CHAPTER 5
TECHNIQUES FOR MAINTAINING STABLE DRILLED SHAFT EXCAVATIONS

The stability of the drilled shaft excavation must be maintained during the entire construction process from the start of drilling to the completion of concrete placement and removal of temporary casing. A stable excavation is critically important for several reasons. First and most importantly, the safety on the jobsite relies on a stable hole because a collapse could undermine the supporting platform for workers and equipment near the hole. Ground movements related to instability of the excavation can potentially impact nearby structures as well as the integrity of the bearing formation into which the drilled shaft is constructed. Sloughing or collapse of an unstable hole during placement of reinforcement and concrete can jeopardize the structural integrity of the completed foundation, as well as the geotechnical available resistance.

Some ground conditions are very favorable to easy drilled shaft construction because of their inherent natural stability, but, more typically, the use of steel casings, drilling fluids, or some combination of both, are required to maintain stability of the shaft excavation.

This chapter provides an overview of the various techniques that may be employed to maintain the stability of the drilled shaft excavation.

5.1 NATURALLY STABLE CONDITIONS

When ground conditions are inherently stable, as illustrated in Figure 5-1, excavation for drilled shaft construction can often proceed without the need for additional support. These conditions are typically limited to:

- Dry soil (little or no seepage into the hole)
- Strong cohesive or cemented soils
- Intact rock

Of course, the relative strength of the soil needed to provide construction stability depends on factors such as the diameter and depth of the hole, the loads on the ground surface nearby, potential vibrations during construction, and the length of time the hole must remain open. Local experience often provides a good guide, but does not eliminate the need for site-specific geotechnical information. Many developed areas of the southwestern U.S. (e.g. parts of Texas, Colorado, and Nevada) have conditions which are conducive to open-hole excavation, and in such conditions drilled shafts can be constructed very economically.

In some cases the soil may have inherent stability for a portion of the construction process, but additional measures may be needed at the start or completion of the drilled shaft. An example might include a drilled shaft which is to be constructed through cohesive soil with an extended embedment into granular soil or rock. In this circumstance, the portion of the excavation extending through the cohesive overburden may be performed as an open, dry hole, after which additional measures are employed for the remainder of the excavation. For example, it may be possible to excavate using an open hole through overburden soils to the top of rock or strong layer before seating a steel casing into the stronger material and completing the installation within a dry, stable excavation below the casing (see Figure 5-2). If the strong layer has very low permeability (such as shale, chalk, or massive intact rock), then it may be possible to excavate a dry hole even below the groundwater surface.

Figure 5-1 Dry Cohesive or Cemented Soils May Provide Naturally Stable Ground Conditions

Figure 5-2 Inserting Casing into an Open Hole Prior to Rock Excavation at a Site in Georgia

Rock, even formations with moderate groundwater conductivity, and cemented materials may provide inherent stability even below the groundwater. Examples include porous limestone or permeable sandstone. In general, however, it is desirable to add water to the hole during the excavation of such materials rather than allow flow from the ground into the hole, which can bring fines or cause sloughing of weak layers, and degrade the structural integrity of the drilled shaft concrete.

Although cohesive soils with low permeability may appear to provide a dry excavation, it is important to anticipate the requirements of subsequent strata. For example, advancing a dry excavation through a clay soil into a water-bearing sand stratum could result in “flowing” sands or bottom heave if the groundwater level in the sand is higher than the base of the excavation.

5.2 TEMPORARY CASING

Temporary casing is used to stabilize the drilled shaft excavation and then removed after or during placement of fluid concrete. Contractors like to emphasize the fact that the casing that is used temporarily in the drilling operation is essentially a tool, so it is sometimes termed "temporary tool casing." The temporary casing remains in place until the fluid concrete has been placed to a level sufficient to withstand surrounding ground and groundwater pressures, and then is removed. Additional concrete may be placed as the casing is being pulled to maintain the pressure balance. The fluid pressure of the concrete is relied upon to provide borehole stability. The use of temporary casing has been described briefly in Chapter 3.

When approved by the engineer, temporary casing used solely for support of the drilled shaft excavation may be left in place. In such cases, the engineer must assess the influence of the casing on the axial and lateral resistance of the completed drilled shaft. In some soils, such as soft cohesive soils that may be prone to squeezing or bulging if the casing is removed, the engineer may require the temporary casing to remain permanently in place through potentially unstable soil layers.

Temporary casing must be cleaned thoroughly after each use to have low shearing resistance to the movement of fluid concrete. Casing with a rough interior surface may drag on the column of concrete as the casing is lifted, cause necking or voids in the shaft, displace the reinforcement, or even cause the casing to become stuck. The casing should be free of soil, lubricants and other deleterious material.

5.2.1 Types and Dimensions

Most drilling contractors will maintain a large supply of temporary casing of various diameters and lengths in their construction yards. A typical view of stored temporary casing is shown in Figure 5-3. Casing from the stockpile may be welded or cut to match the requirements of a particular project.

Temporary casing must sometimes be seated into an impervious formation such as rock if the excavation is to be advanced below the casing in the dry. In such a circumstance, it will normally be necessary to use the casing as a tool, with twisting or driving forces applied through the casing. The end of the casing may be equipped with cutting teeth or additional thickness in order to facilitate installation and avoid distorting the casing.

Figure 5-3 A Typical View of Stored Temporary Casing

ADSC: The International Association of Foundation Drilling, has adopted the outside diameter of casing as a standard and uses traditional units [e.g. 36-in. O.D.] because used pipe in O.D. sizes is available at much lower cost than specially rolled pipe with specified I.D. (ADSC, 1995). Specially ordered pipe of a specific size can be ordered, but at higher cost and with the added requirement of lead time for fabrication. Ordinarily, O.D. sizes are available in 6-inch increments from 18 to 120 inches. Larger sizes, as shown in Figure 5-4, typically require special order and fabrication.

It is also noted that the use of manufactured segmental casing typically comes in metric sizes because of the worldwide distribution of this equipment. It is therefore advisable that the design include some flexibility on sizes where the use of temporary casing is anticipated in order to facilitate the cost-effective use of segmental casing. For example, 1.2 m (47.25 in.) diameter for 48-in. size, or 3 m (118 in.) diameter for a 10-ft (120-in.) size can normally be accommodated with small adjustments in the acceptable sizes, otherwise the contractor would be forced to upsize the diameter at considerable additional cost to employ segmental casing.

If the temporary casing size is not specified, most contractors will usually employ a casing that has an O.D. that is 6 inches larger than the specified drilled shaft diameter below the casing to allow for the passage of a drilling tool of proper diameter during final excavation of the shaft. A drilling tool with a diameter equal to the specified shaft diameter below the casing will usually be used. If boulders are anticipated, or if the contractor otherwise decides to use telescoping casing, the first casing that is set may have an O.D. that is more than 6 inches larger than the specified shaft diameter.

The contractor is usually responsible for selecting a casing with sufficient strength to resist the pressures imposed by the soil or rock and internal and external fluids. Most steel casing has a wall thickness of at least 0.325 inches, and casings larger than 48 inch O.D. tend to have greater wall thicknesses. Installation with vibratory or impact hammers may require greater wall thickness than would be used for casing installed in an oversized hole. Most contractors rely on experience in the selection of casing wall thickness. However, if workers are required to enter an excavation, the temporary or permanent casing should be designed to have an appropriate factor of safety against collapse.

Figure 5-4 Exceptionally Large Temporary Casings

The computation of the allowable lateral pressure that can be sustained by a given casing is a complex problem, and methods for such computations are beyond the scope of this publication. The problem is generally one of assuring that buckling of the casing does not occur due to the external soil and water pressures. Factors to be considered are: diameter, wall thickness, out-of roundness, corrosion, minor defects, combined stresses, microseismic events, instability of soil on slopes and other sources of nonuniform lateral pressure, and lateral pressure that increases with depth.

Semi-rigid liners can be used for liners or surface casing that may be left in place. They can consist of corrugated sheet metal, plain sheet metal, or pressed fiber. Plastic tubes or tubes of other material can also be used. These liners are most often used for surface casing where it is desirable to restrain unstable surface soil that could collapse into the fluid concrete during placement, or to facilitate construction of the drilled shaft to column connection. For example, corrugated sheet metal is often used for this purpose when the concrete cutoff elevation is below working grade. Occasionally, rigid liners, such as sections of precast concrete pipe, are also used effectively for this purpose.

Rotators and/or oscillators with segmental casing (Figure 5-5) are increasingly being used to advance large diameter, deep drilled shafts. The casing penetration is advanced ahead of the excavation, thus providing support for the excavation and eliminating the need for slurry for side wall stability. However, slurry or water may still be necessary to prevent base heave. Soil can be removed within the casing with clam, hammer-grab, or rotary tools. The casing is typically high strength steel, often double-wall, with flush fitting joints between segments. Details of the connection between casing segments allow for the transmission of torque, compression, and tension between casing sections. This allows large torque (in either direction), compression, and lifting forces applied by equipment at the surface to be transmitted from the top section of casing to the bottom section of casing.

Although the double walled casing shown in Figure 5-5 is most often used, it is possible to weld the casing joints to standard pipe as illustrated in Figure 5-6. In this case the casing joint will protrude into the interior of the casing.

Figure 5-5 Segmental Casing Installation with Oscillator System

Figure 5-6 Installation of Casing Joint on Standard Pipe

5.2.2 Installation and Extraction of Temporary Casing

As described in Section 5.1, temporary casing is sometimes placed into an oversized drilled hole and then seated into the underlying formation to provide a stable environment, but temporary casing can also be advanced ahead of or in combination with the advancement of the excavation. Each of these methods may have implications for design because of the effect on the side resistance in the zone through which the temporary casing is installed. Methods for installation and extraction of temporary casing are described below.

5.2.2.1 Casing Seated Through Drilled Hole

Temporary casing can be placed through a pre-drilled hole to seat the casing into an underlying formation of more stable material. The pre-formed hole may be constructed using the wet method with drilling slurry, or may sometimes be advanced without a drilling fluid if the soil will stand for a short period and the seepage into the hole is relatively small. The latter is often the case where the shaft excavation can be drilled relatively quickly through a residual soil to rock; then the more time-consuming rock excavation is facilitated by having a temporary casing to prevent cave-ins of the overlying soil. If the shallow strata are water-bearing sands, it may be necessary to drill the starter hole with slurry to prevent caving. In some instances, contractors may use polymer slurry just to help “lubricate” the casing and make it easier to remove.

The excavation below the casing may be advanced as a dry hole if the casing is seated with a watertight seal into a relatively impermeable underlying formation of clay, chalk or rock. In order to seat the casing, a “twister bar” attachment to the kelly bar may be used to allow the drill rig to apply torque and crowd to the casing and advance it into the underlying soil or rock. Figure 5-7 illustrates casings with J-slots cut into the top to allow a casing twister to be used. In order to help the casing to cut into the underlying formation, the end of the casing is usually equipped with cutting teeth as shown in Figure 5-8. Various types of cutting teeth may be used, depending upon the type of material into which the casing is advanced.

Figure 5-7 J Slots in Top of Casing for Use with Casing Twister

Figure 5-8 Teeth for Use in Sealing Casing into Rock (Photograph at top left courtesy of Herzog Foundation Drilling, Inc.)

A good seal of casing into underlying rock can be very difficult if the rock surface is steeply sloping or highly irregular, or if the rock contains seams or joints that allow water inflow below the casing. It is therefore often necessary that the casing be advanced some distance into the rock; accordingly, in such conditions, the foundation design should include some flexibility with regard to the casing tip elevation. An irregular hard surface presents risks for the casing to deflect off alignment, break cutting teeth, and possibly bend the casing due to concentrated stresses if excessive downforce is applied.

Drilled shaft excavations can be made using more than one piece of casing with the "telescoping casing" process (Figure 5-9). This process has the economic advantage that smaller cranes and ancillary equipment can be used to install and remove telescoping casing than would be required with a single piece of casing. A borehole with a diameter considerably larger than that specified is made at the surface, and a section of casing is inserted. A second borehole is excavated below that section of casing, which is then supported with another section of casing of smaller diameter. This process may proceed through multiple, progressively smaller casings, with the I.D. (O.D- if excavating does not proceed below casing) of the lowest casing being equal to or greater than the specified diameter of the drilled shaft. The O.D. of a lower section of such "telescoping casing" is typically at least 6 inches smaller than the O.D. of the section above it, although larger differential diameters may be used when necessary. This procedure is most often used for drilled shafts that are bearing on or socketed into rock and where no skin friction is considered in the soils or rock that is cased. Care must be taken by the contractor that the process of removing the smaller section(s) of casing does not disturb the larger section(s) of casing still in place, or deposit water, slurry or debris behind casings still in place, thereby contaminating the fluid concrete.

Telescoping casing may also be used to case through boulder fields where some boulders are removed as the casing is screwed ahead to refusal. The smaller inner casing is advanced through the first casing which retains the zone where the larger boulders were removed. The placement of concrete within a hole stabilized using telescoping casing is described in Chapter 7.

Figure 5-9 Use of Telescoping Casing to Complete a Dry Excavation at a Site Near Dallas, Texas

5.2.2.2 Casing Advanced Ahead of Excavation

The contractor may choose to advance the casing ahead of the excavation in cases where the hole will not stand open for short periods or where slurry drilling techniques are considered less attractive from a cost or performance standpoint. There are two primary methods used to advance casing ahead of the excavation. The contractor may drive the casing in advance using a vibratory hammer, or by twisting using the drill rig or using oscillator/rotator equipment.

In either case it is important to note that the friction of the soil acting against the side wall of the casing must be reduced to a sufficient degree that the casing can be advanced. The vibratory hammer accomplishes this reduction by temporarily reducing the strength of the soil along the sidewall. In order to twist the casing into the soil, a reduction in friction is achieved by a small overcut achieved with the casing shoe or cutting teeth. These techniques allow the soil to “arch” around the circular drilled shaft excavation; the horizontal stresses acting in the radial direction against the side of the casing are thereby transferred into hoop stresses arching around the hole, as illustrated in Figure 5-10.

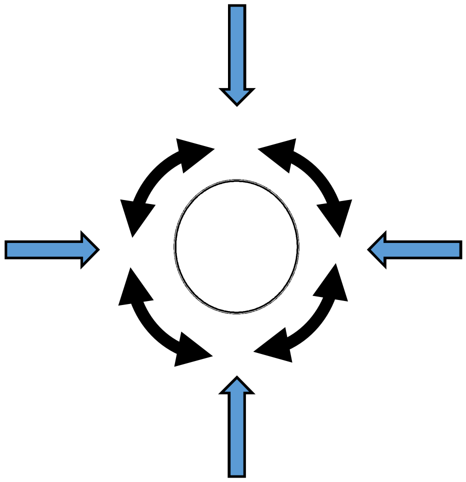


Figure 5-10 Reduced horizontal stress due to soil arching, which develops as soil moves inward

5.2.2.2.1 Vibro-Driven Casing

When casing is driven, a vibratory hammer is almost always used for temporary casing; an impact hammer may be used to install permanent casing, but temporary casing will require a vibratory hammer for extraction since casing installed with an impact hammer may be impossible to remove due to increased friction resistance. In principal, jetting could be utilized as an aid to installation, but jetting around the casing would not be advised during extraction due to the potential for jet water to adversely affect the fluid concrete.

In planning the construction of drilled shafts in congested areas, it should be noted that the use of vibratory installation of casing can cause significant vibrations that can affect nearby structures, or cause settlement in loose sands (which can affect nearby structures and utilities). The attenuation of vibrations with distance away from the source is affected by the size of the hammer and casing, the operating frequency of the hammer, the soil and rock properties, the localized stratigraphy, groundwater, and other factors that are likely site-specific. In most cases, vibrations from casing installation are extremely small at distances of 50 to 70 ft from the source, but may extend to greater distances when penetrating hard or cemented layers. In cases where sensitive structures may be present nearby, a program of vibration monitoring should be included in the installation plan. Vibration monitoring can help avoid potential damage and can also provide documentation as protection against lawsuits or claims of damage caused by vibratory installation of casing. Monitoring during construction of the technique and test shaft installations can provide valuable measurements of vibrations at various radial distances from the source before moving the work into more congested production locations. A useful reference on this subject is "Construction Vibrations" by Dowding (2000).

Installation of the casing using a vibratory hammer is most effective in sandy soil deposits, and to penetrate through sandy soils into a clay or marl stratum below. The hammer clamps to the top of the casing (Figure 5-11), which is often reinforced at the end with an extra thickness to aid in resisting the transmitted forces. The vibration of the casing often causes temporary liquefaction of a thin zone of soil immediately adjacent to the casing wall so that penetration is achieved only with the weight of the casing plus the hammer. This technique is particularly effective in sandy soils with shallow groundwater. Penetration of an underlying hard layer such as cemented sand or rock may be difficult or impossible with a vibro-driven casing. Attempts to twist the casing with the drill rig to seat into rock are likely to be ineffective because of the side resistance of the soil against the casing after removal of the vibration.

In general, a vibratory hammer is used to place the entire length of temporary casing into the soil before excavation of soil inside the casing. However, to facilitate penetration through particularly dense soils, the casing can be installed by an alternating sequence of driving the casing and drilling to remove the soil plug within the casing. In this case, it would typically be necessary to install the casing in sections, with the sections joined by welding.

Another technique which might be employed is referred to as "relief drilling" whereby an auger is advanced through a hard layer below the casing to break up the material so that the casing can subsequently be advanced through it. If the soil below the casing is not considered sufficiently stable to stand open prior to advancing the casing deeper, the rotation of the auger can be reversed on extraction to leave the soil in place below the casing to avoid having an uncased hole below the casing.

Removal of the casing with the vibratory hammer must be accomplished while the concrete is still fluid. During extraction, the hammer is attached and powered, and then typically used to drive the casing downward a few inches using the weight of the casing and hammer to break the casing free of the soil. Once the casing is moved, the crane pulls the casing upward to remove it and leave the fluid concrete filled hole behind. The photo in Figure 5-11 shows the start of removal of a casing after completion of concrete placement.

Figure 5-11 Extraction of Temporary Casing Using a Vibratory Hammer

5.2.2.2.2 Twisting/Rotating Method

Installation of temporary casing ahead of the excavation may be accomplished with a drill using special casing and tools, with a cutting shoe designed to minimize the soil friction on the casing. Because of the torque required to twist casing and overcome the soil resistance, the use of conventional drill rigs for this purpose is limited to relatively small diameter casing generally less than 4 ft diameter. Some of the hydraulic fixed mast rigs with a rotary drive system that can move vertically on the leads are well suited for this application, as illustrated in Figure 5-12 where the rig was used to install 39 inch diameter tangent piles for a retaining wall.

Figure 5-12 Segmental Casing Installed with a Hydraulic Drill Rig

The torque required to install larger diameter casings by twisting or rotating typically demands a specialized oscillator or rotator machine; a general description of the machines and procedures used for the oscillator/rotator method of construction is provided in Chapter 4. The oscillator or rotator clamps onto the casing with powerful hydraulic jaws and uses hydraulic pistons to twist the casing and push it downward, reacting against a large drilling machine or temporary frame. Figure 5-13 illustrates an oscillator attached to the drill rig, which installed temporary segmental casing to the top of rock prior to drilling the rock socket. The soil may also be excavated using a grab tool as illustrated in Figure 5-5.

Figure 5-13 Segmental Casing Installed with an Oscillator Attachment to a Hydraulic Drill Rig

Where casing is twisted or rotated to advance into soil or rock ahead of the excavation, the casing is provided with cutting teeth extending slightly beyond the outside dimension of the casing. The bottom section of casing is fitted with a cutting shoe to promote penetration (Figure 5-14) by cutting a slightly oversized hole to relieve the stress against the sides of the casing. The soil on the interior of the casing is excavated concurrent with casing installation to remove the resistance of this portion of the soil.

Figure 5-14 Cutting Shoe for Segmental Casing

During installation of the casing, it is essential that a plug of soil remain inside the casing so that the bottom of the excavation does not become unstable during installation. The thickness of soil within the casing may vary depending upon the strength and stability of the material at the base of the casing. In water-bearing soils, the head of water inside of the casing must also be maintained so that bottom heave does not occur. It is possible to use polymer or mineral based drilling fluids inside the casing to maintain stability, but the need for these fluids is usually avoided by maintaining a soil plug and, when needed, a head of water. It is necessary to maintain stability during installation because heave of soil into the casing would cause loosening of the ground around the excavation with adverse effects on side resistance and possible subsidence around the shaft.

At completion of the excavation, the soil plug may be removed to the base of the casing (or below) if the casing is extended into rock or a stable formation, or if a head of drilling fluid is used to maintain stability. If the hole terminates in water-bearing soil with only a water head for stability, it may be necessary that the casing extend below the base of the final excavation to avoid instability at the base. However, this procedure may result in an annular zone of loosened soil at the base of the drilled shaft excavation.

The thicker casing (typically about 2 to 2.5 inches) used with this method of construction is a consideration in selection of the cover and the spacers on the reinforcement cage. If a single wall pipe is used with the casing joints as shown in Figure 5-6, the joints will protrude inside the casing because the joint is typically thicker than the pipe. In such a case, the reinforcing cage will need to be fabricated and placed carefully so that nothing hangs on the casing joints during installation of the cage and/or extraction of the casing during concrete placement.

To avoid potential torsional deformation of reinforcement, the casing is typically oscillated back and forth during extraction, even if a continuous rotation was used during installation. The casing is typically extracted simultaneously as concrete is placed into the excavation, and concrete head above the tip of the casing must be maintained so that a positive concrete pressure is provided against the hole. If exterior groundwater pressure is present, the head of concrete and water inside the casing must exceed the exterior water pressure to prevent inflow of water and contamination of the concrete. It is also essential that the concrete remain fluid so that the oscillation of the casing does not transfer twisting forces into the reinforcing cage and cause distortion of the cage.

5.2.3 Possible Effects of Temporary Casing on Axial and Lateral Resistance

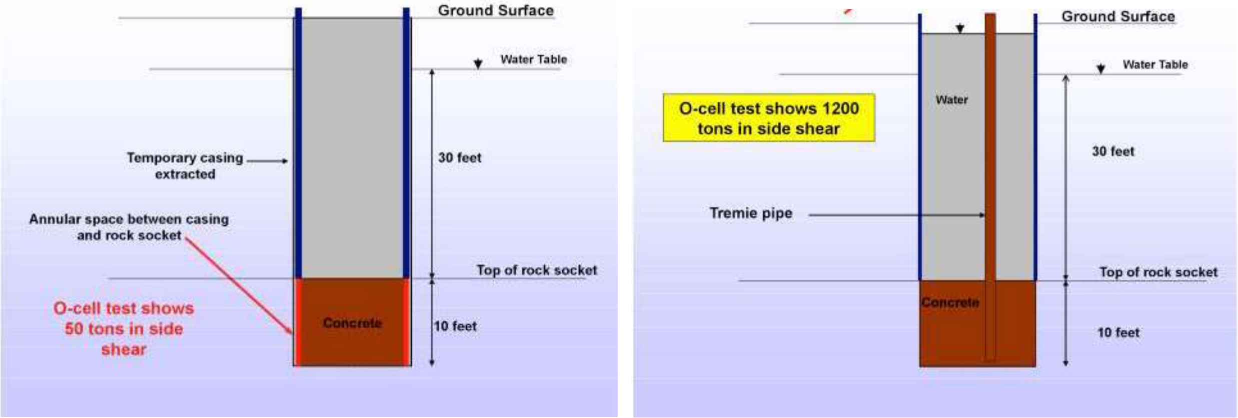
If temporary casing is to be used in construction, it is appropriate that the designer consider the possible effects of casing on axial and lateral resistance.

In general, no deleterious effect on the lateral resistance of a drilled shaft should occur due to the removal of temporary casing. However, an exception may be where the casing is installed in an oversized, pre-drilled hole that collapses into the void outside the casing prior to concrete placement and casing extraction, resulting in a zone of loosened soil around the casing. Temporary casing which cannot be removed and is left in place in an oversized hole may also reduce the lateral stiffness of the shaft due to the void; in this case, it is recommended that the void be filled with grout or flowable cementitious material to ensure transfer of lateral soil resistance around the shaft even if there is no reliance on the cased zone for axial resistance.

However, the axial resistance can be significantly affected by the method of casing installation, as discussed below.

If the axial resistance of the drilled shaft is derived entirely from the soil or rock below the temporary casing, there is little concern regarding any adverse effects of the casing on load transfer in side resistance. Designers should consider the relative magnitude of the contribution to axial resistance derived from the temporary casing zone; if this contribution is relatively small compared to the drilled shaft below this level, then it is appropriate and cost-effective to ignore the axial resistance of this portion of the shaft so that the constructor can be permitted to use the most cost-effective strategy to install the drilled shaft. If the side resistance of the temporary cased zone is significant, then there are important considerations as outlined below.

Casing installed into a predrilled hole may affect side resistance within the cased portion of the shaft if contaminants or debris or loosened soil are trapped behind the casing and are left between the concrete and native soil or rock. Contaminants can become trapped if thick, heavy slurry is used and left in the annular space behind the casing, or as a result of the casing being extracted too quickly, before the slurry can be effectively displaced by the flow of concrete. In addition, debris can fall into this annular space. Where temporary casing is installed into rock via a predrilled hole, it is likely that debris will collect in this space and a good concrete to rock bond will not be developed. An example of this problem is reported by Osterberg and Hayes (1999), and illustrated in Figure 5-15. A shaft was constructed using a casing extending the full length into a 10-ft deep rock socket to provide a dry excavation so that the base of the shaft in rock could be inspected. A bi-directional load test (described in Chapter 16) performed on the completed drilled shaft measured only 50 tons of side resistance in the rock socket, presumably because of trapped debris between the concrete and rock along the sidewall of the socket. At another drilled shaft, constructed by terminating the casing above the rock and constructing the rock socket "in the wet" under water, the load test measured 1200 tons of side resistance in the rock socket. This extreme example illustrates the importance of a simple detail in constructing drilled shafts into rock with casing.



a) Dry hole with temporary casing through the rock section

b) wet hole with casing section at top of rock

Figure 5-15 Adverse Effect of Casing Extended into Rock Socket (Osterberg and Hayes, 1999)

Temporary casing installed ahead of the shaft excavation using a vibratory hammer should generally have no adverse effect on soil resistance in sands and can even have a beneficial effect by densifying the sand around the drilled shaft. However, a casing installed into and then extracted from a cohesive soil with a vibratory hammer is likely to result in a relatively smooth surface compared to a rough drilled hole. Camp et al. (2002) noted the relatively lower side resistance of the upper portion of a marl formation when temporary casing was used compared to an uncased shaft drilled with slurry, a difference which was attributed to the smoother shaft surface.

Segmental casing advanced ahead of the drilled shaft excavation using the oscillator/rotator system is generally considered to have no significant effect on side resistance so long as a stable excavation is maintained. The use of cutting teeth on the bottom of the casing and the oscillation of the casing during withdrawal tends to leave a rough surface texture on the drilled shaft, as reported by Brown (2012) and illustrated in Figure 5-16. Comparative tests by Brown (2002) and others reported by Katzenbach et al. (2008) suggest that this rough texture and other factors contribute to reasonably good unit side shear for drilled shafts constructed with this method compared to slurry methods, and possibly improved performance relative to shafts constructed using bentonite slurry. Since construction of very large or deep drilled shafts with bentonite slurry can be difficult to accomplish within the short time frame needed to avoid bentonite contamination at the interface, full length segmental casing can be a more favorable option for achieving the design side resistance. However, failure to maintain stability at the base of the excavation can result in loosening of the soil around the shaft excavation and a reduction of side resistance.

Figure 5-16 Exposed Surface of Drilled Shafts Constructed Using Oscillated and Rotated Casing

For cases where a temporary segmental casing extends into soil below the final bottom of the drilled shaft (as described in Section 5.2.2.2.2), an annular zone of loosened soil may form below the base of the drilled shaft. This disturbed annular zone may result in slightly reduced base resistance unless corrected by base grouting beneath the completed drilled shaft.

If the constructor is unable to extract the temporary casing, the responsible engineer needs to apply judgment to evaluate the effect of the casing on the axial resistance of the drilled shaft. Expedient load-testing methods, such as those described in Chapter 13, may be helpful in evaluating side resistance around casings that are unintentionally left permanently in place. Although it is not possible to make general statements that apply to all cases, many studies have been conducted that show that the load transfer from the casing to the supporting soil can be significantly less than if concrete had been in contact with the soil (Li et al, 2017, Lo and Li, 2003; Owens and Reese, 1982).

5.2.4 Removing Casing after Concrete Sets

Drilled shafts installed through a body of water typically use a permanent casing that serves as a form until the concrete sets, and then is left permanently in place. It is preferable to leave the casing in place rather than to attempt to remove it for several reasons. Firstly, the casing provides additional corrosion protection for the reinforcement, since chlorides must penetrate not only the concrete cover but also the outer permanent casing. Secondly, leaving it in place avoids the construction difficulties in removing the casing that could damage the concrete. Thirdly, there can be irregularities in the surface texture of the concrete after removal of casing due to small bleed channels or other surficial imperfections that require additional surface preparation. Any perceived aesthetic benefits of exposed concrete compared to steel casing can often be mitigated with coatings on the casing, or by other means.

An example of a removable casing is shown in Figure 5-17; this photo is taken from the I-95 Fuller Warren Bridge over the St. Johns River in Jacksonville, Florida. For this project, the removable casing was fabricated with a split seam that extended the entire length of the casing and was joined by a mechanical pin arrangement that kept the joint closed during casing installation and concrete placement, and then expanded to facilitate removal of the casing after the concrete achieved the required strength. A rubber gasket was placed in the joint in an effort to make the joint water tight. In this example, the 72-inch diameter casings were advanced with a vibratory hammer through soft river bottom deposits either to a stiff silty clay layer or to limestone. After the drilled shaft concrete set, the pin mechanism was lifted to expand the joint, making the inside diameter of the casing slightly larger than the diameter of the drilled shaft, and allowing the casing to be lifted off the drilled shaft. The contractor selected this method to allow re-use of the casings for a number of offshore foundations, and thereby reduce the cost of steel casing. However, the use of removable casing for this project presented several problems that are often encountered with this type of solution:

a. After the initial use of the casing, the joint was typically not water tight despite cleaning and repair of the joint,

b. The contractor had difficulty opening the split joint, possibly due to fouling of the mechanism with concrete,

c. Once the joint was opened, the contractor had difficulty lifting the casing off the drilled shaft even with the use of a vibratory hammer,

d. When the casing was removed, diver inspection identified surface defects on the drilled shaft, including washout of cement along portions of the drilled shaft that had been adjacent to the split joint, numerous spalls and bleed water cavities around the remainder of the drilled shaft, and locally exposed steel reinforcement, and

e. To correct the observed defects, costly underwater remediation measures had to be implemented.

As this project case history illustrates, the use of removable casing may pose risk of structural defects to the drilled shafts. In addition, inspection of the completed drilled shafts and repair of any identified defects is complicated since this work must be accomplished under water, sometimes working under difficult conditions of limited visibility and swift currents. Accordingly, the use of removable casing at offshore foundations should generally be avoided.

Where it is specified to remove portions of exposed permanent casing, removal should generally be limited to the section of the drilled shaft above water level. In such cases, the removal would typically be accomplished by torch cutting the steel into sections, taking care to avoid damaging the underlying concrete surface, and detaching the individual sections from the surface of the concrete. Any concrete defects exposed after removing the casing segments can then be repaired using appropriate methods. If the exposed concrete is entirely above the water level, such repairs can be accomplished with less effort and with greater reliability.

Figure 5-17 Locking Mechanism for a Removable Casing

An alternative approach that may entail less risk of defects in the shaft is illustrated in Figure 5-18. This approach uses a temporary casing which is sufficiently large to function as a cofferdam. The drilled shaft constructed through the temporary casing may include a permanent casing or may simply be constructed using a drilling fluid in an uncased hole. The concrete placement can be terminated below the water surface and a removable form placed inside to form the column and splice the column reinforcement to the drilled shaft reinforcement. With this solution, the removable form is not subject to the handling stresses of a temporary casing, and the concrete within the form can be placed in the dry after removal of laitance at the cold joint. After removal of the column form, the temporary casing extending above the top of shaft cutoff can be removed with torches, using divers for casing removal below water level.

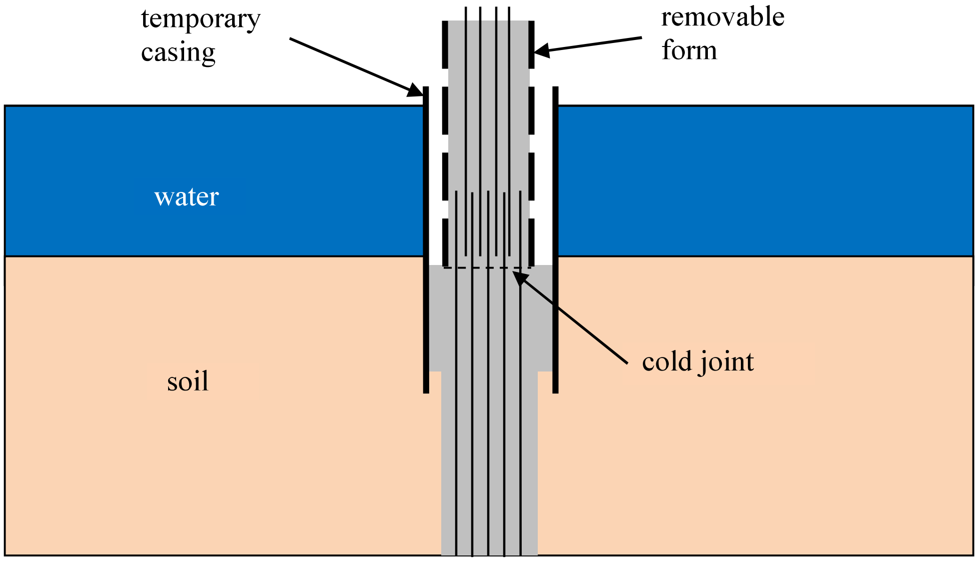


Figure 5-18 Construction Joint Below the Water Surface

5.3 PERMANENT CASING

As implied by its name, permanent casing remains and becomes a permanent part of the foundation. An example of the use of permanent casing is when a drilled shaft is to be installed through water and the protruding portion of the casing is used as a form. A possible technique that has been used successfully is to set a template for positioning the drilled shaft, to set a permanent casing through the template with its top above the water and with its base set an appropriate depth below the mudline, to make the excavation with the use of drilling slurry, and to place the concrete through a tremie to the top of the casing.

One consideration for using permanent casing is the time that will be required to place the concrete for a deep, large-diameter, high-capacity drilled shaft founded in sound rock. Control of the concrete supply may be such that several hours could pass between placing the first concrete and extracting temporary casing. In that case, the concrete may already be taking its initial set when the seal is broken by raising the casing, making it difficult to extract the temporary casing without damaging the concrete in the drilled shaft. In such as case, permanent casing may be specified.

Another common situation for using permanent casing is when the drilled shaft must pass through a cavity, as in a karst formation. The permanent casing becomes a form that prevents the concrete from flowing into the cavity. In addition to the cost of the additional concrete lost due to exterior voids in the rock, the flow of concrete into large cavities can result in mixing of soil or water into the drilled shaft, producing a void in the structure. It can also lead to distortion of the steel reinforcement cage.

Permanent casing is also commonly used for drilled shafts that extend through very soft soils, such as marsh deposits, to reach an underlying stratum which is more stable. In such cases, the permanent casing is used to prevent the outward bulging of the fluid concrete into the surrounding soft soils. If a bulge forms at an elevation corresponding to an extremely soft stratum, there can be a risk of defects in the concrete due to a neck in the shaft above the bulge, or deformation of the reinforcement cage.

5.3.1 Types and Dimensions

The types and dimensions of permanent steel casing are similar to those described previously for temporary casing. The major difference is that the permanent steel casing can be installed in longer sections of pipe and may be driven into place (similar to the installation of a steel pipe pile) since it does not need to be extracted. If the permanent casing is to be used as a structural component within the drilled shaft, the casing dimensions, material properties, and welds are typically shown in the contract documents and are subject to quality control and documentation as would be required for a steel pipe pile or any steel structure.

The left photo in Figure 5-19 shows permanent casings extending into a cofferdam after placement of the seal concrete and dewatering of the cofferdam. These permanent casings were used to extend the shafts through the river water to an underlying rock bearing layer. The casings were also designed to utilize the bond between the casing and the seal concrete to engage the axial resistance of the drilled shaft against the upward water pressure on the base of the seal; in this way, the thickness of the seal was reduced compared to the thickness of seal that would be required based on the dead weight of concrete alone. The right photo in Figure 5-19 shows the drilled shaft reinforcement after the exposed casings were removed.

Figure 5-19 Permanent Casing Used for a Shaft Group Foundation in a River

Some additional types of materials might be used for permanent liners, such as the corrugated metal pipe (CMP) illustrated in Figure 5-20. This material is sometimes used for a liner at shallow depth because of the relatively low cost. However, CMP is relatively flexible and cannot be subject to installation stresses as conventional thicker walled steel pipe.

A semi-rigid liner may also be used to minimize the skin friction that results from downdrag or from expansive soils. Coatings that have a low skin friction (such as bitumen) have also been used. Liners made of two concentric pressed-fiber tubes separated by a thin coating of asphalt have been found to be effective in reducing skin friction in drilled shafts constructed in expansive soils by as much as 90 per cent compared to using no liner.

Flexible liners are used infrequently in the United States, but can have an important role in certain situations. Flexible liners can consist of plastic sheets, rubber-coated membranes, or a mesh. The rebar cage can be encased in the flexible liner before being placed in a dry or dewatered hole; then, the concrete is placed with a tremie inside the liner. The procedure is designed to prevent the loss of concrete into a cavity in the side of the excavation or perhaps to prevent caving soil from falling around the rebar cage during the placement of the concrete. Flexible liners are applicable only to those cases where the drilled shaft is designed to develop the required resistance entirely below the level of the liner, because skin friction in the region of the liner cannot be computed with any accuracy.

Figure 5-20 Corrugated Metal Pipe (CMP) Used as Permanent Liner

5.3.2 Installation of Permanent Casing

Permanent steel casing may be installed using any of the methods described previously for temporary casing, or the permanent casing may be driven into place using an impact hammer. Permanent casing installed into an oversized hole may be sealed into an underlying rock formation by twisting or driving. In this case, it is often necessary to fill the annular space with tremie grout in order to provide transfer of lateral soil resistance. Filling of the annular space may be unnecessary if the overburden soil is neglected for lateral loading or subject to scour.

Installation of the casing by driving can be an effective and efficient means of installing a permanent casing, since it will not need to be extracted. Since installation of a large steel pipe using an impact hammer subjects the pipe to driving stresses, the drivability of the pipe must be considered as described in the FHWA Driven Pile Manual (FHWA-NHI-16-009 by Hannigan et al., 2016). There are obvious limitations to the ability to drive large diameter steel pipe into hard soils or rock, and boulders can be particularly troublesome. Where rock or boulders are anticipated, impact driving of permanent steel casing into these materials can result in deformation of the end of the casing so that drill tools cannot pass; in such cases a more attractive alternative may include the placement of permanent casing into a pre-drilled hole.

5.3.3 Effects of Permanent Casing on Axial and Lateral Resistance

If the soil within the cased zone is scourable or not capable of providing a significant contribution to the design, then the resistance of the soil around the permanent casing should not be considered a part of the design, and the method of installing the casing is unimportant from this perspective. If the soil within the cased zone is considered to provide a significant contribution to axial resistance, then the casing must be installed in such a way as to provide good load transfer through side resistance. Casing installed into an oversized hole generally cannot be relied upon to provide axial load transfer.

Even if there is no reliance placed on the cased zone for axial resistance, there may be other considerations related to the use of an oversized hole around the outside of a permanent casing. If lateral resistance is required within the zone of a permanent casing installed into an oversized hole, then the annular space around the outside of the casing should be filled with grout. An unfilled oversized hole can also provide an unintended seepage conduit, which could present a problem when working near flood control levees or other water retention structures, or when there is a risk of cross contamination of aquifers in areas where contaminated soils are present. Expansive soil or rock strata at depth could also be exposed to increased water content if an oversized hole allows downward migration of water alongside the permanent casing.

Casing which is driven using an impact hammer and left in place should provide similar axial side resistance to that of a driven steel pipe pile and may be considered as such. Caltrans often refers to this type of permanent cased hole as a “Cast-in-Steel-Shell” (CISS) pile. Where permanent casing is vibrated into place, the axial resistance of the casing in side shear may be less than that of an impact driven casing. Because steel bearing piles are not normally installed in this way, the normal methods of estimating axial side resistance for steel pile piles may not apply.

A permanent casing can contribute to the structural capacity and bending stiffness of the drilled shaft as discussed in Chapter 12. However, since corrosion will decrease the thickness of the steel casing with time, this should be considered in determining the contribution of the casing to structural capacity. Aggressive conditions are a particular concern for casings in contact with fill soils and low pH soils, and those located in marine environments. Aggressive conditions are identified by determining specific properties of the fill, natural soil, and groundwater. Aggressive conditions are identified if the soil has a pH less than 4.5, or if the soil resistivity is less than 2000-ohm-cm. Chloride ion content and/or sulfate ion content should be conducted for soil resistivity values between 2000-5000 ohm-cm. Aggressive soil conditions exist if the sulfate ion content exceeds 200 parts-per-million (ppm), or the chloride content exceeds 100 ppm. Soils with resistivity greater than 5000 ohm-cm are considered non-aggressive. Hannigan et al. (2016) report a conservative estimate for a corrosion rate of 0.003 inch/year for steel piles buried in fill or disturbed natural soil. An in-depth review of corrosion is beyond the scope of this manual, and the reader is referred to FHWA-NHI-16-009 (Hannigan et al., 2016); AASHTO Standard R 27-01 (2004); and FHWA-NHI-00-043 (Elias, et al., 2001).

5.4 CONSTRUCTION USING DRILLING FLUIDS

Another means to stabilize a drilled shaft excavation is with the use of drilling fluids within the hole. Fluids can include water or water mixed with minerals (typically bentonite clay) or synthetic polymers. Drilling fluids provide stability by providing a fluid pressure within the drilled shaft excavation greater than the pressure of the groundwater to prevent destabilizing seepage into the hole, as illustrated in Figure 5-21.

Additives, such as minerals (bentonite) or polymer, are used to help contain the fluids within the hole and minimize fluid loss through 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".

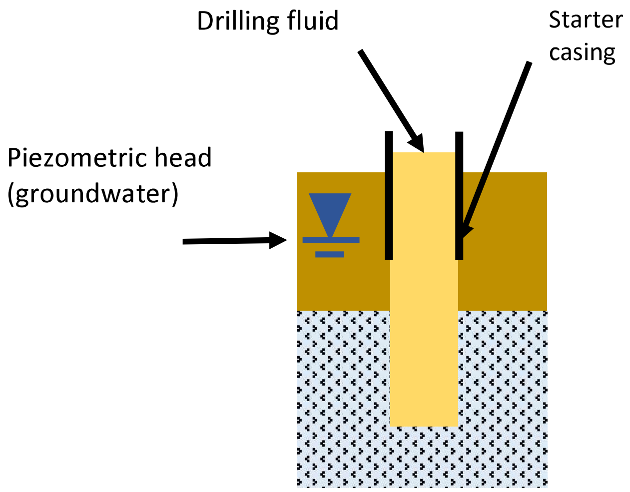


Figure 5-21 Differential Fluid Head Pressure Used to Maintain Borehole Stability

5.4.1 Water as a Drilling Fluid

Water alone is not typically suitable for use as a drilling fluid in uncemented granular soils because water flows out of the hole too fast to maintain a positive head pressure, and therefore the fluid would provide no stabilizing effect. However, if the soil has sufficient cementation or if the uncased excavation is entirely in rock, water may be utilized effectively as a drilling fluid for several purposes.

In a wet, but otherwise stable excavation through pervious rock or other strong and stable materials, the excavation may simply be filled with water in order 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 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 (Figure 5-22).

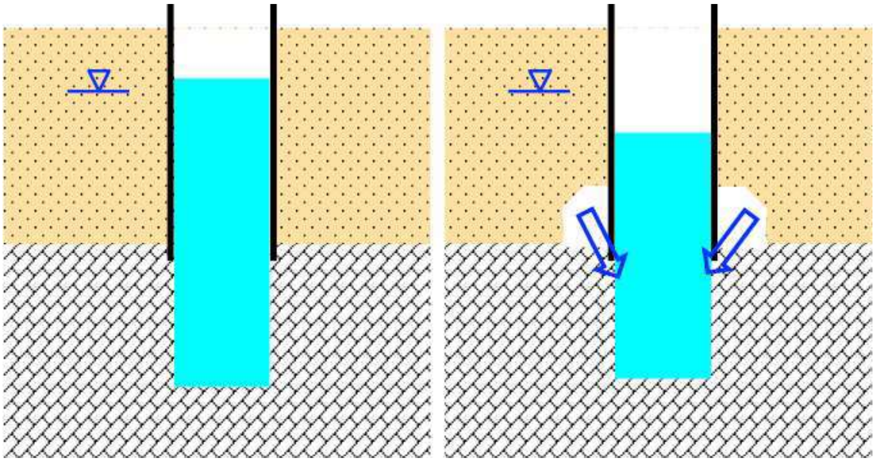
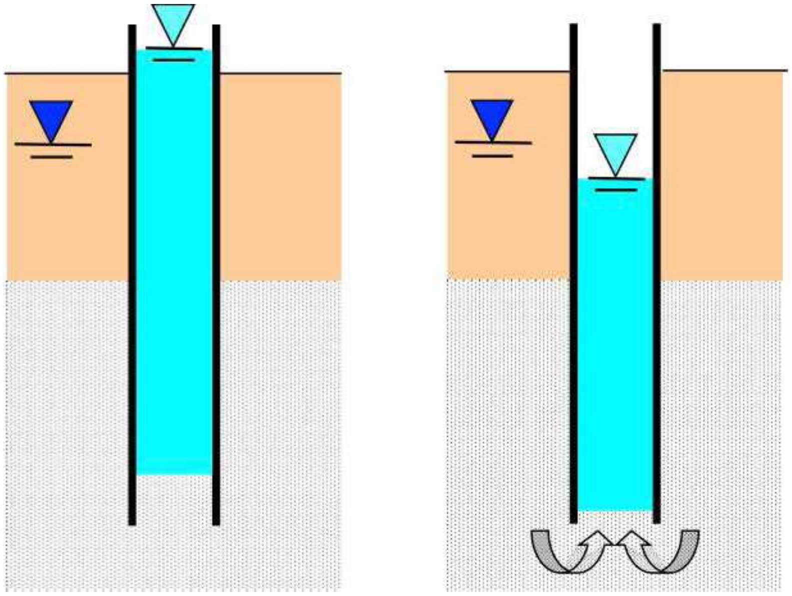

a) Acceptable Practice
b) Inadequate Head

Figure 5-22 Effect of Seepage Around Imperfectly Sealed Casing Due to Lack of Positive Head Pressure

Seepage into the hole (Figure 5-23) during concrete placement can adversely affect the quality of the concrete, because the groundwater head will continue to drive water into the fluid mix until sufficient concrete head is established to overcome the groundwater head. In these situations, water should be added to the excavation to counterbalance this seepage into the hole. Maintaining a positive head pressure within the hole prior to the start of concrete placement protects 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.

Figure 5-23 Excessive Seepage into a Drilled Shaft Rock Excavation (photo courtesy of PennDOT)

Positive water head may be needed where full length casing is employed to provide sidewall stability in permeable or unstable soils (Figure 5-24). In this situation, a positive water head is needed to avoid upward directed flow into the base of the excavation. The upward flow could produce softening of the material at the base, or piping of cohesionless soils. In some cases, instability of the base could lead to flow of soil up and into the casing with attendant loosening of the soil around the excavation and possible subsidence at the ground surface. A positive water head within the casing, often with a plug of soil at the bottom of the casing, is used to mitigate the risk of instability at the base. More details on construction with the fully cased method is provided in Section 5.2.2.2.



a) Acceptable Practice b) Inadequate Head

Figure 5-24 Effect of Fluid Head on Bottom Stability in a Fully Cased Excavation

Water may also be used as a drilling fluid for rock excavation with tools and equipment that utilize fluids to flush cuttings from the excavation face. Examples include percussion tools, double walled core barrels, or full face rotary tools. Air may be used as the flushing mechanism in some tools, with the hole filled with water to maintain a positive head in the excavation. More details on construction with these types of tools is available in Chapter 4.

5.4.2 Mineral Drilling Fluid

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 resulting fluid has an appearance similar to that of chocolate milk, as seen in the photo in Figure 5-25.

Figure 5-25 Mineral Based Drilling Fluid (Bentonite Slurry)

Much of the commercial bentonite used in the construction industry in North America comes from Wyoming, the name bentonite having derived from the Benton Shale there. Bentonite is a natural material composed of clays with a high proportion of montmorillonite. The desirable bentonite for construction is referred to as a high grade sodium bentonite because the clay contains a high concentration of sodium ions. Compared to other types of clay (calcium bentonite, for example), the sodium bentonite hydrates a larger volume of water in proportion to its own weight and therefore the fluid contains a relatively small volume of suspended solids at the time of introduction.

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 of the perimeter soils and thereby helps to contain the fluid (Figure 5-26). 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.

A key factor in the successful use of bentonite slurry is that a positive fluid head be maintained above the level of the surrounding groundwater, so that the stabilizing fluid pressure supports the sidewall of the excavation. The stabilizing pressure at any given depth is then related to the combination of head differential and unit weight as illustrated in Figure 5-27. A typical unit weight of bentonite slurry is in the range of 65 to 70 pcf, compared to 62.4 pcf for fresh water.

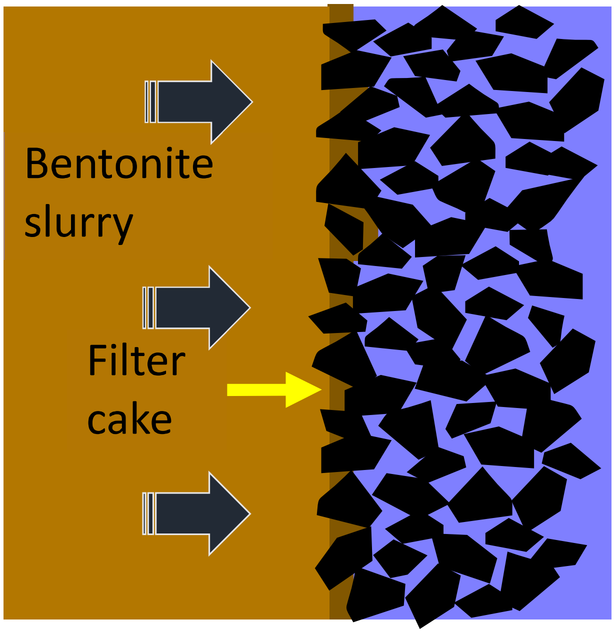


Figure 5-26 Filter Cake Formation at Borehole Sidewall with Mineral Slurry

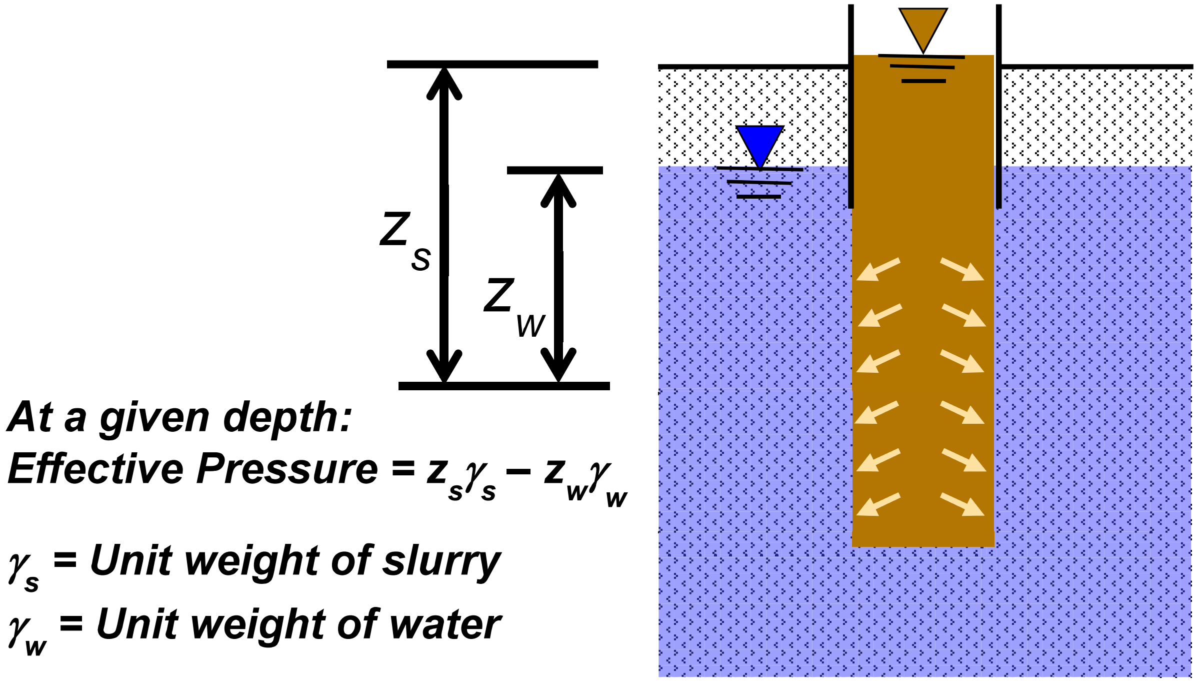


Figure 5-27 Effective stabilizing pressure provided with bentonite slurry

Although a 10-ft head differential between support fluid and groundwater is generally considered desirable, with bentonite slurry a 5-ft minimum head differential is often sufficient because of the additional benefit of the unit weight difference. The filter cake formation at the borehole wall is also beneficial in that the pressure gradient occurs over a very short distance at the very face of the excavation.

Prior to introduction into the excavation, bentonite slurry must be thoroughly mixed with vigorous shearing, and a sufficient period of time is needed for hydration of the bentonite in water (typically 24 hrs minimum). A typical mixing plant setup is illustrated in the photo of Figure 5-28. This process also minimizes the unmixed clay in the suspension which could either contaminate the concrete or lead to excessive buildup of thick filter cake at the borehole wall.

Figure 5-28 Mixing plant and holding tanks for bentonite slurry preparation

Because of the concern about potential detrimental effects of excess filter cake thickness, the exposure time of the excavation should be limited prior to placement of concrete. This may not be much of an issue for smaller drilled shafts in soil where excavation and concrete placement can be completed in the same day, but can be a consideration for larger diameter or deeper holes that are left open under bentonite slurry overnight. If the excavation cannot be completed and concrete placement commenced within a few hours, it may be necessary to take active measures to remove filter cake buildup with a special tool such as a bucket equipped with a sidewall wire brush or an auger with protruding teeth around the perimeter, as discussed in Chapter 4. The final cleanout of the hole must then be completed, rebar placed, and concrete placement begun in a timely manner. Bentonite materials can also adversely affect axial resistance for circumstances in which drilled shafts are advanced into rock and the side resistance in a rock socket is an important part of the design.

When the pore sizes in the formation being excavated are large (as in gravelly soils or poorly graded coarse sands) the filter cake may not form as effectively at the borehole wall. Bentonite slurry may still be effective for restricting fluid loss and providing stability in gravel if the gravel contains sufficient fines and the fluid has sufficient gel strength. If the bentonitic slurry proves ineffective, special techniques (for example, use of casings, additives or other types of drilling fluids, or grouting of the formation) may be required to stabilize the borehole.

Control of the unit weight and suspended solids content within the slurry is required for successful completion of a drilled shaft. After mixing, mineral slurries have unit weights that are slightly higher than the unit weight of the mixing water, with a specific gravity typically about 1.03 to 1.05 after initial mixing. During excavation, particles of the soil or rock being excavated will be mixed into the slurry and become suspended. Below a certain concentration, the soil particles will stay in suspension long enough for the slurry to be pumped out of the borehole and/or for the slurry (with suspended cuttings) to be completely displaced by an upward flowing column of high-slump fluid concrete. However, as drilling progresses and the slurry picks up more soil, its unit weight and viscosity will increase.

The slurry must be cleaned prior to concrete placement because excessive suspended soils can settle out, either onto the base of the excavation after the bottom of the hole is completed and inspected. Excess suspended soils can also tend to settle onto the fluid concrete during concrete placement, leading to entrapped pockets of sand within the completed drilled shaft. A small amount of suspended material will generally remain in suspension during concrete placement, particularly for a smaller drilled shaft where the concrete placement time may only take an hour or less. For a large diameter and deep drilled shafts, where concrete placement may require several hours, the slurry must be cleaned to a greater degree.

Suspended sand particles in a mineral slurry can be removed by processing the fluid through a de-sanding unit as shown in Figure 5-29. The fluid is pumped from the base of the excavation using an air-lift or hydraulic pump (the bottom of the fluid column will contain the highest amount of sediments) and circulated through this plant while fresh, clean slurry is added at the top of the excavation. The plant shown in Figure 5-29 contains cyclones and screens that are capable of removing sand-sized and larger particles. After processing the fluid in this manner, the slurry is checked for sand content, density, and viscosity to ensure that the fluid in the completed hole is ready for concrete placement.

Figure 5-29 De-sanding plant for bentonite slurry

Silt and clay sized particles can be removed using centrifuge equipment, but normally if the slurry becomes too heavy or viscous in spite of a low sand content it is just discarded and replaced with fresh fluid.

Groundwater that has a high salt content may cause flocculation and failure of the particles to remain in suspension. Bentonite can sometimes be used for limited periods of time in saline water by first mixing it with fresh water and then mixing the resulting fluid with additives such as potassium acetate to impede the migration of salt into the hydrated zone around the clay plates, sometimes referred to as the "diffuse double layer." With time, however, the salts in salt water will slowly attack the bentonite and cause it to begin to flocculate and settle out of suspension. Therefore, in this application, careful observation of the slurry for signs of flocculation (attraction of many bentonite particles into clumps) should be made continuously, and the contractor should be prepared to exchange the used slurry for conditioned slurry as necessary.

Minerals other than bentonite are used in limited amounts under certain circumstances. The most common are the minerals attapulgite and sepiolite. Typically, these are used for drilling in permeable soils in saline environments at sites near the sources of the minerals (*e.g.*, Georgia, Florida, and Nevada), where transportation costs are relatively 1ow. Unlike bentonite, attapulgite and sepiolite are not hydrated by water and therefore do not tend to flocculate in saline environments. These minerals do not tend to stay in suspension as long as bentonite, and require very vigorous mixing and continual remixing to place and keep the clay in suspension. However, since hydration is not a factor, the slurries can be added to the borehole as soon as mixing is complete. They do not form solid filter cakes, as does bentonite, but they do tend to form relatively soft, thick zones of clay on the borehole wall, which are generally effective at controlling filtration and which appear to be relatively easy to scour off the sides of the borehole with the rising column of concrete. It should always be verified by testing or experience that the mineral selected for slurry is compatible with the groundwater chemistry, especially at sites with low pH or contamination.

Because of turbidity issues with bentonite slurry and the relative inability to remove bentonite once it is mixed, the disposal of bentonite can be a significant cost and/or environmental consideration in some areas.

5.4.3 Synthetic Drilling Fluid

In the last 20 years, synthetic (polymer) drilling fluids have replaced bentonite slurry on most drilled shaft applications in North America, although the prevalence varies locally. The use of polymer drilling materials worldwide has also increased dramatically. Polymers function in a different way than bentonite, with some advantages and some limitations as discussed below.

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. The appearance of the polymer fluid is that of a slippery, slimy, viscous liquid as is evident from the polymer fluid dripping off the tool in the photo in Figure 5-30. A scanning electron micro-photograph of a polymer slurry magnified to 800 times its actual size is shown in Figure 5-31(a). The polymeric strands form a three-dimensional lattice or web-like structure that can form a membrane (Figure 5-31(b)) on the excavation sidewall if a positive fluid head is maintained. This membrane can be noticeable in some cases when a drill tool excavates a clump of soil that has a sticky, wetted surface but appears to have little penetration of fluid into the mass.

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. Without a low-permeability filter cake, polymers may have a greater tendency to lose fluid into the soil around the excavation with time compared to bentonite. However, this lack of filter cake provides 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 effect on concrete/soil bond that is associated with bentonite filter cake buildup.

Figure 5-30 Synthetic (polymer) Drilling Fluid

a) Scanning Electron Micro-Photograph
Photo Courtesy of University of Missouri-Columbia

b) Polymer Membrane
Photo Courtesy of Ken Goodhue

Figure 5-31 Photographs of Polymer Fluid

Polymers are delivered in either liquid or dry granular form and are mixed and hydrated prior to introduction into the excavation (Figure 5-32). The amount of polymer required to prepare the slurry is generally much smaller compared with the quantity of bentonite clay to prepare a similar volume of bentonite slurry. The mixing includes agitation and circulation to disperse the polymer, but the shearing action that occurs with some types of pumps (beneficial to bentonite) can break down the long chain polymer molecules and is therefore avoided. For similar reasons, polymers are not typically used with circulation drilling or with hydromill equipment for diaphragm walls or barrette construction (see sections 4.2.3.6 and 4.2.4), because the continuous pumping tends to break down the polymer.

Figure 5-32 Mixing Polymer Based Drilling Fluid

Since the polymers add little weight to the fluid, the unit weight of the drilling fluid is not much greater than that of the water used to prepare it. Given the low unit weight, lack of filter cake and potential fluid loss, the positive fluid head is critically important to achieve a stabilizing effect on the excavation with polymer slurry.

The chemistry of polymer fluids is such that the fluid tends not to incorporate dispersive clays into the fluid and thereby reduces the tendency of native soil or rock particles to become part of the slurry. This effect can also help to preserve the integrity of the rock socket into clay-shale formations which may be prone to rapid weathering upon exposure in a borehole (Axtell et al., 2009).

Another notable difference compared to bentonite is the fact that the polymer fluids do not hold soils in suspension; consequently, settlement of even fine grained soils such as silt can occur after completion of the excavation if the slurry is not adequately cleaned. The de-sanding plant used for cleaning bentonite is not suitable for polymer because the polymer tends to clog the screens, and the shearing action of the equipment tends to break down the polymer. The typical method for cleaning a polymer is to add flocculating agents to help drop suspended solids out of suspension and then provide quiet time for the sediments in the fluid to settle out. A good practice is to fully exchange the drilling fluid with fresh slurry by pumping from the base of the excavation to holding tanks (Figure 5-33) where the sedimentation can take place.

After completion of the work, the polymers can be broken down with a de-activating agent (bleach works on most types of polymers), causing the suspended solids to drop out quite easily. This property provides one of the attractions with polymer slurry in that disposal can often be accomplished with relatively little cost or effort compared to bentonite.

Figure 5-33 Sedimentation Tanks for Polymer Drilling Fluid

A comparison of the polymer drilling fluids to bentonite suggests that there are advantages and limitations of each, as indicated in the table below.

Polymer	Bentonite
Easy to mix, less time to hydrate	Mixing, hydration more involved
Time required for de-sanding, removal of fines	De-sanding equipment, handling more efficient
No filter cake – greater fluid loss and less stabilization of the hole	Filter cake + weight improves stabilization of hole, especially in coarse granular soils
No filter cake – less detrimental impact on side resistance	Filter cake can affect side resistance; exposure time should be limited; additional preparation may be needed
Polymers can break down due to shearing, pumping, but easy to dispose	Generally more costly to dispose, but easier to reuse

5.4.4 Mineral/Polymer Blended Drilling Fluid

Blended slurries consist of mixtures of minerals (generally bentonite) and polymers. In some situations, blended slurries can potentially be designed and used in a manner that takes advantage of the beneficial characteristics of each. For example, the inclusion of polymers within a bentonite drilling fluid can be effective in minimizing the filter cake thickness and can also reduce the tendency of the fluid to incorporate native clays (and increase density, viscosity, etc.) during drilling.

The use of blended drilling fluids represents a specialty field that requires expertise beyond what is normally available on most drilled shaft projects, and there is relatively little experience in U.S. practice with blended slurries. Specifications developed for mineral slurries or commercially available polymer slurries likely will not be suitable for blended slurries. Blending is not recommended unless those involved have the knowledge and experience to determine appropriate specifications and quality control/quality assurance procedures for its use, given the site-specific ground conditions.

Blended bentonite and polymers are also available as packaged products that are marketed as "extended" bentonites. The polymer additive reduces the quantity of bentonite needed to produce a given amount of slurry, which is an economic consideration, since high-quality bentonite is becoming harder to find. However, since the properties of extended bentonites can be affected significantly by the type of polymer used, it is important for the end user (contractor) to work closely with the bentonite supplier to understand the composition and the behavior of the resulting slurry.

5.4.5 Quality Control and Inspection

Cleaning the excavation

Both the base of the excavation and the drilling fluid itself should be reasonably clean and free of debris. If excessive amounts of cuttings or other debris are trapped on the bottom of the hole, the base resistance of the completed drilled shaft could be affected by these compressible materials. Even if the base resistance is relatively unimportant for design, an excessive amount of debris could become mixed with the concrete during tremie placement, leading to possible defects in the concrete. If the fluid contained excessive suspended solids that could settle out during tremie placement, this material could also contaminate the concrete. So it is important that the fluid-filled excavation be cleaned prior to concrete placement.

It is important to understand that it is not physically possible or necessary to have perfect cleaning of the base of the excavation; a small amount of material left on the base typically has little or no consequence to the performance of the completed foundation. A typical specification (Chapter 14) requires that no more than three inches of sediment or loose or disturbed material may be present just prior to concrete placement to avoid concrete contamination, and that 50 percent or more of the shaft area should have no more than 1/2 inch where base resistance in rock or strong material is considered for design. Some agencies limit the maximum thickness to 1-1/2 inches for drilled shafts that rely on base resistance for a large portion of the required axial resistance.

It may be possible to remove debris simply by using a flat-bottomed cleanout bucket as shown in Figure 5-34, especially if the hole has had a quiet period to allow any suspended materials to settle out. Depending on the depth of the hole and type of drilling fluid, settlement of most suspended solids may occur overnight if the fluid is not agitated, and then a few passes of the cleanout bucket may successfully remove most materials. More photos and information on this type of tool are provided in Chapter 4.

Figure 5-34 Flat Bottomed Cleanout Buckets

Even after waiting for suspended solids to settle to the bottom, if many passes of a bucket are needed to remove the material this process may stir the sediments up again. A more effective tool for cleaning the fluid is a pump like the airlift or hydraulic pumps shown in Figure 5-35 and Figure 5-36, which lift fluid that is laden with sediment from the base of the excavation while the hole is replenished with clean fluid at the top. Airlift pumps work by injecting air into the bottom of the fluid-filled pipe, and the buoyancy within the pipe begins the circulation process removing fluid from within the drilled shaft excavation. The action of the hydraulically operation mechanical pump can be controlled more easily than an airlift; sometimes an airlift can pump so fast that it is a challenge to keep the hole recharged and avoid losing the positive head pressure that is essential to stability. A hydraulic pump can be operated at a speed more compatible with the recharge at the top of the hole.

Following completion of excavation and bottom cleaning operations, an inspection is performed to confirm that the base of the excavation has been cleaned sufficiently to meet the requirements of the project. Criteria typically specified for bottom cleanliness are noted in the Guide Specifications presented in Appendix D, and methods commonly used for inspection of bottom conditions are discussed in Chapter 15.

Figure 5-35 Airlift Pump for Cleaning Bottom and Pumping Slurry

Figure 5-36 Hydraulic Pump for Cleaning Bottom and Pumping Slurry

The photo in Figure 5-37 shows the base of a 6-ft diameter drilled shaft constructed under slurry that was exhumed as a part of a research project into drilled shaft concrete. This lowermost piece of the concrete was cut using a wire saw and stood upside down, so that the top of the concrete provides a casting in concrete of the bottom of the drilled shaft excavation; the pattern on the concrete represents the impression left by the cleanout bucket on the bottom of the hole after cleaning. This photo is evidence that the base of a drilled shaft constructed with slurry can be cleaned effectively by using the correct equipment and techniques.

Figure 5-37 Photo of the Base of an Exhumed Drilled Shaft, Cast Under Drilling Fluid

Sampling and testing the drilling fluid

Sampling and testing the drilling fluid helps to ensure that the characteristics of the fluid are within generally accepted guidelines and project specifications. This operation is most important just prior to concrete placement, but it is also important that the slurry properties be appropriate for maintaining stability during excavation. The slurry may be sampled for testing and evaluation using a device such as the one shown in the photo in Figure 5-38(a). Samples may be obtained throughout the fluid column, and tests of the fluid near the bottom are important because that's where the fluid is likely to have the most sediment in suspension.

The viscosity of the fluid is an important property for stability and to avoid fluid loss during excavation. Viscosity is not typically measured directly, but rather by using a simple standardized test to provide a measurement that reflects the fluid viscosity. The Marsh funnel shown in Figure 5-38(b) is a standard size funnel that is used to measure the time required for a certain volume of slurry to pass. The more viscous the fluid, the longer this will take. Water takes about 26 seconds for a quart to pass, and a typical time for bentonite drilling fluid is in the 30 to 45 second range. Many project specifications allow 28 to 50 seconds, but that can depend on the application. Higher viscosity would be better for stability of the excavation, but the filter cake for bentonite could be so thick as to be detrimental to the side resistance. Polymers are often used with higher viscosity, in the range of 32 to 135 seconds, partly because the lack of filter cake may require higher viscosity to limit fluid loss, and partly because the lack of filter cake eliminates the concern about detrimental effects from it.

a) Slurry Sampler
b) Marsh Funnel Test

Figure 5-38 Sampling and Testing of Drilling Fluids

Another simple test is the mud balance to measure unit weight of the fluid. The device and scale shown in Figure 5-39(a) is calibrated to indicate the unit weight for a specific volume of fluid held in the little cup on the right. Bentonite fluid with excessive density is likely to be too contaminated with soils for concrete placement, even though a heavy slurry may be beneficial for stability. Density is not normally an issue for polymer, which does not typically hold a lot of material in suspension.

a) Mud Balance for Density Testing
b) Sand Content Test

Figure 5-39 Testing of Drilling Fluids

Sand content, using a device as shown in Figure 5-39(b), gives a direct measure of the suspended particles, at least those that will not pass a #200 sieve. Although the sand content may vary during excavation, the upper limits prior to concrete placement of 4% for bentonite and 1% for polymer are typical guidelines that are routinely incorporated into project specifications. It may be necessary to reduce the sand content well below these limits for large diameter or deep drilled shafts because the extended time required for concrete placement presents greater exposure to potential sedimentation during this operation. For example, concrete placement in a 3-ft diameter shaft that is 40 ft deep may take only 15 to 20 minutes with relatively little time for settlement of suspended solids. However, concrete placement in an 8-ft diameter shaft that is 150 ft deep may take several hours, allowing more time for suspended solids to settle out during concrete placement. It is recommended that more restrictive sand content specifications be considered for any case in which concrete placement operations under slurry can potentially extend beyond two hours.

Hardness, as indicated by the pH, is important for the bentonite or polymer to work properly, and so this is normally checked at the beginning with the make-up water. pH is particularly important for polymers since the chemical reactions which cause the polymers to form is sensitive to the pH. Soda ash is typically used to increase the pH.

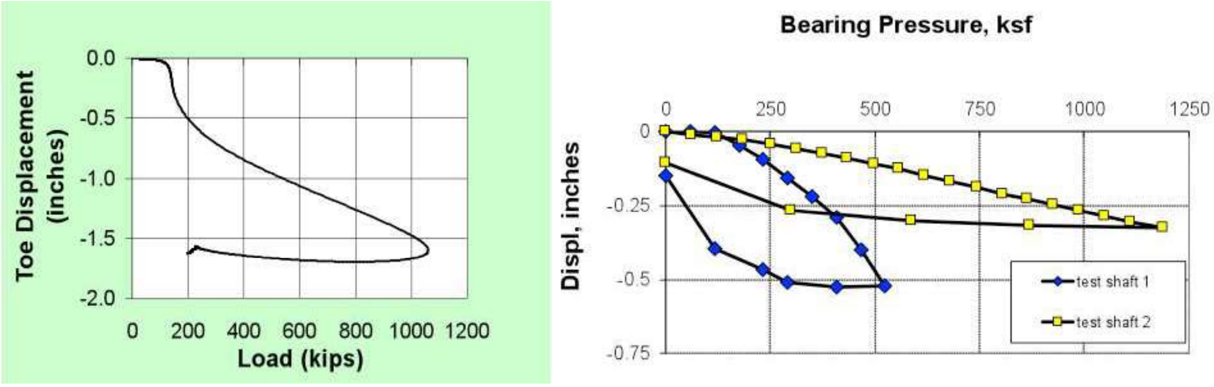
A device called a filter-press may be used for testing the tendency of the drilling fluid to form a filter cake. Although not a routine inspection test, this test provides a relative indication that is useful for adjusting the fluid properties so as to control the filter cake thickness with bentonite slurry. The device consists of a small slurry reservoir that is installed in a frame, a filtration device, a system for collecting and measuring a quantity of free water, and a pressure source. The test is performed by forcing slurry through a piece of filter paper under a pressure of 100 psi for a period of 30 minutes. The free water that is recovered is measured in cubic centimeters, and the thickness of the cake that is formed is measured to the nearest millimeter. Before measuring the cake thickness, any superficial slurry that is not part of the filter cake is washed away.

5.4.6 Effects of Drilling Fluid on Axial Resistance

The most important influence of drilling fluid on axial resistance is a positive one, by keeping a stable hole and maintaining the integrity of the bearing materials. The excavation shown in Figure 5-40 obviously needed some support, and the caving that is visible might have been avoided with the effective use of either drilling fluids or casing. If seepage into the hole occurs, even with casing, debris can flow into the excavation and be deposited onto the bottom. Uncontrolled seepage into the hole is also detrimental to concrete quality, as described previously.

Figure 5-40 Caving in an Unsupported Drilled Shaft Excavation

With the practices described in the previous section, it is often actually easier to clean the bottom of a drilled shaft under fluid than it is to clean a "dry" excavation. Use of proper drilling fluid with good base cleaning operations can avoid a "soft toe" effect that is evident in the load test results presented in the plot in Figure 5-41(a). This little "duck tail" at the beginning suggests that the bottom didn't provide much resistance on initial loading and then became stiffer after about 1/2 inch of displacement. The bottom debris effectively required some additional larger displacement to mobilize the base resistance. The plots in Figure 5-41(b) are from two load tests that illustrate the behavior of drilled shafts on rock at a site near Atlanta with a clean base. High base resistance is mobilized at very small displacements. Test shaft 1 is on weathered rock and test shaft 2 is on hard rock, but both exhibit very stiff initial resistance.



a) Load Test Results Indicating Soft Base b) Load Test Results Indicating Clean Base

Figure 5-41 Field Load Test Results Showing Effect of Base Cleanliness

Previous discussion has alluded to the fact that an excessive build-up of bentonite filter cake at the borehole wall could be detrimental to side resistance. There is increasing evidence that the unit side resistance of drilled shafts constructed in granular soil using polymer fluids is superior to that of drilled shafts constructed using bentonite, even with accepted practices. The plot in Figure 5-42 shows data from one of the earlier full scale comparison studies, which has been corroborated by other studies that show similar evidence. This effect would not be expected and has not been observed in low-permeability cohesive soils, likely because the lack of fluid loss does not result in a filter cake deposit at the borehole wall. It is also of interest to note that the side resistance in either case appears to be mobilized at small displacements, but exhibits ductile behavior out to nearly 2 inches of displacement. It is reassuring to note that the side resistance does not typically drop away in a brittle manner; however, the magnitude is clearly influenced by the construction means and methods.

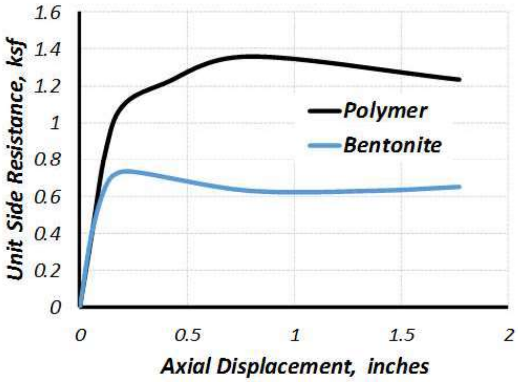


Figure 5-42 Field Load Test Comparison of Side Resistance with Different Drilling Fluids (Brown, 2002)

Another potential benefit with polymer slurry materials has been identified in recent years, and that is the tendency of the polymer to reduce the amount of “wetting” and degradation of shales at the borehole wall. Many geotechnical engineers have experience with the rapid degradation of shale exposures in road cuts, and the same thing can happen in a drilled shaft excavation. The result of degradable shale could be that the side resistance of a rock socket in such material would be affected by the degraded shale rather than the stronger intact material. Slake durability tests suggest that the polymers can reduce the tendency of some shales to degrade quickly in the presence of water (Axtell et al., 2009). Anecdotal evidence from several load tests on projects in these materials support the conclusion that polymers can be beneficial in preserving the integrity of shale bedrock bearing materials.

5.5 SUMMARY

Casing provides a variety of functions in the construction of drilled shafts, ranging from short surface casing for protecting the top of the shaft excavation, to temporary casing for supporting the hole within unstable or water bearing soil layers during shaft excavation, to permanent applications where the casing may serve as a concrete form through water or as a structural component of the completed drilled shaft, to note just a few. Whether temporary or permanent, however, the method used for installation of the casing, and for removal of temporary casing, can have a significant influence on the performance of the drilled shaft.

Drilling fluids provide a means to enhance stability during drilled shaft construction. It is therefore critically important for designers and other construction professionals to recognize and understand this technology and the role it provides in drilled shaft construction. The range of fluids can vary depending upon the application, but a consistent theme is the need to maintain a positive head pressure within the excavation at all times during excavation and concrete placement. Good practices, combined with careful quality control and quality assurance provisions, are needed to ensure that the desired foundation performance is achieved.

The information in this chapter, provides a general understanding of the construction techniques available to maintain hole stability and to facilitate installation of drilled shafts in difficult ground and groundwater conditions. This chapter provided an overview of the various applications for casings and liners, identified the common methods and equipment used for casing installation and extraction, and discussed potential effects of casings on the axial and lateral resistance of the completed shaft. Experience and research have demonstrated that drilling fluids made from both bentonite or polymers can provide a highly effective means for constructing quality drilled shafts when used properly. Factors that lead to successful performance and potential adverse impacts on performance are identified in this chapter.