CHAPTER 4
TOOLS AND EQUIPMENT

4.1 INTRODUCTION

Most contracts for drilled shaft construction establish that the means and methods are the contractor's responsibility. Therefore, the final choice of the types of drilling rigs and drilling tools that are to be used to make excavations for drilled shafts on a specific project are almost always chosen by the contractor. These choices are made based upon:

- The subsurface conditions that are encountered as a part of the site investigation and presented to bidders via the contract documents. As discussed in Chapters 2 and 3, the geotechnical investigation is essential to appropriately characterize the existing subsurface conditions for the purpose of construction planning.
- Additional indications of subsurface conditions that may be revealed as a part of a site visit by the prospective bidder. Therefore, it is important that the site be accessible to potential contractors. In some cases it may be warranted to perform a pre-bid exploratory shaft excavation so that bidders have an opportunity to directly observe conditions in a full size shaft excavation.
- The contractor's personal experience in similar geologic conditions.
- The contractor's available equipment and experience with that equipment.
- The experiences of other contractors in the local area on similar projects and in similar geology, provided this information is available to the contractor. Where a transportation agency has documented information available on previous drilled shaft projects, this information can be extremely valuable in terms of minimizing uncertainty and contingency costs in the bid, and in avoiding potential claims. There is also great value in post-construction documentation of "lessons learned" for future use by transportation agencies.

The choice of rigs and tools is critical to the success of a project. Sometimes an apparently minor change in a drilling tool can change the rate of excavation dramatically. Because of the importance of selecting proper tools and equipment, it is critical for both engineers and inspectors to understand the general types of rigs and tools available in the United States. Although the burden of risk in the choice of specific tools and equipment is typically the contractor's responsibility, the list above underscores the importance of engineers and owners to understand the types and capabilities of tools and equipment, and the information needed by the contractor to make an informed decision regarding their selection.

This chapter provides a general description of the drilling machines and tools used for excavation of drilled shafts.

4.2 DRILLING MACHINES

The machines used for drilling shaft excavation have evolved over the years from primitive mechanical systems (e.g., Figure 4-1 from the 1930's) supplemented by heavy reliance on manual excavation to sophisticated and powerful hydraulic machines with extensive in-cab instrumentation and controls. This section provides an overview of the broad range of drilling machines available in current (2018) U.S. practice.

4.2.1 Overview of Rotary Systems

Most excavations for drilled shafts in the United States are made by some type of rotary-drilling machine. The machines vary greatly in size and in design, as well as by the type of machine on which the drilling rig is mounted. The machine transmits force from the power unit through the rotary to a kelly bar to the tool attached to the end of the kelly, as illustrated on Figure 4-2.

Figure 4-1 An Early Drilled Shaft Machine and Crew

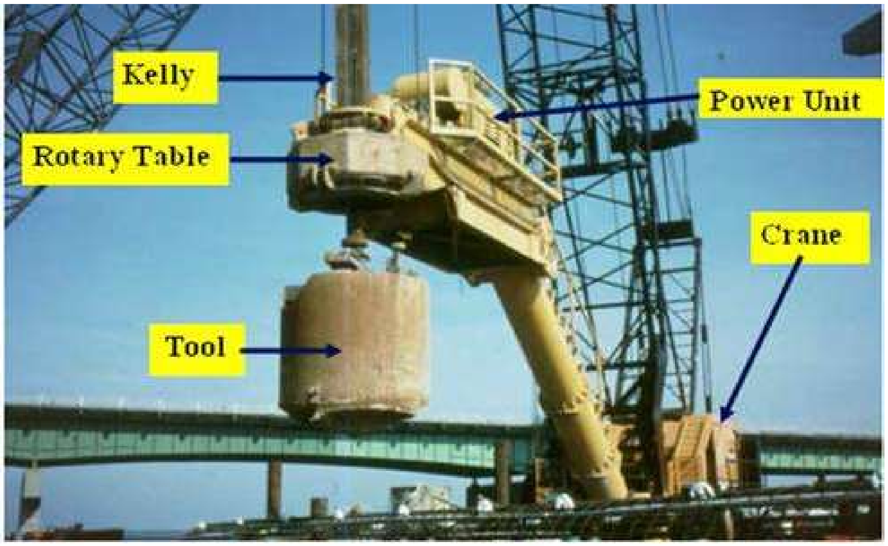

Figure 4-2 Drill Rig Terminology

The capacity of a drilling rig is often expressed in terms of the maximum torque that can be delivered to the drilling tools and the "crowd" or downward force that can be applied. Other factors can have great impact on the efficiency of the rig in making an excavation, particularly the type and details of the drilling tools, but the torque and crowd are important factors affecting the drilling rate.

Torque and crowd are transmitted from the drilling rig to the drilling tool by means of a drive shaft of steel, known as the kelly bar, or simply the "kelly." The drilling tool is mounted on the bottom of the kelly. Kellys are usually either round or square in cross section, and may be composed of a simple single piece (up to about 60 ft long) or may telescope using multiple inner sections to extend the depth to which the kelly can reach. Square kelly bars often require a worker to insert a pin to lock the outer bar to the inner telescoping kelly piece, whereas round kellys often include an internal locking mechanism. In some rigs, the weight of the kelly and the tool provides the crowd. In others, hydraulic or mechanical devices are positioned to add additional downward force during drilling.

Specific details relating to the capabilities of individual drilling machines are readily available on the websites of equipment manufacturers. A contractor will normally provide these details as a part of the drilled shaft installation plan for a specific project.

4.2.2 Mechanical vs. Hydraulic Systems

The drilling machines used in the drilled shaft industry are typically powered by either mechanical or hydraulic systems. Examples of each type are shown in Figure 4-3.

A typical mechanical drive system delivers power to the rotary via a direct mechanical drive shaft or sometimes a right angle drive from a multiple speed transmission. This type of system has a long history of use, is mechanically simple, and is relatively lightweight. Most lightweight truck-mounted drill rigs use direct drive mechanical systems. Large crane attachments, as shown in Figure 4-2, are also direct drive mechanical systems.

Recent years have seen an increase in the use of hydraulic systems to deliver force to the rotary table. The potential high pressures available in modern hydraulic systems can provide rigs with a higher torque range, and the use of the hydraulic drive allows the rotary to move up and down the mast rather than restrained to a location fixed by the drive system. The movable rotary provides versatility in that the rotary can elevate above casing and even be used to install casing. Hydraulic rigs are sometimes heavier and more expensive than a similar size mechanical machine.

Mechanical drive systems often apply crowd through a pull-down system applied to a drive bar atop the kelly, in which the drive bar is guided within the leads as it travels up and down the mast. Although the same crowd system can be applied to a hydraulic driven kelly, more often the crowd in a hydraulic system is applied through the rotary.

4.2.3 Methods of Mounting Drilling Machine

The drilling machine must be mounted on some type of carrier in order to drill and move about the site. The type of carrier has an effect on the versatility of the machine and the efficiency of the overall operation. Drill rigs may be mounted on trucks, crawlers, excavators, cranes, or may even be designed to operate directly as a top drive unit mounted onto a casing. The following sections provide a brief description of drill rigs by methods of mounting the machine.

Figure 4-3 Mechanical (left) and Hydraulic (right) Powered Drilling Machines

4.2.3.1 Truck Mounted Drilling Machines

Mobility is the greatest advantage of truck-mounted drilling machines, which can range widely in size and drilling capabilities. As shown in Figure 4-4, truck-mounted rigs can range from small, extremely mobile rigs most suited to small holes to large, heavy rigs capable of drilling rock. If the site is accessible to rubber-tired vehicles and conditions are favorable for drilling with truck-mounted rigs, construction of drilled shafts can be accomplished very efficiently with these machines. With the mast or derrick stored in a horizontal position, lighter units can move readily along a roadway. The truck can move to location, erect the derrick, activate hydraulic rams to level the rotary table, and begin drilling within a few minutes of reaching the drilled shaft location.

Truck-mounted rigs are normally mechanically-driven with a fixed rotary, and therefore may have limited capability to reach over tall casing or to handle tall drilling tools. The space below the rotary table can be increased by placing the rig on a ramped platform, but this procedure is obviously slow and expensive and would be used only in unusual circumstances. However, some truck-mounts are now supplied with a hydraulic sliding rotary which can overcome many of the limitations of older truck-mounted rigs.

While the truck-mounted unit has a secondary line with some lifting capacity, that capability is necessarily small because of the limited size of the derrick. The drilling tools can be lifted for attachment to and detachment from the kelly, but, if a rebar cage, tremie or casing must be handled, a service crane is usually necessary. Some truck rigs can handle light rebar cages and tremies of limited length.

Figure 4-4 Truck Mounted Drilling Rigs

4.2.3.2 Crane Mounted Drilling Machines

A power unit, rotary table, and kelly can be mounted separately on a crane of the contractor's choice, as shown in Figure 4-5. Crane mounted drill rigs can have substantial capabilities and versatility on a bridge project, especially over water. The crane-mounted machine is obviously less mobile than a truck unit. Mobilization to the jobsite generally requires “rigging” or assembly of the equipment with significant cost and effort.

Power units of various sizes can be utilized to supply large torque at slow rotational speeds to the drilling tool. Usually, the downward force on the tool is due to the dead weight of the drill string, but the dead weight can be increased by use of heavy drill pipe (drill collars), "doughnuts," or a heavy cylinder. Special rigging is available for crane machines that will apply a crowd for drilling in hard rock. The cross-sectional area of the kelly can be increased to accommodate high crowds.

The framework, or "bridge," that is used to support the power unit and rotary table can vary widely. The rotary table may be positioned 75 ft or more from the base of the boom of a crane by using an extended mount. The ability to reach to access the hole from a distance makes crane mounted machines very attractive in marine construction when working from a barge or work trestle. The bridge for the drilling unit can also be constructed in such a way that a tool of almost any height can fit beneath the rotary table. Therefore, crane-mounted units with high bridges can be used to work casing into the ground while drilling, or for accommodating tall drilling tools.

A service crane, or the drilling crane itself, is used on the construction site for handling rebar cages, tremies, concrete buckets and casings. The secondary lift line on the drilling crane can be used for common lifting by tilting the derrick forward and away from the rotary table, thus making the crane-mounted drilling unit a highly versatile tool.

Figure 4-5 Crane Mounted Drilling Rig

4.2.3.3 Crawler Mounted Drilling Machines

Crawler mounted drilling machines may be less mobile than truck mounted equipment for accessible sites, but can provide excellent mobility on the jobsite. Compared to a crane mounted rig, the drilling equipment is usually a permanent fixture on the crawler with a fixed mast serving as the lead for the rotary or kelly guide system. The crawler mount is the most common system used for hydraulic powered rigs, although it is also a popular system for conventional mechanical rigs; both types can be mounted on crawler equipment.

Lightweight crawler mounted drilling machines can be extremely versatile for work on difficult to access sites for applications such as slope stabilization, sound wall foundations, and foundations for signs, towers, or transmission lines. An example of a mobile crawler mounted drill rig is shown in Figure 4-6.

4.2.3.4 Excavator Mounted Drilling Machines

Another type of crawler mount that has advantages for some special applications is the placement of the drilling machine on the arm of an excavator, as shown in Figure 4-7. These rigs are almost always hydraulic, utilizing the hydraulic system common on an excavator. The advantage of such a mount is that the rig can reach a difficult to access location with low headroom or with limited access immediately adjacent to the hole. Low headroom equipment is often advantageous for applications such as a sound wall where utility lines are overhead, or when installing shafts below or very near an existing bridge structure. The use of low headroom equipment has obvious limitations in terms of the depth and size of hole that can be drilled efficiently. Reduced productivity in drilling under low overhead conditions will affect costs.

Figure 4-6 Crawler Mounted Drilling Rig

Figure 4-7 Excavator Mounted Drilling Machines for Restricted Overhead Conditions

4.2.3.5 Oscillator/Rotator Systems

Oscillator and rotator systems are hydraulic-driven tools for advancing and extracting casing. The casing often is a segmental pipe with bolted joints. The oscillator or rotator grips the casing with powerful hydraulic-driven jaws and twists the pipe while other hydraulic cylinders apply upward or downward force. An oscillator twists back and forth, while a rotator (a more expensive machine) can rotate the casing through a full 360° when advancing casing. An example of an oscillator with segmental casing is shown in Figure 4-8. A rotator is shown installing permanent casing into rock in Figure 4-9.

The tremendous twisting force of these powerful machines must be resisted by a reaction system. The oscillator in Figure 4-8 is resisted by an arm extending to a large crane, and this crane uses dead weight to provide friction of the tracks on the pile-supported work trestle extending into the river. The vertical force acting to push the casing down is normally restricted to the dead weight of the casing plus machine, but the vertical force to pull the casing out (which may be much larger, after the casing is embedded into the soil and may be partially or completely filled with concrete) must be resisted by the work trestle system or the bearing capacity of the ground surface if the machine is on land. The axial and torque capacity of the entire reaction system must be carefully designed (normally by the contractor) to be sufficient for the machine to work efficiently.

Excavation within the casing is often made using a clam or hammergrab, although a rotary drilling machine can be mounted on the casing to operate as a top-drive unit. It is also possible to excavate sand within the casing using a dredge pump or airlift system. Care must be used so as not to remove the soil below the casing and, as with any type of circulation drilling (discussed in the following section), fluid must be pumped into the casing sufficiently fast as to maintain a positive head of water. The oscillator/rotator systems are often used with a fully cased hole, although the drilled shaft excavation can be extended into rock or stable soils below the bottom of the casing.

Figure 4-8 Oscillator Machine

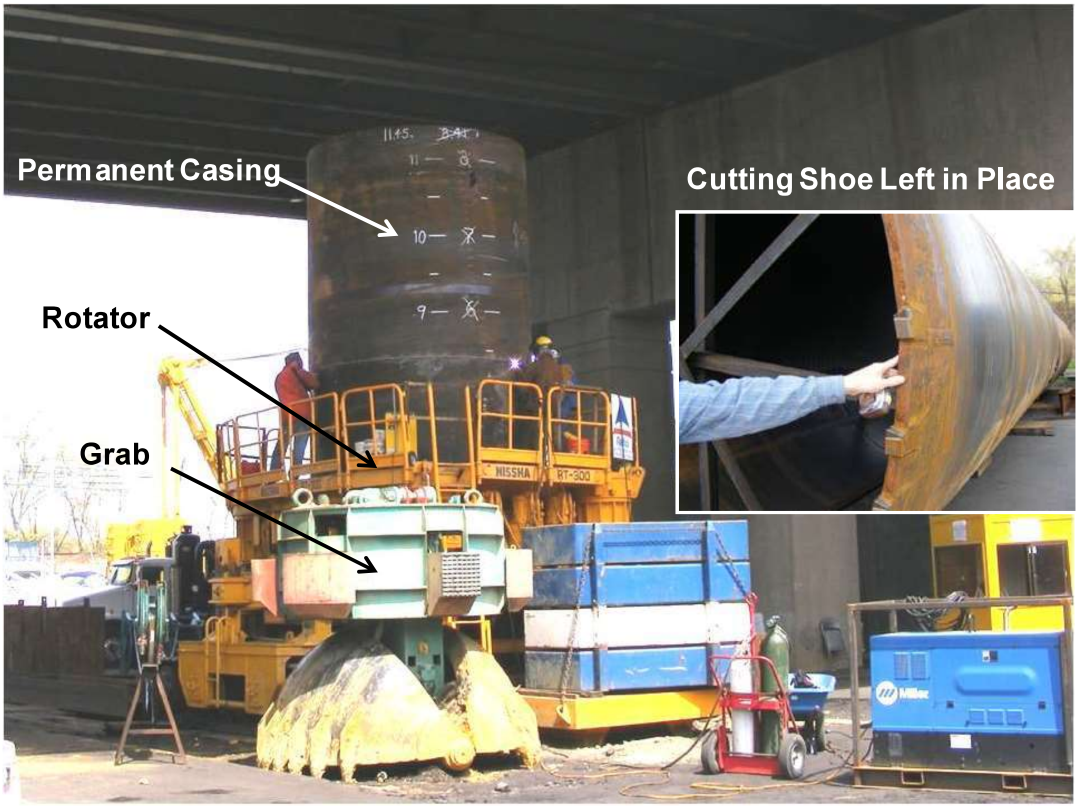

Figure 4-9 Rotator Machine

4.2.3.6 Casing Mounted Top-Drive Systems

Casing mounted top-drive systems are used with reverse circulation drilling, since the rotary machine is mounted on the casing itself. The basic principle of reverse circulation drilling uses a full-face rotary cutting head to break up the soil or rock, and an airlift system is used to pump the drilling fluid containing spoil away from the cutting surface. The drilling fluid is then circulated through a desander and/or settling basin, and returned to the shaft excavation. Slurry or water may be used as the drilling fluid, depending upon the stability of the hole and the length of casing. An example of a top-drive system used for the Fore River Bridge in Massachusetts is shown in the photos of Figure 4-10. The photo on the right shows the machine during operation with the circulation system in place; cuttings are lifted from the bottom of the excavation through the central pipe, through the swivel at the top of the drill string, and through the discharge hose to a spoil barge. As the hole is advanced, short sections of drill pipe are added. The photo at left shows the top drive system with the drill being inserted. The cutting head and lowermost portion of the drill string is shown on Figure 4-11.

The top-drive system mounted on the casing must react against the casing during drilling, so the casing must be sufficiently embedded into firm soil to provide a stable platform on which the machine can work. The excavation below the casing must be stable not only for support of the casing, but also to avoid the collapse of soil or rock into the hole above the cutting head that could make the cutting head difficult or impossible to retrieve. The casing may be installed using a vibratory or impact hammer, or using an oscillator/rotator.

Figure 4-10 Top-Drive Reverse Circulation Drill

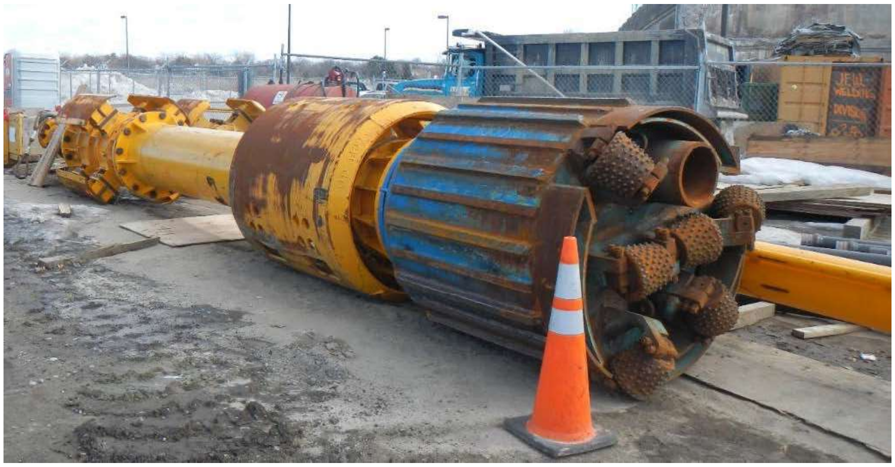

Figure 4-11 Reverse Circulation Cutting Heads for Top-Drive Drill

4.2.4 Other Excavation Systems

Although the vast majority of drilled shafts are excavated using rotary machines, other systems may be employed to advance an excavation into the subsurface for a wall or foundation. These include manual techniques and excavation using grab tools or slurry wall equipment.

Manual excavation (Figure 4-12), i.e., vertical mining, has been employed for many years and is still a viable technology in some circumstances, such as for underpinning of existing structures. Excavation using workers below ground obviously requires great attention to safety considerations and is usually quite expensive compared with alternatives. Manual excavation is usually only considered where mechanized equipment is ineffective or where the location is inaccessible, such as to remove a boulder or rock or in a confined space where a heavy machine cannot be positioned. For dry excavations into very strong rock, there may be circumstances where hand excavation might sometimes be employed, for example when it is necessary to penetrate steeply sloping rock, as in a formation of pinnacled limestone, where ordinary drilling tools cannot make a purchase into the rock surface.

Figure 4-12 Manual Excavation in Rock

Safety precautions must be strictly enforced when hand mining is employed. The overburden soil must be restrained against collapse, the water table must be lowered if necessary, and fresh air must be circulated to the bottom of the hole.

Other non-rotary excavation techniques may include the use of a grab or clam or hydromill, as in the construction of rectangular diaphragm wall panels. When used as a foundation, an individual panel is often referred to as a "barrette." These panels can be efficiently oriented to resist large horizontal shear and overturning forces in addition to axial loads, and can even be post-grouted to enhance capacity. The use and testing of barrette foundations in Hong Kong is summarized by Ng and Lei (2003). A barrette is typically excavated under mineral slurry to maintain stability of the excavation.

Photos of a clam system are shown in Figure 4-13; these may have a hydraulically controlled guide system to maintain alignment. Photos of a hydromill (or hydrofraise, as it is known in Europe) are illustrated in Figure 4-14. A hydromill or "cutter" is typically used to excavate rock, and cuts the rock with two counter-rotating wheels at the base of the machine. The excavated materials are lifted from the cutting face using an airlift or pump to circulate the slurry similar to the reverse circulation drill described in Section 4.2.3.6.

4.2.5 Summary

This section outlines what may appear to be a dizzying array of choices of machines for excavating a drilled shaft. The variety of machines available to contractors reflects the maturation of the foundation drilling industry and the development of specialized equipment to optimize productivity for particular applications. The range of mounting systems for the drilling machines, and torque and crowd capabilities of modern equipment has extended the size, depth, and potential applications of drilled shaft foundations far beyond those considered feasible a few decades ago. Still, the most common method used to excavate the majority of drilled foundations for transportation structures is that of a simple rotary drilling machine turning a tool at the bottom of a hole and removing soil or rock one auger or bucketful at a time. Although the capabilities of the drilling machine are critical to the ability of the constructor to complete the drilled shaft excavation to the size and depth required, the choice of drilling tools is often as (or more) important to the productivity of the excavation process. Drilling tools are discussed in the following section.

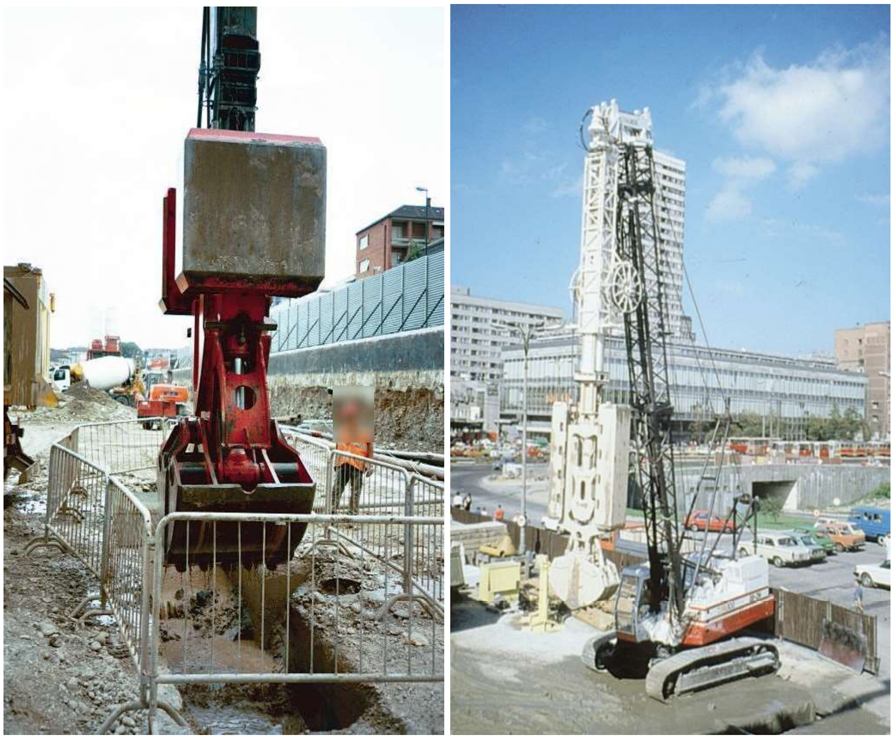

Figure 4-13 Excavation of a Diaphragm Wall or Barrette Using a Clam

Figure 4-14 Excavation of a Diaphragm Wall or Barrette Using a Hydromill

4.3 TOOLS FOR EXCAVATION

4.3.1 Rotary Tools

The tool selected for rotary drilling may be any one of several types, depending on the type and physical properties of soil or rock to be excavated. Rotary tools described in this section include augers, buckets, coring barrels, full faced rotary rock tools, and other specialized rotary tools for drilling soil and rock The tools for rotary drilling are typically available in sizes that vary in 6 inch increments up to approximately 10 ft in diameter. Larger sizes are available for special cases.

Often, small details in the design of a tool can make a huge difference in effectiveness. For example, it is necessary that the lower portion of the tool cut a hole slightly larger than the upper part of the tool to prevent binding and excessive friction. It would not be unusual for one driller to reach refusal with a particular tool while another driller could make good progress with only a slight adjustment to the same tool. Different contractors and drillers will select different tools for a particular task and in many instances will have their own particular way of setting up and operating the tool. Important details in apparently similar tools may vary, and it is not possible to describe all "standard" tools that are in use in the industry.

The following sections give brief descriptions of some of the common tools used in rotary drilling.

4.3.1.1 Augers

This type of drilling tool can be used to drill a hole in a variety of soil and rock types and conditions. It is most effective in soils that have some degree of cohesion, and rock with low to moderate strength and hardness. The auger is equipped with a cutting edge that during rotation breaks the soil or rips the rock, after which the cuttings travel up the flights. The auger is then withdrawn from the hole, bringing the cuttings with it, and emptied by spinning. Difficulties can be encountered when drilling in cohesionless sands where soil slides off the auger flights, and in some cohesive soils where the tool can become clogged.

Augers for drilling soil and rock vary significantly depending upon the type of material to be excavated. The following sections describe various types of augers used in foundation drilling.

4.3.1.1.1 Earth Augers

Earth augers may have a single or double cutting surface, as shown in Figures 4-15 and 4-16, respectively, and many have a central point or "stinger" that prevents the auger from wobbling. Double-flight augers are usually used for excavating stronger geomaterials than are excavated with single-flight augers. Some augers may be true double flight augers, as on the right of Figure 4-16, and some may have a “dummy flight” to provide a double cutting surface but feed the cuttings into a single auger flight. The stinger for a single-flight auger is typically more substantial than for an auger with a double cutting surface because the single-flight auger must sustain a greater unbalanced moment during cutting. Double flight augers are generally preferred for large diameter holes (Figure 4-17) so that the cutting resistance on the base of the tool is more evenly balanced. Some contractors have found that double-flight augers without stingers can be used efficiently.

The flighting for augers must be carefully designed so that the material that is cut can move up the auger without undue resistance. Some contractors have found that augers with a slight cup shape are more effective at holding soils when drilling under slurry than standard non-cupped augers. The number and pitch of the flights can vary widely. The type of auger, single-flight or double-flight, cupping, and the number and pitch of flights will be selected after taking into account the nature of the soil to be excavated. The length of the auger affects the amount of material that may be excavated in one pass, and the maximum length may be limited by the torque and/or lifting capability of the drilling machine. Longer augers also tend to drill straighter holes, but are heavier to hoist.

The cutting face on most augers is such that a roughly flat base in the borehole results (that is, the cutting face is perpendicular to the axis of the tool). The teeth in Figures 4-15 and 5-16 are flat-nosed for excavating soil or decomposed rock, whereas the rounded teeth in Figure 4-17 are for ripping harder material. The shape and pitch of flat-nosed teeth can be varied; modifying the pitch on auger teeth by a few degrees can make a significant difference in the rate at which soil or rock can be excavated, and the contractor may have to experiment with the pitch and type of teeth on a project before reaching optimum drilling conditions.

Figure 4-15 Single Flight Earth Augers

Figure 4-16 Double Flight Earth Augers

Figure 4-17 Large Diameter Auger with Double Cutting Edge

An important detail, particularly in soils or rock containing or derived from clay, is that softened soil or degraded rock is often smeared on the sides of otherwise dry boreholes by augers as the cuttings are being brought to the surface in the flights of the auger. This smeared material is most troublesome when some free water exists in the borehole, either through seeps from the formation being drilled or from water that is introduced by the contractor to make the cuttings sticky for facilitating lifting. Soil smear can significantly reduce the side resistance of drilled shafts, particularly in rock sockets. A simple way to remove such smear is to reposition the outermost teeth on the auger so that they face to the outside, instead of downward, and to insert the auger and rotate it to scrape the smeared material off the side of the borehole prior to final cleanout and concreting.

Care must be exercised in inserting and extracting augers from columns of drilling fluid, as the fluid is prone to development of positive (insertion) and negative (extraction) pressures that can destabilize the borehole. The addition of teeth on the side of the auger to excavate a hole larger than the size of the tool can be beneficial in allowing slurry to pass. The tool may also be equipped with one or more slurry bypass ports; the tool shown in the foreground of Figure 4-18 incorporates a slurry bypass sleeve around the kelly connection.

Cobbles or small boulders can sometimes be excavated by conventional augers. Modified single-helix augers (Figure 4-19), designed with a taper and sometimes with a calyx bucket mounted on the top of the auger, called "boulder rooters," can often be more successful at extracting small boulders than standard digging augers. The extraction of a large boulder or rock fragment can cause considerable difficulty, however. If a boulder is solidly embedded, it can be cored. When boulders are loosely embedded in soil, coring may be ineffective. The removal of such boulders may require that the boulders be broken by impact or even by hand. A boulder can sometimes be lifted from the excavation with a grab, or by cable after a rock bolt has been attached.

Figure 4-18 Auger with Slurry Bypass

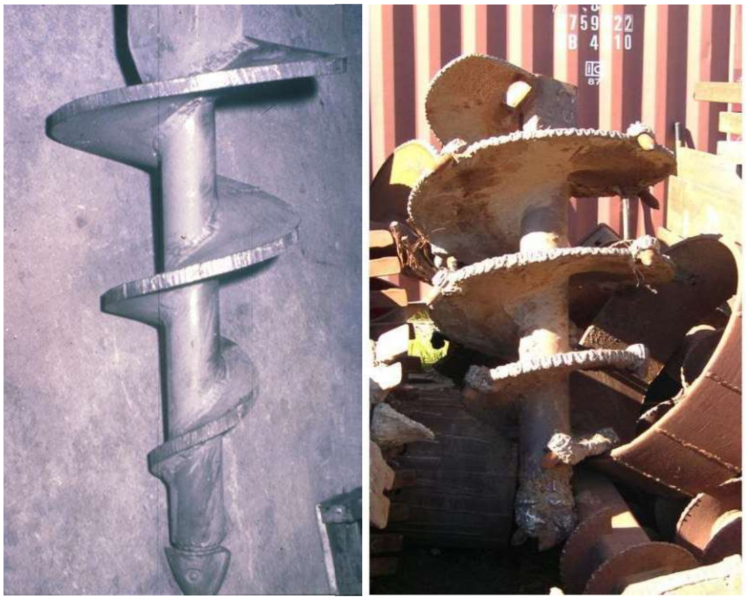

Figure 4-19 Boulder Rooters

4.3.1.1.2 Rock Augers

A flight auger specially designed for rock can be used to drill relatively soft rock (hard shale, sandstone, soft limestone, decomposed rock). Hard-surfaced, conical teeth, usually made of tungsten carbide, are used with the rock auger. Rock augers are often of the double-helix type. Three different rock augers are shown in Figure 4-20. As may be seen in the figure, the thickness of the metal used in making the flights is more substantial than that used in making augers for excavating soil. The geometry and pitch of the teeth are important details in the success of the excavation process, and the orientation of the teeth on a rock auger is usually designed to promote chipping of rock fragments. Rock augers can also be tapered, as shown in Figure 4-20.

Some contractors may choose to make pilot holes in rock with a tapered auger of a diameter smaller than (perhaps one-half of) that of the borehole. Then, the hole is excavated to its final, nominal diameter with a larger diameter, flat-bottom rock auger or with a core barrel. The stress relief afforded by pilot-hole drilling often makes the final excavation proceed much more easily than it would had the pilot hole not been made. It should be noted that tapered rock augers will not produce a flat-bottomed borehole, and an unlevel base in the borehole can be more difficult to clean and to produce a sound bearing surface.

Figure 4-20 Rock Augers

4.3.1.2 Drilling Buckets

Drilling buckets are used mainly in soil formations, as they are not effective in excavating rock. Soil is forced by the rotary digging action to enter the bucket through the two openings (slots) in the bottom; flaps inside the bucket prevent the soil from falling out through the slots. A typical drilling bucket is shown in Figure 4-21. After obtaining a load of soil, the tool is withdrawn from the hole, and the hinged bottom of the bucket is opened to empty the spoil. Drilling buckets are particularly efficient in granular soils, where an open-helix auger cannot bring the soils out.

They are also effective in excavating soils under drilling slurries, where soils tend to "slide off" of open helix augers. When used to excavate soil under slurry, the drilling bucket should have channels through which the slurry can freely pass without building up excess positive or negative pressures in the slurry column below the tool. It is often easier to provide such pressure relief on drilling buckets than on open-helix augers.

The cutting teeth on the buckets in Figure 4-21 are flat-nosed. These teeth effectively "gouge" the soil out of the formation. If layers of cemented soil or rock are known to exist within the soil matrix, conical, or "ripping," teeth might be substituted for one of the rows of flat-nosed teeth to facilitate drilling through alternating layers of soil and rock without changing drilling tools.

Figure 4-21 Typical Drilling Buckets

Drilling buckets are generally not appropriate for cleaning the bases of boreholes. Other buckets are designed to clean the base when there is water or drilling slurry in the hole (Figure 4-22). These are known as "muck buckets" or "clean-out buckets." Clean-out buckets have cutting blades, rather than teeth, to achieve more effective removal of cuttings and a more uniform bottom surface. The operation of the closure flaps on the clean-out bucket, or steel plates that serve the same purpose as flaps, are critical for proper operation of the clean-out bucket. If such flaps or plates do not close tightly and allow soil to fall out of the bucket, the base cleaning operation will not be successful. As with drilling buckets, clean-out buckets should be equipped with channels for pressure relief if they are used to clean boreholes under slurry.

Figure 4-22 Clean-out Buckets

4.3.1.3 Core Barrels

If augers are ineffective in excavating rock (for example, the rock is too hard), most contractors would next attempt to excavate the rock with a core barrel. Coring can be more effective in loading the individual cutting bits since the load is distributed from the crowd to the perimeter rather than to the entire face of the hole. Ideally, the tube cores into the rock until a discontinuity is reached and the core breaks off. The section of rock contained in the tube, or "core," is held in place by friction from the cuttings and is brought to the surface by simply lifting the core barrel. The core is then deposited on the surface by shaking or hammering the core barrel, or occasionally by using a chisel to split the core within the core barrel to allow it to drop out.

The simplest form of core barrel is a single, cylindrical steel tube with hard metal teeth at the bottom edge to cut into the rock, as illustrated in Figure 4-23. These simple core barrels have no direct means to remove rock chips from the cutting surface. The tools in these photos include a variety of cutting teeth positioned in a staggered pattern designed to avoid tracking in the same groove and to cut a hole slightly larger than the tool. The chisel teeth shown at bottom left would be used in soft rock, while the conical points shown at bottom right would be used in somewhat harder material. The “button” teeth shown at center right are used to cut harder rock where the conical points are prone to breaking off. Note also that the oscillator/rotator casing is a type of core barrel which commonly employs the button teeth, as shown in the top most photos.

If the rock is hard and a significant penetration into the rock is required, a double walled core barrel may be more effective. Double walled coring tools are more expensive and sophisticated, and can incorporate roller bits as well as teeth. Some examples are shown in Figure 4-24. The cuttings are removed by circulation of air if a dry hole is being excavated, or by circulation of water in a wet hole. The double wall provides a space through which the drilling fluid is pumped to the cutting surface. Double-walled core barrels are generally capable of extracting longer cores than single-walled core barrels, which constantly twist and fracture the rock without the provision of fluid to remove cuttings.

Figure 4-23 Single Wall Core Barrels

Figure 4-24 Double Wall Core Barrels

One of the problems with the use of the core barrel is to loosen and recover the core (Figure 4-25) after the core barrel has penetrated a few feet. Various techniques can be used for such a purpose. If the core breaks at a horizontal seam in the rock, drillers may be able to lift the core directly or by a rapid turning of the tool. Note the rock core contained within the barrel in the photo at bottom left of Figure 4-25. The photo at bottom right shows a hydraulically operated device for grabbing a core for extraction. When the core does not come up with the barrel, a chisel (wedge-shaped tool) can be lowered and driven into the annular space cut by the core barrel either to break the core off or to break it into smaller pieces for removal with another piece of equipment. Chisels and other percussion tools are described in a following section of this chapter. Blasting may also be employed to break up a core, where permitted. A hammergrab or clamshell can be used to lift loose or broken cores, if necessary.

Figure 4-25 Rock Cores

4.3.1.4 Full-Faced Rotary Tools

Full face rotary tools may be used for drilling rock, particularly at a large depth. Figure 4-26 shows some tools that are used for this purpose and which utilize roller bits that are attached across the entire cutting face of the tool. The roller bits grind the rock, which is transported to the surface by flushing drilling fluid with the reverse circulation technique described earlier. Disk shaped cutter heads or even teeth have been employed with full face tools in soft rock or cemented soils. Full face rotary tools have occasionally been used with direct circulation in small diameter holes (less than 30 inch) in hard rock by forcing compressed air down through the center of the drill string to blow cuttings out.

Figure 4-26 Full-Faced Rotary Cutters

4.3.1.5 Special Rotary Tools

Innovative equipment suppliers and contractors have developed a large number of special tools for unusual problems that are encountered. The tool on the left in Figure 4-27 cuts grooves in the walls of the borehole in order to facilitate development of the shearing strength of the soil or rock along the sides of the drilled shaft. The core barrel on the right in Figure 4-27 has been outfitted with steel wire on the outside of the barrel to scrape cuttings or loose rock (usually degradable shale) from the surface of rock sockets. Such devices are known regionally as "backscratchers." Other tools are used for assistance in excavation. For example, Figure 4-28 shows a drawing and photo of a tool (the "Glover Rock-Grab") that can core and subsequently grab rock to lift it to the surface. This tool is sometimes effective in excavating boulders or fragmented rock where augers or ordinary core barrels are unsuccessful. Numerous other special tools may be developed by equipment suppliers or contractors for specific projects.

Figure 4-27 Special Rotary Tools: Grooving Tool (left) and “Backscratcher” (right)

Figure 4-28 Boulder-Grabber Tool

4.3.2 Percussion and Other Tools

In contrast to rotary drilling, percussion drilling involves the breaking up of rock, boulders or cemented soil by impact. The broken material may be removed with a clamshell-type bucket or other means such as air circulation. The tools used with percussion methods range from the most simple and crude drop tools to sophisticated hammer drills.

4.3.2.1 Clamshell or Grab Bucket

Bucket excavation is initiated by the setting of a guide for the tools, a procedure that corresponds to the setting of a surface casing when rotary methods are being used. The guide may be circular or rectangular and is designed to conform to the excavating tool. The cross sections of such excavations can have a variety of shapes and can be quite large. With the oscillator or rotator systems (Section 4.2.3.5), the circular segmental casing serves as the guide. With the types of clamshell tools used to construct diaphragm walls or barrettes (Section 4.2.4), a guide-wall is often constructed at the ground surface.

Two types of lifting machines may be used to handle the digging tools that are needed for non-rotary excavation. The simplest procedure is to raise and lower the tools with a cable such as provided by a crane (the term "cable tool" is often used to describe tools used in this manner). The jaws of the digging bucket can be opened and closed by a mechanical arrangement that is actuated by a second cable or by a hydraulic system. The other type of lifting machine uses a solid rod for moving the excavating tools up and down. The rod, which may be called a kelly, is substantial enough to allow the easy positioning of the tool. The kelly in this case does not rotate but merely moves up and down in appropriate guides. As with the cable tool, a mechanism must be provided for opening and closing the jaws of the bucket.

Clamshell or grab buckets are often used in situations where rotary tools are unproductive or impractical. For example, a digging bucket can be used to excavate broken rock, cobbles and soils that are loose and that can be readily picked up by the bucket. If hard, massive rock or boulders are encountered, a tool such as a rock breaker may be used. The broken rock is then lifted using a clamshell or a grab bucket. A typical clamshell, with a circular section for use in drilled shafts, is shown on the left in Figure 4-29. Clamshells and grab buckets are available in various diameters up to about 6 ft. Clamshells or grab buckets can also be used to make excavations with noncircular cross sections, as shown at right in Figure 4-29. The transverse dimension of the tool must conform to the shape of the guides that are used.

Figure 4-29 Clam-shell Buckets

4.3.2.2 Hammergrabs

Hammergrabs are percussion tools that both break and lift rock. Examples of hammergrabs in use are shown in Figure 4-30. Hammergrabs are made heavy by the use of dead weight. The jaws at the bottom of the tool are closed when the tool is dropped, and the wedge formed by the closed jaws breaks the rock. The jaws have strong, hardened teeth and can open to the full size of the tool to pick up the broken rock. Hammergrabs are heavy and relatively expensive devices; however, they have the advantage over rock breakers and clamshells in that the tool does not need to be changed to lift out the broken rock, which speeds the excavation process. Hammergrabs can also be used to construct noncircular barrettes by changing the length of the long side.

Figure 4-30 Hammergrabs

4.3.2.3 Rock Breakers and Drop Chisels

These types of tools (Figure 4-31) are generally composed of a heavy object that is lifted and dropped to break up boulders, cores, and strong soils in order to break up the material and permit it to be lifted by a clamshell or a grab bucket. These tools may even be used to break rock at the bottom of the hole in order to advance the hole more easily. Several types of tools are made to be dropped by a crane. Chisels have a single point designed to help break off a core or to break off a boulder or ledge on the side of the hole. Some examples of rock breakers shown in Figure 4-31 are referred to as a "churn drill" or a "star drill." The bottom of these tools has a wedge shape so that high stresses will occur in the rock that is being impacted by the tool.

After the rock is broken, the broken pieces may be removed with a clam or hammergrab, or sometimes with a rotary auger.

4.3.2.4 Downhole Impact Hammers

To excavate hard rock across the full face of the shaft, a large diameter downhole hammer can be used in a drilling operation to make an excavation up to about 7 ft in diameter through very hard rock such as granite. Examples of downhole hammers are shown in Figure 4-32. The tool at left is a cluster of air-operated hammers, sometimes referred to as a “cluster drill.” Downhole hammers are typically employed for rock which has proven extremely difficult to remove by core barrels or other means. The debris is typically raised by the use of air (i.e., debris is blown out of the borehole) if the hole is dry. The excavation of rock in such a manner is obviously extremely expensive and rock sockets in such hard material are best avoided, especially in urban environments where rock dust can create a hazard.

Figure 4-31 Drop Chisels and Rock Breakers

Figure 4-32 Downhole Impact Hammers

4.3.2.5 Blasting

Blasting is usually not permitted for excavation of drilled shafts because of the safety hazard and because of the potential for fracturing of the surrounding bearing formation. Fractures in the rock around the shaft could be detrimental to the performance of the foundation.

Explosives may be considered on rare occasions to aid in hand excavation of rock near the surface. For instance, explosives might be used to break through a boulder or obstruction within the hole. Explosives might also be employed through small predrilled holes to help level a steeply sloping surface and allow a casing to be more easily seated, or through hard pinnacle limestone above the zone relied upon for capacity. Primer cord has reportedly been used successfully to break cores away in the shaft by wrapping the cord around the base of the core at the bottom of the kerf. This small shock is not thought to affect the surrounding rock. Highly expansive cements have on occasion been used as alternates to explosives by placing cement paste in small holes drilled using air tracks into rock to split the rock and permit it to be excavated easily.

Explosives must be handled by experts and should be used only with the permission of the regulating authorities.

4.4 OTHER TECHNIQUES

4.4.1 Tools for Cleaning the Base of the Drilled Shaft Excavation

Other than the cleanout buckets described in Section 4.3.1.2, other non-rotary tools may be very useful for removing cuttings and debris from the base of the shaft. Most common is some type of pump to lift cuttings for removal. Figure 4-33 illustrates two types of pumps used to lift cuttings. The one on the left is an air-lift pump which operates by pumping air down the supply line alongside the air-lift pipe. As the air enters the pipe a few feet above the bottom, the rising column of air lifts the fluid within the pipe. The buoyant lifting of this column causes suction at the bottom of the pipe which will lift sand or loose material. The photo on the right of Figure 4-33 is of a hydraulic pump, which operates via the two hydraulic lines to rotate the impeller that pumps fluid upward from the base of the pump. Hydraulic pumps are more controllable than the airlift system in that the volume and velocity of pumping can be regulated more easily. Airlifts tend to remove larger particles than pumps.

Figure 4-33 Airlift and Hydraulic Pumps for Shaft Base Cleanout

Note that while pumping systems as shown in Figure 4-33 are probably the most effective means of removing loose cuttings or debris from the base of a wet hole, the aggressive use of these tools in cohesionless sands can advance the shaft excavation. The effectiveness of shaft base cleanout tools and techniques in wet holes can best be evaluated using a downhole camera, as described in Section 15.2.4.

4.4.2 Methods for Stabilizing Soils or Formation

On rare occasions, permeation or compaction grouting may be employed to stabilize a particularly unstable stratum or around a very large or deep hole. Baker et a1. (1982) report that grouting in advance of excavation can sometimes be used to reduce water inflow effectively and even to permit construction of under-reams in granular soil. Examples were given where the technique was used successfully in Chicago.

The principles and use of grouting to enhance base resistance in granular soils was described in Chapter 3. Skin grouting through sleeve-port tubes along the side of the shaft has been used on rare occasions internationally, but is rarely employed in U.S. practice.

4.5 SUMMARY

This chapter described a variety of drilling machines and tools used for construction of drilled shafts. In recent years, the variety of machines and tools has increased as the industry matures and equipment becomes more specialized. The specific choice of tools and equipment is generally the responsibility of the contractor, and different constructors may approach the project differently depending upon their personal experience and resources. Engineers charged with design, specification, and inspection of drilled shafts must be knowledgeable of drilling equipment in order to provide appropriate specifications, and a constructable and cost efficient design. Sufficient subsurface information must be provided so that bidders can make an informed decision about equipment to use on the job. The tools and equipment that are planned for use by the contractor should be described in the contractor's drilled shaft installation plan and the equipment actually used documented in the construction records.

Temporary or permanent casings are additional tools that may be used to complete the drilled shaft, as described in detail in Chapter 5.