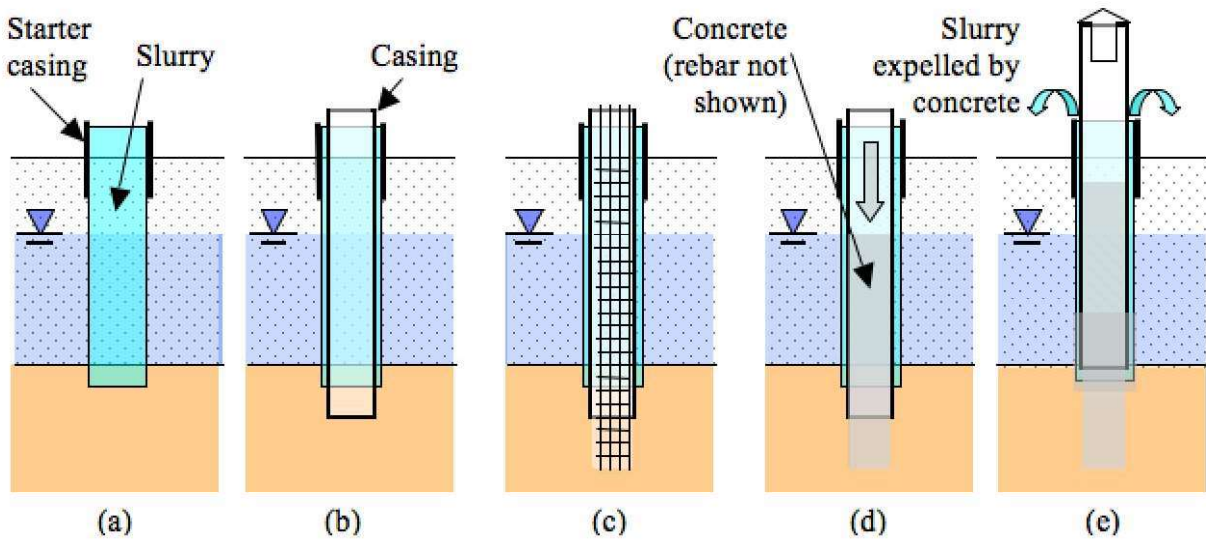


Figure 3-7 Construction Using Casing Through Slurry-Filled Starter Hole: (a) drill with slurry; (b) set casing and bail slurry; (c) complete and clean excavation, set reinforcing; (d) place concrete to head greater than external water pressure; (e) pull casing while adding concrete

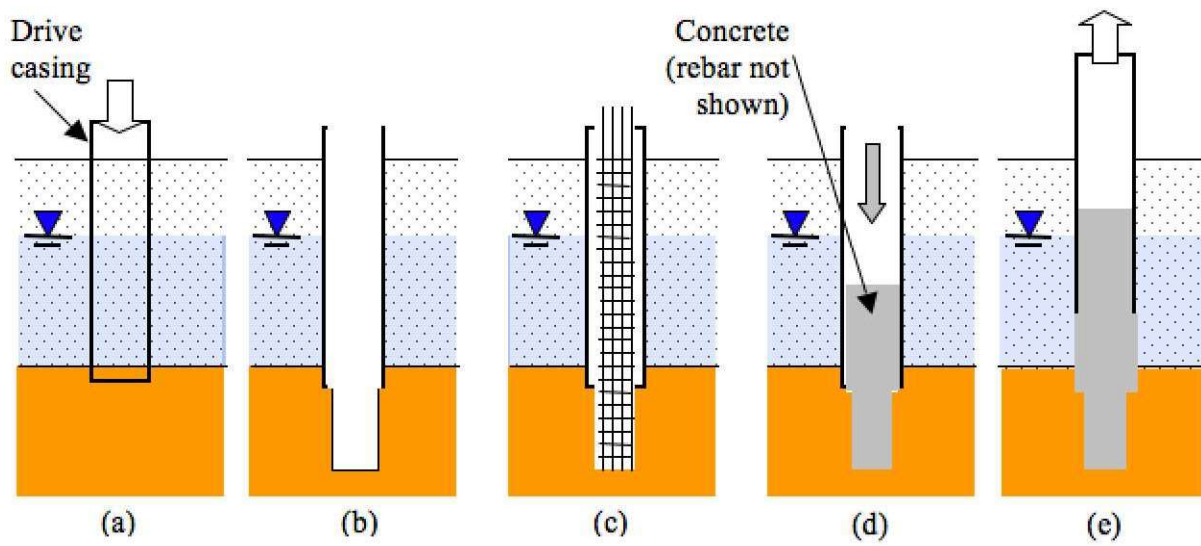


Figure 3-8 Construction Using Casing Advanced Ahead of Excavation: (a) drive casing into bearing stratum; (b) drill through casing; (c) complete and clean hole, set reinforcing; (d) place concrete to head greater than external water pressure; (e) pull casing while adding concrete

In most cases, the shaft excavation will be advanced below the base of the casing for some distance into the bearing formation of soil or rock, using the casing to achieve a seal into this bearing formation to control caving or seepage around the bottom of the casing. Casings may be equipped with cutting teeth to help penetration into a hard layer, but it may not be possible to completely seal the casing, especially if the underlying layer is a rock formation with an irregular or highly fractured surface. In this circumstance a drilling fluid and wet construction (described in the next section) must be employed for the remainder of the work.

If the casing cannot be sealed into a watertight formation, continued attempts to dewater the hole can result in the inflow of groundwater and soil around the bottom of the casing, forming a cavity around the casing. Such a cavity could produce soil loosening, ground subsidence or even collapse at the ground surface. Besides the obvious deleterious effect of ground disturbance and the safety hazard that would be associated with ground movements, this unstable condition can affect adjacent structures. In addition, a large cavity outside the shaft excavation could require a large and unexpected volume of concrete during concrete placement. If a large volume of concrete is lost into a cavity at the time the casing is pulled (step *e*) in Figure 3-7 or Figure 3-8), the level of concrete inside the casing could drop so much that the seal of the casing into the concrete could be breached allowing inflow of groundwater or drilling fluid. This breach would result in contamination of the concrete, as illustrated in Figure 3-9. To minimize the risk of a large drop in the concrete head within the casing, most contractors would only pull the casing a small amount to break the seal and initiate the flow of concrete behind the casing, and then immediately add more concrete into the casing.

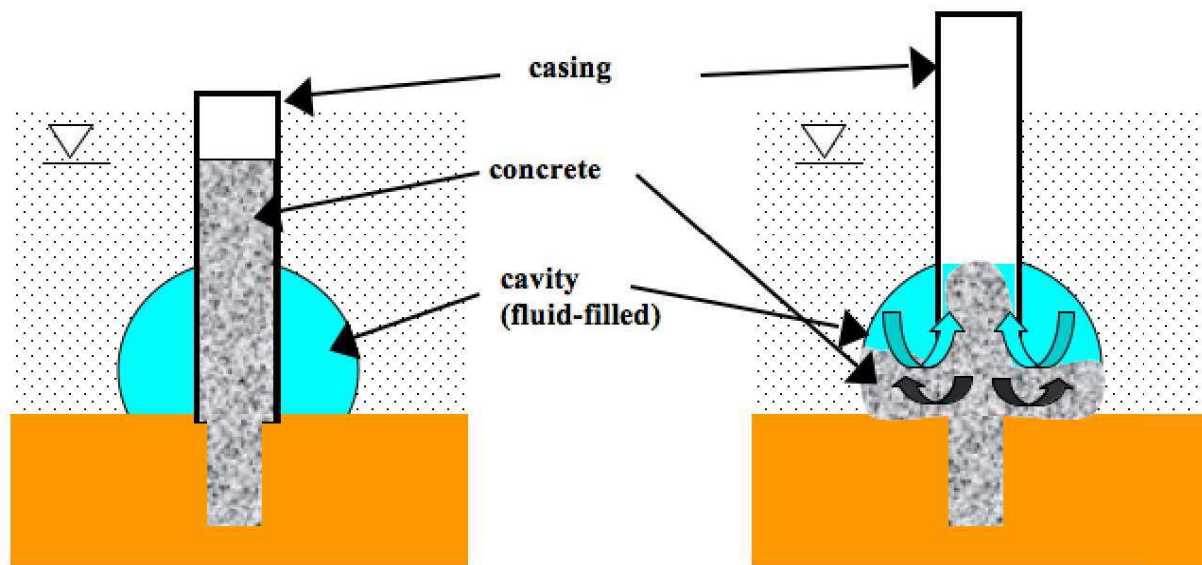


Figure 3-9 Breach of Casing/Concrete Seal During Casing Extraction Due to Cavity

The reinforcing cage is subject to additional constructability requirements for construction with temporary casing. Out-hook bars should be avoided because of the need to withdraw casing over the cage. Since it is generally necessary to release the cage during withdrawal of the casing, it is necessary that the cage be sufficiently stable that it can stand freely under self-weight in the hole during construction without racking or distortion. Because the concrete must flow through the cage to fill the space of and around the casing, there must be sufficient space between bars to permit the free flow of concrete during concrete placement. Additional details relating to reinforcement are provided in Chapter 6.

The concrete used with the casing method must have good flow characteristics in order to flow easily through the reinforcing to fill the space outside the casing and displace any water or slurry around the casing from the bottom up. It is critical that the concrete maintain a hydrostatic pressure greater than that of the fluid external to the casing (trapped slurry or groundwater) as described previously and illustrated in Figure 3-7 and Figure 3-8. The concrete will then flow down around the base of the casing to displace any trapped fluid upward and fill the annular space. The casing should be pulled slowly in order to avoid excessive drag forces from the downward-moving concrete on the rebar cage.

The concrete must also retain workability *beyond* the duration of the concrete placement operations until the casing is completely removed. If the workability of the concrete (slump) is too low, arching of the concrete will occur and the concrete will move up with the casing, creating a gap into which slurry, groundwater, or soil can enter. Typically, the concrete slump should be between 8 and 10 inches for drilled shaft construction requiring casing removal. The rebar cage could also be pulled up along with the casing and stiff concrete. Even if arching within the casing does not occur, concrete with inadequate workability will not easily flow through the cage to fill the space between reinforcing and the sides of the hole. Downward movement of the cage upon casing withdrawal could indicate that the concrete is pulling the cage laterally toward a void or that the cage is dragged downward into a distorted position due to the downdrag from concrete with inadequate workability. Downward movement of the column of concrete will cause a downward force on the rebar cage; the magnitude of the downward force will depend on the shearing resistance of the fresh concrete and on the area of the elements of the rebar cage. The rebar cage can fail at this point by torsional buckling, by slipping at joints, and possibly by single-bar buckling (Reese and O'Neill, 1995). Additional details relating to concrete are provided in Chapter 7.

The casing method of construction dictates that the diameter of the portion of the drilled shaft below the casing will be slightly smaller than the inside diameter of the casing. Most casing is dimensioned by its outside diameter and comes in 6-inch nominal increments of diameter. A contractor would ordinarily use a casing with the increment of outside diameter that is the smallest value in excess of the specified diameter of the borehole below the casing. If the casing diameter is specified in other than standard sizes, special pipe may have to be purchased by the contractor, significantly increasing the cost of the job.

3.4 USE OF DRILLING FLUIDS IN DRILLED SHAFT CONSTRUCTION

Fluids help to provide stability by counteracting the head pressure of the groundwater that would tend to flow into the hole, and by providing some support via the differential head pressure when the fluid head within the hole is greater than the groundwater pressure in the soil. Fluids can include water or water mixed with additives such as minerals (bentonite) or polymer. The additives are used to help contain the fluids within the hole and minimize fluid loss due to seepage out through the borehole wall, thereby allowing the positive head pressure to be maintained. Water mixed with additives to alter the fluid properties is typically called “slurry” and the construction technique is sometimes referred to as “slurry drilling”.

The steps in the process of constructing a drilled shaft using drilling fluids for stability are summarized as follows:

1. Excavate the hole while maintaining a positive fluid head pressure at all times
2. Clean the hole and prepare for concrete by removing any loose debris from the base of the excavation and by cleaning the fluids to remove excessive suspended materials
3. Inspect the excavation to ensure that the base is sound and the fluid is reasonably clean
4. Place the reinforcement
5. Place the concrete using a tremie, minimizing the exposure of the concrete to the drilling fluid by maintaining embedment of the tremie below the rising surface of fresh concrete
6. Extract any temporary casing as necessary and clean the top of the concrete surface in preparation for the connection to the structure

Drilled shafts can sometimes be constructed in a wet, but otherwise stable excavation through pervious rock or other strong and stable materials. In such a case, the excavation may simply be filled with water to counter the tendency for seepage into the excavation to occur. An example would be a drilled shaft that has casing seated into rock which is not sufficiently water-tight to prevent seepage into the hole. Seepage into the hole is generally undesirable because it may wash fines into the hole and cause voids around the bottom of the casing which could result in ground subsidence or loss of support around the casing. Seepage into the hole during concrete placement can adversely affect the quality of the concrete. In these situations, water should be added to the excavation to counter this seepage and protect the integrity of the fluid concrete mix. As a general guide, seepage into an excavation which exceeds more than one inch in 5 minutes is considered excessive and the hole should be flooded prior to concrete placement using the tremie method.

To maintain a positive fluid head within the drilled shaft requires knowledge of the groundwater levels in the soil, including the levels in all permeable strata (which may contain groundwater with differing head levels). It is therefore essential for the geotechnical investigation to define the existing groundwater conditions. Where seasonal or other variations in groundwater can be significant, it may be necessary to update the groundwater information at the time of construction.

Where slurry is used to stabilize a drilled shaft excavation, it is necessary that a positive fluid head be maintained at all times within the hole so that a stabilizing internal pressure in excess of the external groundwater head is provided. An excess head pressure of 5 to 10 ft or more within the hole (above that of the natural groundwater) may be sufficient to provide stability through granular soils, if the head differential can be continuously maintained. However, slurry with a higher viscosity than water is typically used to maintain the positive head during excavation because water flows out too fast through permeable strata. It is also important that the drilling operations and tools be used in such a way that pressure reduction (“swab pressure” or suction pressure) below the tool does not cause loss of positive head in the hole. A surface casing is typically used to contain slurry and allow the hole to be filled to the proper level, as illustrated in Figure 3-10.

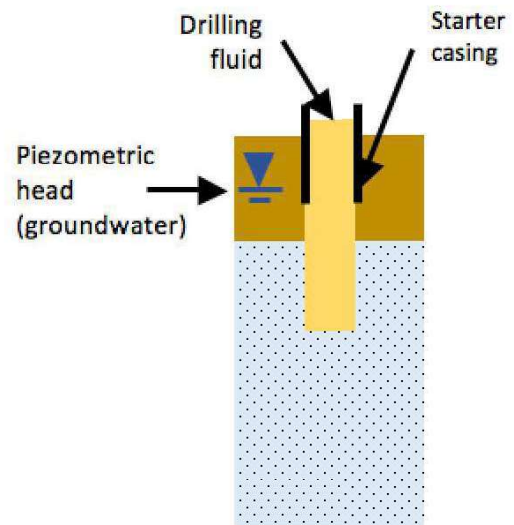


Figure 3-10 Maintaining Positive Fluid Head Pressure in the Drilled Shaft Excavation

The need to maintain positive fluid head can be a challenge and influence the construction methods when groundwater is very shallow. As the excavation advances and the volume of the hole increases, it is necessary to continuously add slurry to maintain the positive head. The drop in slurry level that occurs during extraction of the drill tool can also cause the slurry head to drop below the required minimum level. To address these conditions, an oversized second surface casing has sometimes been used to provide a reservoir for extra fluid volume, as shown in Figure 3-11. Another technique would be to elevate the casing above the ground surface to maintain positive head, as shown in Figure 3-12. Artesian groundwater (levels above the ground surface) can pose special problems to construction because of the need to maintain the slurry level some height above the ground surface to achieve positive head pressure.

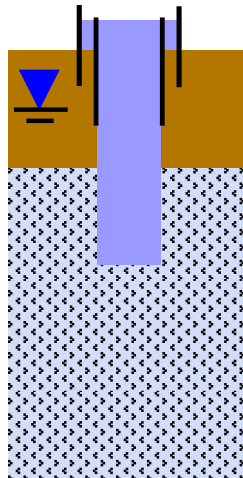


Figure 3-11 Use of Surface Reservoir for Drilling Fluid

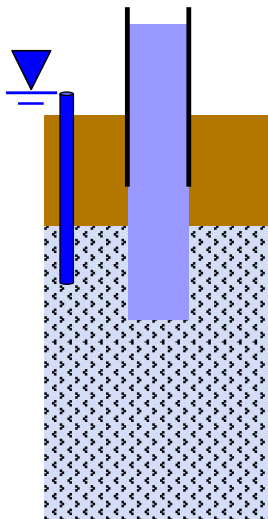


Figure 3-12 Elevated Surface Casing to Provide Fluid Head Above Artesian Groundwater

As noted above, drilling fluids can include water or a slurry composed of water mixed with minerals (typically bentonite clay) or synthetic polymers. These types of drilling fluids, and their applications, are further described below.

Water as a Drilling Fluid. Water alone can function as a drilling fluid in situations where the formation is inherently stable but permeable, such as some rock formations as noted earlier. Casing may be employed through the unstable overburden to provide a stable environment to excavate the rock using only water. In this situation, it is desirable to maintain a fluid head of water sufficient to avoid infiltration in the rock socket and particularly around the bottom of the casing if a complete seal cannot be achieved into impermeable rock.

Mineral Drilling Fluids. Bentonite clay is the most commonly used mineral additive for drilling fluid, and is widely used in oilfield drilling applications. Bentonite is a clay composed primarily of montmorillonite clay minerals which can absorb water to many times its own weight. When added to water, relatively small amounts of bentonite form a colloidal mixture (referred to as a bentonite slurry)

with the effect of increasing the viscosity of the fluid over that of water, along with a small increase in unit weight.

The other significant property of a bentonite slurry is that some of the minerals are filtered out at the borehole wall as the fluid passes into the soil, thereby forming a “filter cake” that reduces the permeability and helps to contain the fluid. This filter cake formation is the main difference between the performance of bentonite slurry and other commonly used drilling fluids in the construction industry. The filter cake greatly improves the ability of the fluid to maintain stability of the excavation during construction, but can also adversely affect the bond between the concrete and the soil at the interface.

Synthetic (Polymer) Drilling Fluids. In the last 20 years, synthetic (polymer) drilling fluids have replaced bentonite slurry on a majority of drilled shaft applications in North America, although the prevalence varies locally. The use of polymer drilling materials worldwide has also increased dramatically, although perhaps polymers have been more slowly adopted in Europe than in Asia and the Middle East. The type of synthetic polymers used in drilling slurry are long chain-like hydrocarbon molecules which interact with each other, with the soil, and with the water to effectively increase the viscosity of the fluid.

Although there may be some indication of a polymer membrane at the soil interface, there is no formation of a filter cake as with bentonite. As a result of this lack of filter cake, polymers have a greater tendency to lose fluid into the soil around the excavation with time compared to bentonite. The absence of this filter cake also reduces the effectiveness in supporting coarse grained soils and non-circular excavations such as barrettes and slurry wall panels. However, this lack of filter cake appears to provide a benefit in terms of the side resistance at the concrete/soil interface, since the polymers fluids that are in widespread use have not exhibited the detrimental behavior that is associated with bentonite filter cake buildup.

Construction of a Drilled Shaft with Drilling Fluids. The construction of a drilled shaft with drilling fluids is illustrated on the diagram of Figure 3-13. Typical construction would include a starter or surface casing extending above the ground surface as shown in Figure 3-13a. This surface casing may extend as deep as necessary to prevent surface cave-ins and may extend above the ground surface to elevate the surface level of the slurry in the hole, as shown in Figure 3-13b. Note that the groundwater elevation (piezometric surface) is shown by the blue triangle in Figure 3-13. In order to maintain the head of slurry at least 5 ft above the piezometric surface, it is essential that the piezometric surface be known in advance. The presence of overlying cohesive soils may mask the actual elevation of the piezometric surface; drilling into the underlying water-bearing sand stratum without sufficient head of slurry could lead to liquefaction conditions at the base of the hole during drilling, loosening of the stratum, and possibly collapse of the hole or creation of a large cavity.

After completion of the excavation and cleaning of the base, the reinforcing cage is positioned, and then concrete placement is performed using a tremie (Figure 3-13c-e). The tremie delivers concrete to the base of the shaft and displaces slurry upwards. Typically, the slurry is pumped to a holding tank for reuse or disposal. Concrete placement continues through the tremie, always keeping the bottom of the tremie at least 10 ft below the rising surface of the fresh concrete so that the concrete does not mix with the slurry. It is important to avoid potential inclusions of slurry or sediments which may be in suspension within the slurry into the concrete. Therefore, the slurry must be appropriately cleaned of suspended solids to meet the guidelines outlined in Chapter 5. It is also important that the concrete have sufficient workability to flow easily through the tremie and reinforcing throughout the duration of the concrete placement operations, including the time needed to extract temporary casing. Typically, the concrete slump should be between 8 and 10 inches for drilled shaft construction excavated with use of drilling fluids. More details on the important properties of concrete are provided in Chapter 7.

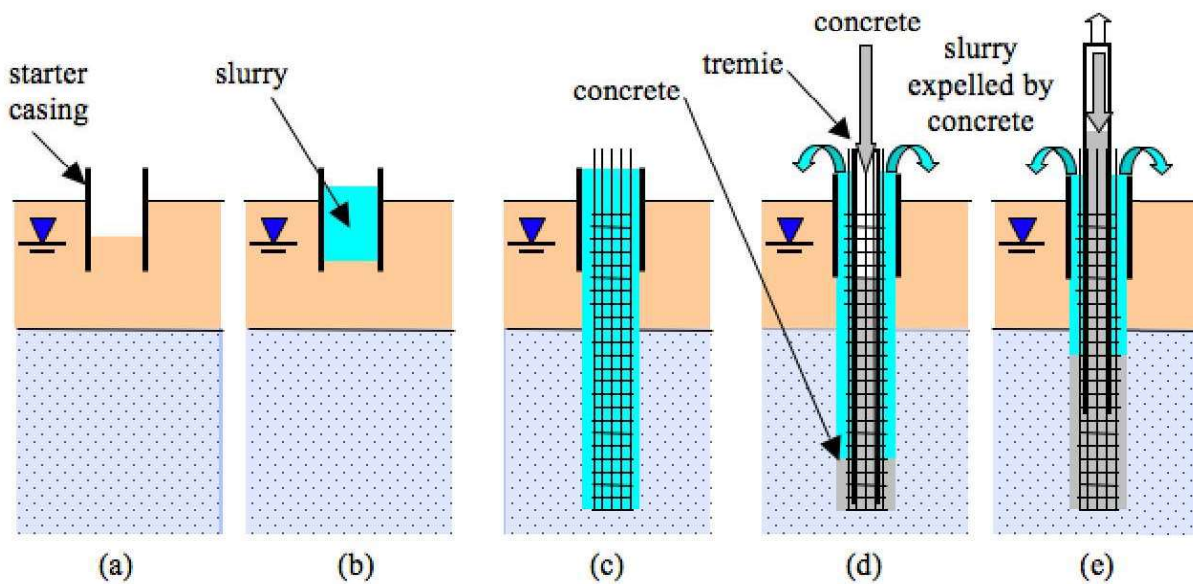


Figure 3-13 Slurry Drilling Process: (a) set starter casing; (b) fill with slurry; (c) complete and clean excavation, set reinforcing; (d) place concrete through tremie; (e) pull tremie while adding concrete

When advancing a shaft excavation through unstable soil using full length temporary casing, drilling fluid head is needed within the casing to avoid an unstable bottom condition as illustrated in Figure 3-14. If excavation within the casing is performed as the casing is advanced, the construction crew should generally maintain a soil plug of sufficient thickness within the casing to avoid bottom heaving. The plug should be maintained until the excavation reaches either a stable stratum (such as rock, cemented soil, or cohesive soil) or the final shaft bottom elevation.

Upon completion of the shaft in cohesionless soil, care must be taken to avoid instability at the base of the casing as bottom heave could produce loosening of the bearing stratum. The drilling fluid inside the casing should be kept at a high elevation by pumping to maintain an excess head in the hole and a positive seepage pressure against the soil at the base. If the casing is seated into strongly cemented soil, very stiff to hard cohesive soils or rock, bottom stability may be less of a concern.

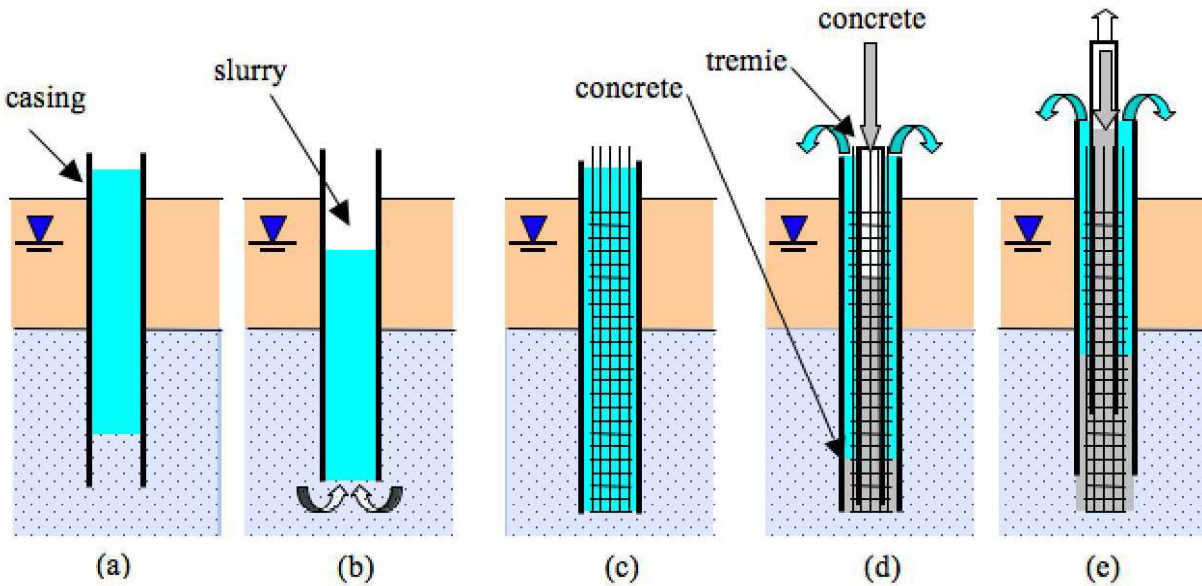


Figure 3-14 Wet Hole Construction Using Full Length Temporary Casing: (a) advance casing and excavating, while maintaining soil plug within casing through caving soils; (b) bottom instability due to inadequate slurry level and/or soil plug at base in caving soils; (c) complete and clean excavation, set reinforcing; (d) place concrete through tremie; (e) pull tremie, casing while adding concrete

3.5 THE ROLE OF ARCHING IN EXCAVATION STABILITY

Arching is an important concept for understanding how the techniques described above can be effectively employed for drilled shaft excavation and stability. When a circular vertical hole is excavated into the soil, arching allows the in-situ lateral stresses in the ground to be transferred around the opening so that the opening can be maintained (Figure 3-15a). Even with the use of casing or drilling fluids for support, most of the lateral stresses in the ground must transfer around the hole via arching.

As the drilled shaft excavation is advanced, the soil around the hole moves inward slightly, thereby allowing lateral stress to be transferred via arching around the hole as shown in Figure 3-15a. This transfer of radial stress to tangential stress around the hole allows a small amount of fluid pressure to stabilize the excavation. Arching can also effectively reduce the external earth pressure acting on casing.

Geotechnical engineers can relate the movement required to mobilize arching to earth pressure forces on retaining structures. As a retaining wall moves toward the excavation, the lateral earth pressures reduce from the at-rest condition to an “active” earth pressure condition as the soil strength is mobilized. Engineers typically design earth retaining structures to resist this lower “active” earth pressure force but recognize that some wall movement will be observed. The reduction in lateral stress in the radial direction due to arching around a vertical hole is far more pronounced than for a two dimensional retaining structure. A vertical cut can be sustained only in soil with sufficient cohesion that the active earth pressure force goes to zero.

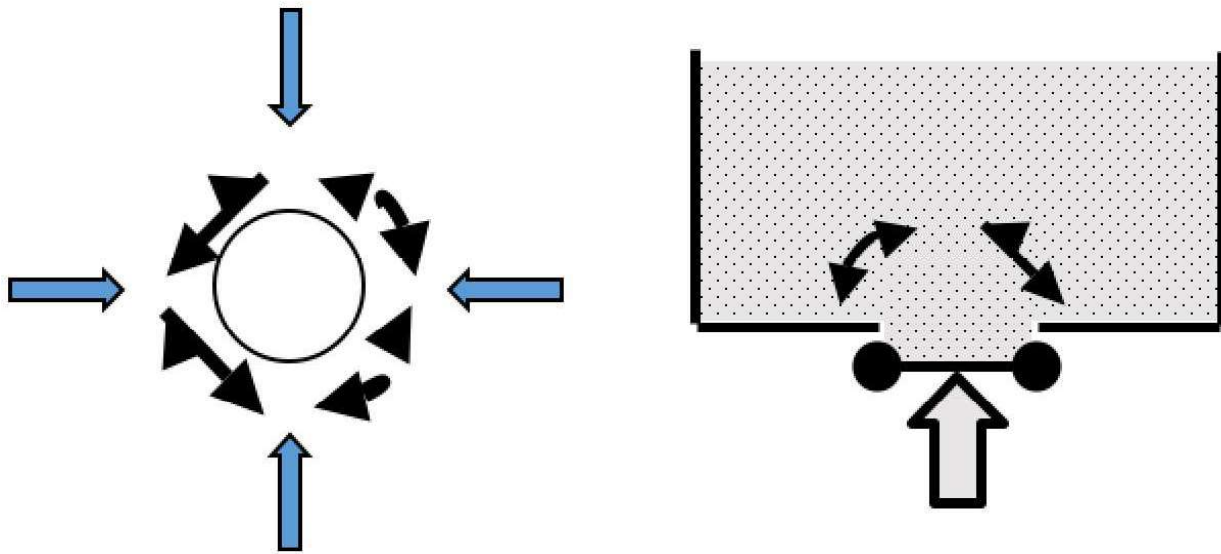


Figure 3-15 a) arching around a hole (plan view) b) schematic of Terzaghi's trap door experiment

This effect was demonstrated in a famous experiment by the father of soil mechanics, Karl Terzaghi, in which he measured the force required to support a trap door in the bottom of a sand-filled box as sketched in Figure 3-15b. His measurements demonstrated that the force on the trap door was greatly diminished as the door moved down away from the box, and explained this reduction as attributed to the arching effect as the interlocking soil particles redistribute the stresses around the opening. The force was observed to diminish to a much smaller magnitude for dense sand than for loose sand, an effect that was recognized as the more effective arching in the stronger soil. Additionally, arching developed at smaller displacements in the stronger soil compared to the loose sand, an observation consistent with the smaller retaining wall movement needed to develop active earth pressure conditions in dense soils. As the door progressively moved further, the arching collapsed and the force on the door returned to levels near the original values.

Similar principles are at work during drilled shaft construction. The stabilizing radial stress provided by 10 ft of excess fluid head pressure is relatively low (about 650 psf) compared to in-situ lateral earth pressures, but it is still observed to be quite effective at maintaining stability. The inward movement of the soil is accommodated during casing installation by using a cutting shoe at the bottom of the casing to reduce friction on the outer face of the casing, but this small overcut also allows some stress relief on the casing. Without this allowance for inward movement around the casing, the lateral stress on the casing would be high and the casing can become stuck. Digging a relief hole ahead of the casing accomplishes a similar stress relief function, allowing arching around the hole to develop and thereby reducing the radial stress on the casing.

Factors affecting the arching stress reduction include:

- The depth of the overburden soil
- The diameter of the hole
- The friction angle of the granular soils
- The relative inward displacement around the hole

Experienced constructors know that denser soil (higher friction angle) is more easily stabilized than loose soils, and the reason for this observation is explained by arching. Looser soils will also require greater

inward displacement to develop arching. A small diameter hole is more forgiving than a larger diameter hole, because arching is more easily accomplished. And just like Terzaghi's trap door experiment, if the radial support is insufficient or too much inward movement occurs, collapse of the soil ensues and the radial stress on the support casing increases.

The science of arching that is underlying these important concepts is well established and applied to other fields of civil engineering, including culvert design and even masonry arch structures that date back thousands of years. The application to drilled shaft construction remains largely an art at the present, due to the many variables and unknowns relative to soil conditions and the dynamics of the drilling process.

3.6 POST-GROUTED DRILLED SHAFTS

For some projects, drilled shafts may be post-grouted to produce improved performance compared to that for a similar ungrouted shaft (FHWA-HIF-17-024 by Loehr, et al., 2017). Post grouting generally entails installing a grout delivery device at the tip of drilled shafts by attaching the device to the bottom of the reinforcing cage, as shown in Figure 3-16, so that it rests on the bottom of the excavation prior to placing concrete. Following concrete placement, and after the concrete has gained sufficient strength, grout is injected through the installed grout delivery device at relatively large pressure using a simple pump. The grout most commonly used for post grouting is a neat cement grout composed of water and cement. The degree of improvement achieved due to post grouting varies with the magnitude of the grout pressure applied, which commonly ranges from 100 psi to over 900 psi, which is typically limited by either the capability of the pumping equipment or the effective overburden pressure in the soil at the depth of the shaft. Post grouting is a subject of ongoing research. Additional information regarding post-grouted drilled shafts can be found in FHWA-HIF-17-024 (Loehr, et al., 2017), and preliminary guidance for application of post grouting for drilled shafts is provided in Appendix F.

Grouting is also sometimes performed on drilled shafts after-the-fact by coring to the tip and stem grouting. This type of grouting is fundamentally different from post grouting in that it is generally performed as a remedial measure to repair drilled shafts determined to have concrete defects. While this is a viable remediation technique, it is a costly and difficult procedure, particularly for deep shafts, and should not be considered as post grouting.



Figure 3-16 Post Grouting Devices Attached to Reinforcing Cage: Flat-jack device (left) and Tube-a-manchette device (right)

3.7 SUMMARY

An understanding of drilled shaft construction is critical to a successful foundation design and installation for the reasons outlined in the introduction to this chapter. Although the means and methods of construction are usually delegated to the contractor (along with the contractual obligation to complete the work in a timely manner), engineers must recognize that construction procedures have a major influence on the performance of the drilled shafts. The design methods that are presented in this manual generally do not distinguish among construction methods, but assume that good practices are followed. There may be occasions when it is necessary for the designer to specify a particular construction method; for example, use of full-depth casing to protect adjacent structures, but doing so will almost always add significantly to the cost of the job. Similarly, the specifications may exclude one or more methods that the designer considers unsuitable for the existing ground conditions; for example, precluding the use of the dry method of construction where the risk of caving is considered unacceptable, or requiring the use of permanent casing where extremely soft soils are present.

This chapter provided an overview of general construction methods used for drilled shafts. Subsequent chapters provide more details on the specific issues relating to selection of construction tools and materials.