9.0 Drilling Techniques

9.1 Purpose

Drilling techniques commonly used to displace and/or remove material during advancement of a borehole are detailed in this document. Other ground penetrating techniques (termed “direct-push” technologies, such as cone penetrometer testing) are also presented. Hand augering is not presented here, and is included in SOP No. 12.

Each drilling method has its advantages and disadvantages. The method of drilling employed at a site depends on: site geology; available equipment; time and budget constraints; site conditions (such as vapors or seeps which can be exacerbated by certain drilling techniques); borehole diameter and depth requirements.

9.2 References

The following ASTM Standards were consulted in the preparation of this SOP:

D 2113-83(93) Practice for Diamond Core Drilling for Site Investigation
D 4700-91 Guide for Soil Sampling from the Vadose Zone
D 5088-90 Practice for Decontamination of Field Equipment Used at Nonradioactive Waste Sites
D 5299-92 Guide for Decommissioning of Ground Water Wells, Vadose Monitoring Devices, Boreholes, and other Devices for Environmental Activities
D 5730-95a Standard Guide for Site Characteristics for Environmental Purposes with Emphasis on Soil, Rock, the Vadose Zone and Ground Water
D 5781-95 Guide for Use of Dual-Wall Reverse-Circulation Drilling for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices
D 5782-95 Guide for Use of Direct Air-Rotary Drilling for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices
D 5783-95 Guide for Use of Direct Rotary with Water-Based Drilling Fluid for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices
D 5784-95 Guide for Use of Hollow-Stem Augers for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices
Z2761Z New Standard Practice for Using Hollow-Stem Augers for Sampling and Geotechnical Exploration
Z5945Z New Standard Guide for Using the Electronic Cone Penetrometer for Environmental Site Characterization
Z6418Z New Standard Practice for Direct Push Characterization of Petroleum Contaminated Sites with Laser-Induced Fluorescence

Note: an ASTM serial designation in bold type denotes a major reference used in the preparation of this SOP. Non-bold serial designations denote references useful in obtaining additional information pertinent to the subject matter.

The following additional references were also used in the preparation of this document:

Acker III, W.L., 1974, *"Basic Procedures for Soil Sampling and Core Drilling"*, Acker Drill Co., Inc., Scranton, PA.
American Society for Testing and Materials, reapproved 1972, *"Standard Method for Soil Investigation and Sampling by Auger Boring"*, ASTM: D1452-65 (1972), Philadelphia, PA.
Driscoll, Fletcher G., Ph.D., 1986, *"Groundwater and Wells"*, Second Edition, Johnson Division, St. Paul, MN.
Mohr, H.A., 1943, *"Exploration of Soil Conditions and Sampling Operations"*, Bulletin No. 376, Soil Mechanics Series No. 21, Graduate School of Engineering, Harvard University, Cambridge, MA.
U.S. Department of Army, 1972, *"Soil Sampling"*, Engineer Manual EM1110-2-1907, U.S. Government Printing Office, Washington, D.C.

9.3 Drilling Techniques

9.3.1 Solid-Stem Auger Drilling

Solid-stem auger drilling is used in support of geoenvironmental exploration where shallow boreholes must be drilled into unconsolidated materials. The advantages of solid-stem auger drilling over other methods include:
the ability to drill without the addition of drilling fluid(s) to the subsurface; and
the ability to drill rapidly through shallow, unconsolidated material.

Solid-stem auger drilling is generally restricted to the drilling of shallow, unconsolidated materials or softer rocks. It is not a favorable method for obtaining subsurface samples because undisturbed samples cannot be collected without first removing the augers from the hole, and caving or soughing of the borehole wall may occur. For this reason, the installation of monitoring devices (e.g., groundwater monitoring wells) is not recommended using solid-stem augers, however, this method may be necessary in confined areas where only a small solid-stem auger drill rig will fit. Subsurface soil characteristics can be logged during solid-stem auger drilling by inspection of materials brought up by the auger flights, but specific depths and “undisturbed” characteristics of the material can only be inferred.

Solid-stem auger apparatus consists of the following:
individual auger sections of the auger-column assembly, which consists a pipe with spiral flanges welded to the pipe. Each section of auger is referred to as a flight. The first auger flight is equipped with a bit with cutters or teeth for cutting through hard ground. The cutter head is usually slightly larger than the flights;
a coupling at each end of the auger section for attachment of additional auger sections at the top end to make up the articulated solid-stem auger column; A pin is placed at the junction of each auger flight connecting one to the next;
the auger-drive assembly which attaches to the uppermost hollow-auger section and transfers rotary power and axial force from the drill rig to the auger-column assembly;
auxiliary components consisting of various devices such as auger-connector wrenches, auger forks, hoisting hooks, etc.; and

a drill rig used to rotate and advance the auger column. The drill rig should be capable of applying the rated power at a velocity of 50 to 100 revolutions per minute (r/min) and should have a feed stroke of at least the effective length of the auger sections plus the effective length of the auger couplings plus about 100 mm (4 in.)

Solid stem augers capable of drilling a hole as large as 54 inches in diameter are available; however, the larger sizes are not common. The auger flights are turned by means of a rotary drive head mounted on a hydraulic feed system that pushes down or pulls back on the flight. Drill cuttings are brought to the surface by the flights which act as a screw conveyor. As the hole is advanced, more auger flights are added until the hole reaches the desired depth.

In order to obtain split-spoon samples from solid stem auger borings, the augers must be completely withdrawn at each sampling depth. Solid stem augers are usually used to advance a hole in stable formations. This method is not effective in unconsolidated material or below the water table because the borehole will collapse when the flights are removed.

The procedure to follow when drilling with solid-stem augers is the same as that for hollow-stem augers (see below) except that a pilot assembly is not used and equipment cannot be lowered into the borehole while the auger is in the hole.

9.3.2 Hollow-Stem Auger Drilling

Hollow-stem auger drilling is widely used in support of geoenvironmental exploration and for installation of subsurface water quality monitoring devices in unconsolidated materials. The advantages of hollow-stem auger drilling over other methods include:
the ability to drill without the addition of drilling fluid(s) to the subsurface (except where heaving sands are encountered); and
hole stability for sampling purposes and monitoring well construction in unconsolidated to poorly indurated materials.

Hollow-stem auger drilling is generally restricted to the drilling of shallow, unconsolidated materials or softer rocks. Maximum drilling capability is about 200 to 300 ft. depending on torque and pull down/retract capacity of the drilling equipment and subsurface conditions. It is a favorable method to be used for obtaining cores and samples and for the installation of monitoring devices (e.g., groundwater monitoring wells) in many, but not all geologic environments. difficulties may occur if loose, cohesionless soils are drilled below the water table. Heaving sands may present a problem (discussed in Section 9.3.3, below). Also, sand lock or wedging of cuttings may occur.

Hollow-stem augers are more versatile than solid stem augers because they can act as temporary casing to prevent caving and sloughing of the borehole wall. They allow soil samples to be obtained more easily and accurately. Small diameter wells can be installed and sand/gravel packed without the use of casing or drilling fluids.

Hollow-stem auger apparatus consists of the following:

individual auger sections of the auger-column assembly, which consists of a cylindrical tube with cylindrical helical flighting rigidly attached to the outer surface of the tube;

a coupling at each end of the auger section for attachment of a hollow-auger head to the bottom of the lead auger section and for attachment of additional auger sections at the top end to make up the articulated hollow-stem auger column;

a hollow auger head which is attached to the lead auger of the auger column and usually contains replaceable, abrasion-resistant cutters or teeth. As the hollow auger is rotated it cuts and directs the cuttings to the surface;

the auger-drive assembly which attaches to the uppermost hollow-auger section and transfers rotary power and axial force from the drill rig to the auger-column assembly;

the pilot assembly which may consist of: (1) an auger-head aperture plugging device with or without a center cutting head to prevent soil from coming up into the auger during drilling, or (2) a sampling device that is used to sample simultaneously with advancement of the auger column;

auxiliary components consisting of various devices such as auger-connector wrenches, auger forks, hoisting hooks, and fluid-injection swivels or adaptors; and

a drill rig used to rotate and advance the auger column. The drill rig should be capable of applying the rated power at a velocity of 50 to 100 revolutions per minute (r/min) and should have a feed stroke of at least the effective length of the auger sections plus the effective length of the auger couplings plus about 100 mm (4 in.)

Figure 9-1 is a schematic drawing of a rod type auger system with a pilot bit.

The following procedure is followed when drilling with hollow-stem augers:

Select hollow-stem augers with an inside diameter that is large enough for insertion of monitoring-device components such as well casing and filter pack and installation devices such as tremie pipe. The opening should also permit easy insertion and retraction of a sampler or core barrel.

Hollow stem augers are available with outer diameters ranging from 6¼ inches to 22 inches (I.D.'s 2½ inches to 6 inches). Common auger sizes are 6¼ inches to 13 inches.

The drill rig, drilling and sampling tools, rotary gear or chain case, the spindle and all components of the rotary drive above the auger column should be decontaminated prior to drilling (see Section 9.3.9, below, for decontamination procedures). The rig should be monitored during drilling for leaks. Any instances of possible contamination caused by such leaks should be documented.

At each drilling location, first stabilize the drill rig using the rig's stabilizing jacks.

Prior to raising the drill mast, look up to see if any overhead utilities exist in proximity to where the mast will be when raised. If so, make move the rig

to a location that is a safe distance from the utilities. Once overhead utilities are safely cleared, raise the drill mast.

Prior to commencement of drilling, each selected drilling location must be cleared of underground utilities in advance. SOP No. 6 presents the standard procedure for locating underground services. Even after utilities are cleared, drilling of the first several feet of the borehole should be done initially with a hand auger and the mechanical auger should be advanced very slowly while the hole is closely inspected for any indication of underground services.

Attach an initial assembly of hollow-auger components to the rotary drive of the drill rig. When sampling is not required, the center pilot bit assembly will be used to keep the center of the hollow-stem auger open.

A datum for measuring hole depth should be established and documented. This datum will consist of a stake driven into stable ground or the drilling deck. If the hole is to be surveyed later for elevation, record and report the height of the datum to the ground surface.

Push the auger-column assembly below the ground surface and initiate rotation at a low velocity. If surface contamination is suspected, special drilling procedures may be required to deter transport of contaminated materials downhole, such as removing and decontaminating augers and auger head following drilling of the initial increments.

Continue drilling, usually at a rotary velocity of about 50 to 100 r/min, to a depth where intermittent sampling or in-situ testing is required, or until the drive assembly is advanced to within about 0.15 to 0.45 m (6 to 18 in.) of the ground surface.

Soil sampling is usually accomplished by either of two methods: (1) removing the pilot assembly and inserting and driving a sampler through the hollow stem of the auger column, or (2) using a continuous sampling device within the lead auger section. The standard procedure for collecting soil samples while drilling is presented in SOP No. 12. Removal of the pilot bit assembly prior to sampling should be performed slowly so that the entrance of material into the bottom of the hollow auger stem is minimized.

Water sampling can be done through the hollow-stem augers when using augers with watertight connections by: (1) allowing the auger column to fill with water through the use of screened lead auger section, (2) allowing the auger column to fill from the bottom, or (3) using a soil-penetrating water sampling device that can be lowered into the hollow auger column and driven into the undisturbed material below the auger head.

Accomplish drilling at greater depths by attaching additional hollow-auger sections to the top of the previously advanced hollow-auger column assembly.

While drilling, cuttings are removed periodically from around the top of the auger column. If drilling is performed in contaminated soil and cuttings control is required, drilling through a hole in a sheet of plywood or similar material held securely above the borehole by the rig's stabilizing jacks will usually facilitate cuttings control. Contaminated cuttings must be handled and disposed of according to all safety and regulatory requirements for hazardous materials.

When drilling must progress through materials suspected of being contaminated, installation of a single or multiple (nested) casings may be required to isolate zones of suspected contamination. Isolation casings can be installed in a predrilled borehole or by using a casing advancement method. When attempting to auger inside the casing, the column of cuttings return may cause the augers to bind in the casing. If so, a grout seal must be installed be applying grout at the bottom of the annulus with the aid of a tremie pipe and a grout shoe or a grout packer. Allow the grout to set before drilling activities are continued.

If sampling or in-situ testing is not required during drilling for installation of a water-quality monitoring device, the boring can be advanced (for some geologic conditions) using an expandable, knock-out plate or plug or flexible center plug in lieu of a pilot assembly. These center plugs will be left in place below the installed monitoring device. It may be necessary to fill or partially fill the auger stem with water to prevent "blow-in" or "sanding in" at the time of plug removal.

If heaving sands or silts (water-saturated material that is under hydrostatic (upward) pressure) are encountered during drilling, follow the procedure presented in Section 9.3.3, below.

Subsurface water-quality monitoring devices (e.g., groundwater monitoring wells) are generally installed using hollow-stem augers using the following three-step procedure:

1) drilling, with or without sampling;
2) removal of the pilot assembly and insertion of the monitoring device; and
3) incremental removal of the hollow-auger column as completion materials such as filter pack, annular seals, and backfill are installed as required.

The standard procedure for inspecting and recording information while drilling is presented in SOP No. 10. The standard procedure for installing groundwater wells is presented in SOP No. 13.

9.3.3 Hollow-Stem Auger Drilling in Heaving Sands

As drilling progresses in saturated, granular materials, it usually becomes progressively more difficult to maintain the stability of the material below the auger column because of unbalanced hydraulic heads. In some cases, heaving water-bearing sands or silts (also known as "blow-in") may have a tendency to force their way up through the hollow stem of the auger column. Because of this, the drilling techniques used to advance the auger column within heaving sands may vary greatly from those techniques used when drilling in unsaturated materials.

The problem may occur when the borehole is advanced to a desired depth without the use of drilling fluids for the purpose of either sampling the formation or installing a monitoring well. As the pilot assemble is retracted, the hydrostatic pressure within the saturated sand forces water and loose sediments to rise inside the hollow center of the auger column (Figure 9-2). These sediments can rise several tens of feet inside the lower auger sections. The resulting "plug" of sediment inside the hollow auger column can interfere with the collection of formation samples, the installation of the monitoring well or even additional drilling.

The difficulties with heaving sands may be overcome by using the following techniques:

Maintain a positive pressure head within the auger column. A positive pressure head can be created by adding a sufficient amount of clean water or other drilling fluid inside the hollow stem. Clean water (i.e., water that does not contain analytes of concern to a monitoring program) is usually preferred as the drilling fluid in order to minimize potential interference with samples collected from the completed well. It may be necessary to sample the added water to confirm its quality.

The head of clean water inside the auger column must exceed the hydrostatic pressure within the sand formation to limit the rise of loose sediments inside the hollow-stem. Where the saturated sand formation is unconfined, the water level inside the auger column is maintained above the elevation of the water table. Where the saturated sand formation is confined, the water level inside the auger column is maintained above the potentiometric surface of the formation. If the potentiometric surface of the formation rises above the ground elevation, however, the heaving sand problem may be very difficult to counteract and may represent a limitation to the use of the drilling method.

There are several drilling techniques used to maintain a positive pressure head of clean water within the auger column:

(1) This technique involves pumping clean water into the auger column during drilling. This method usually entails removal of the pilot assembly, center rod and drive cap. A special coupling or adapter (water swivel) is used to connect the auger column to the spindle of the drilling rig. Clean water is then pumped either through the hollow-center coupling or through the open spindle of the drill rig as the auger column is advanced (Figure 9-3). Large diameter, side-feed water swivels are also available and can be installed between the drive cap and the hex shank, which connects the auger column to the spindle of the drill rig. Clean water is

injected through the water swivel and into the auger column as the augers are advanced.

(2) Another drilling technique used to overcome heaving sands is to first advance the auger column by using a "non-retrievable" knock-out plate or plug. The knock-out plate is wedged inside the auger head and replaces the traditional pilot assembly and center rod (Figure 9-4). A major disadvantage of this drilling technique is that the knock-out plate cannot be alternately removed and reinserted from the auger column to permit the collection of formation samples as the auger column is advanced. Once the auger column is advanced to a desired depth, the column is filled to a sufficient height with clean water. A ramrod commonly is used to strike and remove the knock-out plate from the auger head (Figure 9-4). The head of clean water in the auger column must exceed the hydrostatic pressure in the sand formation to prevent loose sediments from rising inside the auger column once the knock-out place is removed. The non-retrievable knock-out plate should be constructed of inert materials, such as wood, when drilling a borehole for the installation of a water-quality monitoring well. This will minimize concerns over the permanent presence of the knock-out plate in the bottom of the borehole and the potential effect the plate may have on ground water samples collected from the completed well.

(3) Reverse flight augers represent another unique center plug design that has had measured success in overcoming problems with heaving sands. The flighting on the center plug and center rod rotates in an opposite direction from the flighting on the auger column (Figure 9-5). As the auger column advances through the heaving sands, the sand deposits are pushed outward from the auger head by the reverse flighting on the center plug. A sufficient head of clean water is maintained inside the auger column to counteract further the hydrostatic pressure in the heaving sand formation. Once drilling is completed, the reverse flight center plug is slowly retracted from the auger column so that movement of sand into the hollow stem in not induced.

Although the use of clean water as a drilling fluid is recognized by the U.S. EPA as a proper drilling technique to avoid heaving sand problems (U.S. EPA1986), the use of any drilling fluid may be undesirable or prohibited at some ground water monitoring sites. In these instances, the problem may be overcome by using commercial or fabricated devices that allow formation water to enter the auger column, but exclude formation sands. These devices permit the collection of formation samples as the auger column is advanced through the heaving sands. The following devices are available for this purpose:

(1) A device consisting of a slotted coupling attached to a knock-out plate (Figure 9-6). As the auger column advances below the water table, formation water enters the auger column through the slotted coupling. When the auger column is advanced to the desired depth, a ramrod is used to dislodge the knock-out plate with the slotted coupling from the auger head (Figure 9-7). The slotted coupling generally is successful in counteracting heaving sand problems. However, where clays and silts

are encountered during drilling, the openings in the slotted coupling may clog and restrict formation water from entering the auger column.

(2) To overcome the problem of the slotted coupling (above) being clogged by fine materials, a screened well swab can be used. The swab is connected to a ramrod and is lowered through the auger column once the column is advanced to the desired depth. The ramrod is used to strike and remove the knock-out plate from the auger head (Figure 9-8). The screened well swab filters the sand and allows only formation water to enter the auger column (Perry and Hart 1985). Once the water level rises inside the auger column to a height that offsets the hydrostatic pressure in the formation, the screened well swab is slowly removed so that movement of sand into the hollow stem is not included.

The above devices include a variety of patented designs, including non-watertight flexible center plugs. These devices replace the traditional pilot assembly in the auger head. Some flexible center plugs are seated inside the auger head by means of a specially manufactured groove in the hollow stem. These flexible center plugs allow split-barrel samplers and thin-walled tube samplers to pass through the center plug so that samples of the water-bearing sands can be collected. The flexible center plug, however, cannot be retracted from the auger head and therefore, severely restricts the ability to install a monitoring well through the auger column. The monitoring well intake and casing can be inserted through the flexible center plug, but the plug eliminates the installation of filter pack and annular sealant (e.g., bentonite pellets) by free fall through the working space between the well casing and auger column.

9.3.4 Cable Tool Drilling

The cable tool method of drilling is also known as percussion or churn drilling. Cable tool drilling machines operate by repeatedly lifting and dropping a heavy string of drilling tools into the borehole. In consolidated formations, the drill bit crushes the formation into small fragments. In unconsolidated formations, the action of the bit primarily loosens the material.

The reciprocating action of the tools mixes the crushed or loosened particles with water to form a slurry or sludge at the bottom of the borehole. If no water is present in the formation, water is added to form the slurry. As drilling proceeds, the slurry accumulates in the borehole. Eventually, it reduces the impact of the reciprocating action of the tools. When the action of the tools is reduced sufficiently to slow the rate of penetration, the slurry is removed from the borehole by means of a sand pump or bailer.

The drilling tools consist of:

a) a drill bit,
b) a drill stem,
c) drilling jars,
d) a swivel socket, and
e) a cable.

Samples are obtained by sampling the slurry or by replacing the bit with a traditional sampler after the slurry has been removed and driving the sampler with the heavy, "down the hole" tools drilling jars.

Most boreholes drilled in consolidated formations using the cable tool method are drilled “open hole”, i.e., no casing or pipe is advanced as the hole is drilled. The effectiveness of the drilling in consolidated material is a function of:

a) the hardness of the formation being drilled;
b) formation structure (bedding, fractures, etc.);
c) the weight of the drill tools;
d) the length of the stroke;
e) the strokes per minute;
f) the condition, size and type of the bit;
g) the clearance between the drill tools and the borehole; and
h) the density and depth of accumulated slurry.

Drilling in unconsolidated formations requires that a pipe or casing must follow the drill bit as the borehole is advanced to prevent caving or sloughing and to keep the borehole open. Usually the casing must be driven in a manner similar to pile driving. At the lower end of the casing, a drive shoe is attached to prevent damage to the bottom of the casing while it is being driven. Casing is usually driven 3-10 feet, the material within the casing is mixed with water to form a slurry and the slurry is removed from the casing. After the casing has been cleaned out, it is driven deeper.

Relatively large diameter holes can be drilled used cable tool methodology.

The depth to which cable tool boreholes can be drilled depends on several factors:

The diameter of the borehole. Small diameter holes, in general, can be drilled to greater depth than large diameter holes.

In large diameter holes, the weight of the drill tools and cable may be the limiting factor. Reducing the hole diameter, at depth, may increase the total depth of the borehole.

Collapsing formations may limit the effective depth of a borehole. Casing the hole then becomes necessary.

Friction on the outside of the casing may limit the depth to which a certain diameter hole may be advanced. Telescoping to a smaller diameter casing within the large diameter casing can increase the hole depth.

9.3.5 Diamond Core Drilling

Diamond core drilling is used to obtain core samples of rock and some soils that are too hard to sample by soil-sampling methods. Diamond core drilling rigs consist of the following apparatus:

a drilling machine capable of delivering sufficient rotation, feed and contraction by hydraulic or mechanical means to the drill rods;

fluid pump or air compressor capable of delivering sufficient volume and pressure for the diameter and depth of the hole to be drilled;
core barrels, for collecting rock or soil cores;

longitudinally split inner tubes that fit into the core barrels and allow inspection of and access to the core simply by removing one of the two halves;

core bits which are surface set with diamonds, impregnated with diamond particles, inserted with tungsten carbide slugs, or strips, hard-faced with various hard surfacing materials or furnished in saw-tooth form, all as appropriate to the formation being cored;

reaming shells, impregnated with material similar to the core bits;

core lifters;

casings for lining the borehole as it is drilled;

drill rods which are used to transmit feed, rotation and retraction forces from the drilling machine to the core barrel; and

auxiliary equipment, such as various specialized bits, tools, lubrication equipment, core boxes and marking devices.

The following procedure is used to drill and obtain cores:

Casing is seated on bedrock or in a firm formation to prevent raveling of the borehole or loss of drilling fluid (if fluid is used). Casing may be omitted if borehole will stay open without it.

Core drill proceeds using the appropriate core bit and core barrel until core blockage occurs or the net length of the core barrel has been drilled in.

The core barrel is removed from the hole and disassembled to remove the core which is packaged appropriately. The core barrel is then reassembled and returned to the hole where coring continues.

Core drilling is stopped when soft materials are encountered that produce less than 50% recovery. Core drilling is resumed when hard, recoverable material is again encountered.

If conditions prevent the continued advance of core drilling, the hole is cemented and redrilled, or reamed and cased, or cased and advanced with the next smaller-size core barrel.

9.3.6 Direct Rotary Drilling

Direct rotary drilling may be selected over other method of drilling for geoenvironmental exploration and installation of subsurface water-quality monitoring devices based on the following advantages:
in drilling unconsolidated sediments and hard rock, other than cavernous limestones and basalts where circulation cannot be maintained, direct rotary drilling is faster than the cable-tool method; and
stability of the borehole wall in drilling unconsolidated formations due to the buildup of a filter cake on the wall.

Disadvantages of direct rotary drilling include:
introduction of fluids to the subsurface;

the creation of a filter cake on the borehole wall that may alter natural hydraulic characteristics of the borehole; and

generally more well-development effort required due to the presence of the filter cake.

In direct rotary drilling, the borehole is drilled by rotating a bit and removing the cuttings from the borehole by means of a drilling fluid. (The term *direct* indicates that the drilling fluid is pumped through a drill-rod column to a rotating bit, as opposed to *reverse circulation* which indicates that the drilling fluid is forced down the annular space and back up to the surface through the drill pipe.) The direct rotary drilling system therefore consists of mechanical components and the drilling fluid.

The mechanical components of a direct-rotary drilling system include:

a drill rig with rotary table and kelly or top-head drive unit which rotates the drill-rod column and applies a controllable axial force on the drill bit appropriate to the drilling and sampling requirements and the geologic conditions;

a kelly which is a formed or machined section of hollow drill steel, used with some rotary drilling systems, that is joined to the swivel at the top and the drill rods below;

drill rods, which transfer force and rotation from the drill rig to the bit or core barrel. Drill rods conduct drilling fluid to the bit or core barrel;

a rotary bit or core bit which provides material cutting capability;

a mud pit which is a reservoir for the drilling fluid and, if properly designed and utilized, provides sufficient flow-velocity reduction to allow separation of drill cuttings from the fluid before recirculation. The mud pit can be a shallow, open metal tank or an excavated pit with some type of liner;

a suction hose which conducts the drilling fluid from the mud pit to the drilling-fluid circulation pump;

a drilling-fluid circulation pump which lifts the drilling fluid from the mud pit and moves it through the system against variable pumping heads and provides an annular velocity adequate to transport drill cuttings out of the borehole;

a pressure hose that conducts the drilling fluid from the circulation pump to the swivel; and

a swivel which directs the drilling fluid from the circulation pump to the kelly or drill rod column.

The drilling fluid usually consists of a water base and one or more additives that increase viscosity or provide other desirable physical or chemical properties. The principal functions of drilling fluids are:

a) to seal the borehole wall to minimize the loss of the drilling fluid;
b) to provide a hydraulic pressure against the borehole wall to support the open borehole;
c) to lift drill cuttings generated at the bit from the bottom of the borehole and bring them to the surface; and
d) to lubricate, cool and clean the drill bit.

Some commonly used additives for water-based drilling fluids are:
beneficiated bentonite (containing sodium carbonate and/or polyacrylates), a primary viscosifier and borehole sealer;
unbenificiated bentonite (containing no additives), a primary viscosifier and borehole sealer;
sodium carbonate powder (soda ash), precipitates calcium carbonate hardness from the drilling fluid water base before adding other components;
carboxylmethylcellulose powder (CMC), a viscosifier and an inhibitor to clay hydration;
potassium chloride (muriated potash), an inhibitor to clay hydration;
diammonium phosphate, an inhibitor to clay hydration;
polyacrylamide, a primary viscosifier and clay-hydration inhibitor;
barium sulfate, increases the density of the drilling fluid;
lost-circulation materials, coarse textured materials such as shredded paper or plastic, bentonite chips, wood fibers or mica, used to seal the borehole wall when fluids are being lost through large pores, cracks or joints; and
attapulgite, a primary viscosifier in high-salinity environments.

Caution: The above-listed additives may impact water-quality analyses. Each additive should be evaluated to determine its potential impact on the water quality of the site and its compatibility with the contaminant(s) present at the site. (For example, some drilling fluids which break down under normal conditions do not break down when exposed to hydrocarbon contamination.) The types, amounts, and chemical compositions of all additives used should be documented.

The time required to remove cuttings from the borehole depends mainly on the pumping rate, the cross-sectional area of the borehole, the borehole depth, viscosity of the drilling fluid, and the size of the cuttings. When recirculating drilling fluid, it is important to remember that the viscosity should not be so great that the drill cuttings are not able to settle out of the fluid. Drilling fluids may cause plugging of formations, therefore the amount of drilling fluids used should be minimized. To reduce the amount of plugging of a formation by the fine drilling fluid particles, the fluid should be only heavy enough to maintain borehole stability.

The drilling fluid is pumped down through the drill pipe and out through ports or jets in the drill bit. The fluid then flows upward in the annular space between the drill tools and the side of the hole or the casing, carrying the cuttings in suspension to the surface. At the surface, the fluid and cuttings are channeled into a mud tub settling pit or pits where the cutting settle out. The "clean" fluid is then recirculated into the hole.

Two common types of bits are the drag bit (fishtail) and the roller cone (rock bit, tricone bit). The drag bits have short blades faced with a durable material and nozzles to direct the drilling fluid onto the bit faces to clean and cool them. Drag bits operate by shearing action and are used in cohesive materials such as clay, fine sands, and soft rock formations. Roller cone bits exert crushing and grinding action and are primarily used in harder formations. They are flushed by jets of drilling fluid from the center of the bit.

Down-the-hole stabilizers may be used to maintain st raight holes. Samples can be taken from drill cutting s or by traditional sampling methods (e.g., split spo on).

Air may be used to assist the primary drilli ng fluid in removing the drill cuttings from the bore

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The following procedure is used for direct rotary drilling:

Stabilize the drill rig, assure that underground and overhead utilities have been cleared, and raise the drill-rig mast. Assure that all drilling equipment has been decontaminated prior to commencement of drilling.

Position the mud pit and install surface casing and “seal” at the ground surface.

Mix an initial quantity of drilling fluid, usually using the mud pit as the primary mixing reservoir. Document the final drilling fluid mixture.

Attach an initial assembly of a bit or core barrel, often with a single section of drill rod, below the rotary table or top-head drive unit with the bit or drill head placed within the top of the surface casing.

Activate the drilling-fluid circulation pump, causing drilling fluid to circulate through the system.

Initiate rotation of the bit and apply axial force to the bit.

Continue drilling-fluid circulation as rotation and axial force are applied to the bit until drilling progresses to a depth where: (1) sampling or in-situ testing will be performed, (2) the length of the drill-rod column prevents further penetration, or (3) (when core drilling) the core specimen enters the core barrel.

Stop rotation. Lift the bit slightly off hole-bottom while drilling-fluid circulation is continued to facilitate removal of drill cuttings from the borehole. If sampling is to be done, stop drilling-fluid circulation and rest the bit on the hole bottom to ascertain depth. If caving has occurred, set clean casing to support the boring.

Increase drilling depth by attaching an additional drill-rod section to the top of the previously advanced drill-rod column and resuming drilling operations.

Perform sampling or in-situ testing at any depth by interrupting the advance of the bit, cleaning the hole of cuttings, stopping the fluid circulation, and removing the drill-rod column from the borehole. Drill-rod removal is not necessary when sampling or in-situ testing can be performed through the hollow axis of the drill rods and bit.

When drilling must progress through material suspected of being contaminated, installation of single or multiple (nested) casings may be required to isolate zones of suspected contamination. Isolation casings are usually installed in a predrilled borehole or by using a casing-advancement method. A grout seal is then installed, usually by applying the grout at the bottom of the annulus. Allow the grout to set before drilling activities are continued.

9.3.7 Direct Air-Rotary Drilling:

The direct air-rotary drilling method is similar to direct rotary drilling except that compressed air is circulated through the system instead of water-based drilling fluid to remove cuttings. (The term *direct* indicates that compressed air is injected through a drill-rod column to a rotating bit.)

Several advantages of using the direct air-rotary drilling method over methods include:
the ability to drill rather rapidly through consolidated materials; and
drilling fluids generally do not have to be introduced into the borehole.
Air-rotary drilling is often employed when water-sensitive materials (i.e., friable sandstones or collapsible soils) may preclude water-based rotary-drilling methods.

Some disadvantages to air-rotary drilling include:
poor borehole integrity in unconsolidated sediments without using casing; and
the possible volatilization of contaminants and air-borne dust.

The use of air under high pressures may cause fracturing of the formation materials or extreme erosion of the borehole if drilling pressures ad techniques are not carefully maintained and monitored. In some instances, water or foam additives may be injected into the air stream to improve cuttings-lifting capacity. In unconsolidated formations casing is generally used to stabilize the borehole.

The direct air-rotary drilling system consists of mechanical components and the circulating air (with or without additives). The mechanical components of the direct air-rotary drilling system are very similar to those of the direct rotary drilling system, except that no mud pit is necessary and the drilling-fluid circulation system is replaced by a compressed-air circulation system, which includes:
an air compressor which must provide an adequate volume of air, without significant contamination, for removal of cuttings;
a dust collector which conducts air and cuttings from the borehole past the drill-rod column to an air-cleaning device; and
an air-cleaning device (also referred to as a cyclone separator) which separates cuttings from the borehole by means of a dust collector.

There are two primary methods of drilling with air:

a) Roller-type rock bits, similar to the type used with drilling fluids; and

b) "Down-the-hole" pneumatic drills (air hammers) which rapidly strike the formation while the drill pipe is rotated slowly. The percussion effect is similar to the blows delivered by a Cable Tool bit. Rotation of the bit helps to assure even penetration. Because cuttings are removed continuously and the hammer always strikes a clean surface, air hammers are very efficient.

Samples are obtained from the drill cuttings or using typical down-hole sampling methods. When air alone is used to remove drill cuttings, the formation is not plugged with drilling fluids.

The quality of compressed air entering the borehole and being discharged from the borehole and the cyclone separator must be considered. High-efficiency, in-line air filters are usually required to prevent significant contamination of the borehole from oil lubricants or subsurface contaminants.

Cautions:
compressed air may "push" vapors and/or petroleum products into adjacent structures or surface water bodies;
air hammers may be lubricated with oil and can introduce a source of contamination into the borehole;
all additives used to increase the lifting capacity of the air must be evaluated relative to their potential impact on anticipated water quality testing; and
air, petroleum or groundwater may be blown through the formation and out of other points, such as, other nearby wells, utility lines, or through foundations by the down hole air pressure.

The following procedure is used for direct air-rotary drilling:

Stabilize the drill rig, assure that underground and overhead utilities have been cleared, and raise the drill-rig mast. Assure that all drilling equipment has been decontaminated prior to commencement of drilling.

Position the cyclone separator and seal it to the ground surface. Consider its location relative to prevalent wind direction and the location of the rig exhaust for air quality and vapor monitoring purposes.

If casing is required to prevent hole collapse, position it at the surface.

Attach an initial assembly of a bit or core barrel, often with a single section of drill rod, below the rotary table or top-head drive unit with the bit or drill head placed within the top of the surface casing.

Activate the air compressor, causing compressed air to circulate through the system.

Initiate rotation of the bit and apply axial force to the bit.

Continue air circulation and rotation of the drill-rod column until drilling progresses to a depth where: (1) sampling or in-situ testing will be performed, (2) the length of the drill-rod column prevents further penetration, or (3) (when core drilling) the core specimen enters the core barrel. Air pressures at the bit should be low to prevent fracturing of the surrounding material.

Stop rotation. Lift the bit slightly off hole-bottom to facilitate removal of drill cuttings from the borehole and continue air circulation until cuttings are removed. If sampling is to be done, stop air circulation and rest the bit on the hole bottom to ascertain depth. If caving has occurred, set clean casing to support the boring.

Increase drilling depth by attaching an additional drill-rod section to the top of the previously advanced drill-rod column and resuming drilling operations.

Perform sampling or in-situ testing at any depth by interrupting the advance of the bit, cleaning the hole of cuttings, and removing the drill-rod column from the borehole. Drill-rod removal is not necessary when sampling or in-situ testing can be performed through the hollow axis of the drill rods and bit.

When drilling must progress through material suspected of being contaminated, installation of single or multiple (nested) casings may be required to isolate zones of suspected contamination.

9.3.8 Direct Push Technologies

Direct push or drive/push technologies such as cone penetration testing are being used increasingly for environmental field investigations to depths of 100 to 300 ft. (30.5 to 100 m) depending on geology and push capacity of the system.

9.3.8.1 Cone Penetrometer Testing

The electric cone penetration test (CPT) is an in-situ investigation method involving:

a. pushing an electronically instrumented probe into the ground;
b. recording force resistance, such as:
    - tip resistance,
    - local friction, and
    - pore pressure; and
c. data interpretation.

CPT methods can be used for:
lithologic characterization;
measurement of hydraulic conductivity of soils;
sampling of solids, soil gases and groundwater; and
in-situ chemical detection.

The advantages of CPT over traditional methods are:
increased worker safety;
may be faster;
no cuttings are generated;
improved siting of permanent monitoring wells;
less expensive; and
provides greater resolution.

The most common use of CPT data is stratigraphic interpretation. Accurate lithologic characterization using CPT requires correlation of measured resistance with one or more direct subsurface observations for each site. The pore pressure channel of the cone can be used to determine the depth to the water table or to locate perched water zones. Saturated layers less than 20 mm thick can generally be detected. Pore pressure data is also used to provide a feel for relative hydraulic conductivity.

When attempting to retrieve a soil gas or water sample, it is advantageous to know where the bearing zones (permeable zones) are located. Soil gas and water samples can be removed from non-bearing zones such as clays, but the length of time required makes it impractical.

Depth capabilities of the CPT method are a function of many factors, including:
the force resistance on the tip;
the friction along the push rods;
the force and reaction weight available;
rod support provided by the soil; and
large grained materials (gravels, cobbles, boulders) causing non-vertical deflection or unacceptable tool wear.
Depth is always site dependent, and local experience is desirable. Penetration is not possible in hard rock and not usually in softer rocks such as claystones and shales. Cemented soil zones may be difficult to penetrate.

9.3.8.2 Laser-Induced Fluorescence

The presence of petroleum, oils and lubricants in the subsurface can be accomplished using direct push apparatus containing a fiber optic based laser-induced fluorescence (LIF) sensor system. A cone penetrometer platform is generally used to drive the sensor into the ground.

The chemical sensing scheme utilizes a laser source that emits a pulsed ultraviolet light through window mounted in a penetrometer probe. Laser energy emitted through the window causes fluorescence in adjacent petroleum contaminated media. The fluorescent energy is returned to the surface via optical cables for real-time spectral data acquisition and spectral analysis on the platform.

9.3.8.3 Direct Push Well Installation

Wells can be installed in unconsolidated formations by hand (up to 30 feet deep) and by hammering (to approximately 50 feet). The general installation procedure is as follows:

A hole is bored which is slightly larger than the well point (hand auger, post hole digger). The hole should be straight and as deep as possible.

The well point and casing assembly is lowered into the hole and the hole is backfilled.

A drive cap is attached to the top of the casing. Hand driving can be done with a weighted pipe similar to the type used to drive fence posts or with a maul. Driving tools can be suspended from a tripod or derrick in which case the driver must be suspended directly above the well so that it will strike the drive cap evenly.

To insure the threaded joints remain tight, the casing is turned slightly with a wrench periodically. This should be done carefully so as to minimize possible damage of the well screen.

Driven wells may be installed using protective casing. The casing may be driven to the appropriate depth, cleaned out, and the well point driven out of the bottom of the casing. Alternatively, the well may be protected by protective casing during driving. At the appropriate depth, the casing is pulled out to expose the well screen.

The major disadvantages of driven wells are:

a) the diameter of the well that can be installed is limited;
b) the depth to which the well can be installed is limited;
c) PVC well materials are not generally suitable because they are not durable enough; and
d) no sand/gravel pack can be installed unless the a casing is used.

9.3.9 Decontamination of Drill Equipment

Equipment associated with drilling can be put into one of two categories:

1. non-sample contacting equipment, i.e., equipment associated with the drilling or sampling effort that does not directly contact the equipment, or
2. sample contacting equipment, i.e., equipment that comes in direct contact with the sample or portion of sample that will undergo chemical analyses or physical testing.

Except for sampling devices such as split spoon samplers and core barrels, equipment associated with drilling (e.g., augers, drill rods, etc.) can be classified as non-sample contacting equipment. The following is the decontamination procedure for non-sample contacting equipment. The decontamination of sample contacting equipment is presented in SOP No. 12.

Prior to initiating a field program that will involve equipment decontamination, a site specific decontamination protocol should be prepared. Information in the protocol should include:
site location and description;
statement of the sampling program objective and desired precision and accuracy;
summary of available information regarding soil types, hydrogeology and anticipated chemistry of the materials to be sampled,;
listing of the equipment to be used for drilling/sampling, and materials needed for decontamination;
detailed step-by-step procedure for equipment decontamination for each piece or type of equipment to be used and procedures for rinse fluids containment and disposal as appropriate;
summary of QA/QC procedures and QA/QC samples to be collected to document decontamination completeness including specific type of chemical analyses and their detection limit; and
outline of equipment decontamination verification report.

The general procedure for decontaminating non-sample contacting drilling equipment is as follows:

Clean the equipment with a portable power washer or steam cleaning machine. Alternatively, hand wash with a brush using a non-phosphate detergent solution.

Rinse equipment with control water (i.e., water having a known chemistry). The more rigorous decontamination procedures (i.e., procedures for decontaminating sample contacting equipment, SOP No. 12) may be employed if necessary to meet sampling or QA/QC objectives.

Depending on site conditions, it may be appropriate to contain spent decontamination rinse fluids. If this is the case, the appropriate vessel for fluid containment (i.e., a drum approved by the Department of Transportation or similar container suitable for this purpose) should be used depending on the ultimate disposition of the material.

Depending on site conditions, it may be desirable to perform all equipment decontamination at a centralized location as opposed to the location where the equipment was used. If this is the case, care must be taken to transport the equipment to the decontamination area such that the spread of contamination is minimized.

9.3.10 Borehole Abandonment

If there are no needs for special completion or instrument installations for the borehole, it should be backfilled. The method for backfilling for abandonment depends on the requirements of the exploration program and should be specified as part of the program. Certain state and local regulations may apply. The surface of the hole should be sealed to minimize hazard to those at the surface.

The following procedures apply for abandonment of empty boreholes (consult ASTM Standard D 5299 and relevant state and local regulations for proper well abandonment procedures):

The volume of the plugging material required for the borehole(s) should be calculated in advance, taking into consideration applicable loss of material to the formation, voids intersecting the borehole, changed in borehole diameter, washout zones and swelling or shrinking of material.

In cases where the hole is to be backfilled completely, the condition of the hole should be evaluated and documented. Any zones of caving or blocking which preclude complete backfilling should be documented.

To achieve an effective seal the borehole should be free of debris and foreign matter that may restrict the adhesion of the plugging materials to the borehole wall. Clear the borehole of excessive mud filtercake and any bridges resulting from the removal of temporary casing, or when non-cohesive materials (such as sand and gravel) are encountered that can lead to a collapsed borehole during decommissioning activities. One method commonly used for clearing of these materials is to advance a small grout pipe to the bottom of the hole and flush the hole with either water or a high-grade bentonite slurry.

Grout must be carefully mixed using water of known chemical quality. The quality of water must be compatible with the grouting material and not introduce contamination into the subsurface.

Both cement and bentonite can be mixed on site. Cement can also be purchased and delivered premixed on site. Curing accelerators can be used provided the accelerator is approved by regulatory authorities and it does not degrade the cement or react with the environment.

Backfilling can be performed by addition of backfill materials from the surface or through injection by tremie pipes.

When backfilling from the surface, either drill cuttings, bentonite pellets or granules, or select materials may be added.

If complete backfilling is desired using surface methods, use of uniform backfill materials such as bentonite pellets or granules will reduce the possibility of bridging.

The tremie methods assure the best backfilling and should be performed when exploration plans require assurance of complete backfilling. Tremie methods consist of placing a small diameter grout pipe near the base of the drill hole and pumping either cement or bentonite grouts to the surface while displacing any drill hole fluid. The tremie pipe is withdrawn in increments but the tip is maintained below the grout surface. Typical grout consistencies depend on equipment and needs of the exploration program.

Complete grouting slowly to prevent channeling of the grout around any undesirable material remaining in the hole. Complete the grouting in one continuous operation.

A prescribed grout formula is not presented here because of the wide variety of materials available. Generally, grout will consist of Portland cement with or without a percentage of bentonite to retard shrinkage. Most drilling companies use standard grout mixtures when abandoning boreholes. The drillers should be consulted in advance on their abandonment protocol (including grout mixture)and that protocol should be compared against regulatory requirements to assure that it is legitimate. Prior to abandoning boreholes under unusual or difficult circumstances (such as in the presence of unusual contaminants), the user should consult ASTM Standard D 5299 which contains a detailed discussion on the different types of materials that can be used in the preparation of grout for borehole abandonment.

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ATTACH FIGURE 1 FROM ASTM DRAFT DOCUMENT Z2716Z, LABEL AS FIGURE 9-1
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ATTACH FIGURES 6-1 THROUGH 6-7 FROM FORMER FDGTI SOP NO. 6 AND LABEL AS FIGURE 9-2 THROUGH 9-8
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