Standard Guide for
Selection of Drilling Methods for Environmental Site Characterization[1]

This standard is issued under the fixed designation D6286; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This guide provides descriptions of various drilling methods for environmental site characterization along with advantages and disadvantages associated with each method discussed. A comprehensive description of these drilling methods can be found in individual ASTM standards, see Section 2. This guide is intended to aid in the selection of drilling method(s) for environmental soil and rock borings and the installation of monitoring wells and other water-quality monitoring devices.

1.2 This guide does not address methods of well construction, well development, or well completion. These topics are covered in other ASTM documents, see Section 2.

1.3 This guide cannot address all possible subsurface conditions that may occur such as, geologic, topographic, climatic, or anthropogenic. Site evaluation for engineering, design, and construction purposes is addressed in Guide D420.

1.4 The values stated in SI units are to be regarded as the standard. Because dimensions of materials used in the drilling industry are given in inch-pound units by convention, rationalized inch-pound units also are used in this guide. Each system of units is to be regarded separately as standard.

1.5 This guide does not specifically address methods of lithologic sample collection, such as coring, that may require the use of a specific drilling method. Other ASTM guides should be consulted for sampling methods (see Guide D6169) and equipment necessary for specific projects.

1.6 This guide does not purport to comprehensively address all of the methods and the issues associated with drilling for environmental purposes. Users should seek qualified professionals for decisions as to the proper equipment and methods that would be most successful for their site investigation. Other methods may be available for drilling and qualified professionals should have flexibility to exercise judgment as to possible alternatives not covered in this guide. The guide is current at the time of issue, but new alternative methods may become available prior to revisions; therefore, users should consult with manufacturers or producers prior to specifying program requirements.

1.7 Pertinent guides addressing specific drilling methods, equipment and procedures are listed in 2.1. A comprehensive list of guides, methods, practices, and terminology for drilling is contained in Guide D5730. Other documents covering procedures for environmental site investigations with specific objectives or in particular geographic settings may be available from federal, state, and other agencies or organizations. The appropriate agency or organization should be contacted to determine the availability and most current edition of such documents.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education and experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D420 Guide to Site Characterization for Engineering Design

---

[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

Current edition approved Sept. 1, 2012. Published November 2012. Originally approved in 1998. Last previous edition approved in 2006 as D6286 – 98(2006). DOI: 10.1520/D6286-12.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

and Construction Purposes (Withdrawn 2011)[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D1586 Test Method for Penetration Test (SPT) and Split-Barrel Sampling of Soils

D1587 Practice for Thin-Walled Tube Sampling of Soils for Geotechnical Purposes

D2113 Practice for Rock Core Drilling and Sampling of Rock for Site Investigation

D2488 Practice for Description and Identification of Soils (Visual-Manual Procedure)

D3550 Practice for Thick Wall, Ring-Lined, Split Barrel, Drive Sampling of Soils

D5092 Practice for Design and Installation of Ground Water Monitoring Wells

D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater

D5753 Guide for Planning and Conducting Borehole Geophysical Logging

D5781 Guide for Use of Dual-Wall Reverse-Circulation Drilling for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices

D5782 Guide for Use of Direct Air-Rotary Drilling for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices

D5783 Guide for Use of Direct Rotary Drilling with Water-Based Drilling Fluid for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices

D5784 Guide for Use of Hollow-Stem Augers for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices

D5872 Guide for Use of Casing Advancement Drilling Methods for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices

D5875 Guide for Use of Cable-Tool Drilling and Sampling Methods for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices

D5876 Guide for Use of Direct Rotary Wireline Casing Advancement Drilling Methods for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices

D6001 Guide for Direct-Push Ground Water Sampling for Environmental Site Characterization

D6151 Practice for Using Hollow-Stem Augers for Geotechnical Exploration and Soil Sampling

D6169 Guide for Selection of Soil and Rock Sampling Devices Used With Drill Rigs for Environmental Investigations

D6429 Guide for Selecting Surface Geophysical Methods

D6910 Test Method for Marsh Funnel Viscosity of Clay Construction Slurries

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of general terms used within this guide, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *borehole wall, n*—refers to the naturally-occurring soil(s)/rock(s) surrounding the borehole.

3.2.2 *kelly bar, n*—a formed or machined section of hollow drill steel used in rotary drilling, which is joined directly to the swivel at the top and to the drill pipe below. The flats or splines of the kelly engage the rotary table so that the rotation of the rotary table turns the kelly, which in turn, rotates the drill pipe and the rotary bit.

3.2.3 *mud rings, n*—soil or rock cuttings that form a ring or rings on the drill rod(s) during a rotary-drilling method, and as such, prevent drill cuttings from being carried up and out of the borehole. These rings can cause drill rods to become stuck in the borehole if sufficient drilling fluid is not injected or pumped downhole to keep the cuttings fluid so that the ring(s) cannot form on the drill rods and block the cuttings return as drilling progresses.

3.2.4 *orange-peel bucket or boulder catcher, n*—a bucket-type device, somewhat elliptical in shape resembling an orange peel, that is lowered down the borehole and used to remove boulders from the bottom of a borehole.

4. Significance and Use

4.1 The selection of particular method(s) for drilling monitoring wells (see Table 1) requires that specific characteristics of each site be considered. These characteristics would include, but are not limited to, the ambient hydrogeologic parameters and conditions existing at the site. This guide is intended to make the user aware of some of the various drilling methods available and the applications, advantages and disadvantages of each with respect to determining groundwater chemistry and other hydrogeologic properties data.

4.2 This guide can be used in conjunction with Guide D6169. There are several guides that deal with individual drilling methods (see Guides D5781, D5782, D5783, D5784, D5872, D5875, and D5876) and how to the complete them for water quality monitoring device installation (see Practice D5092).

5. Program Planning and Drilling Considerations

5.1 All factors affecting both surface and subsurface environment at a specific site requires professional judgment and must be considered by the geologist/hydrologist or experienced driller before a drilling method is selected. Significant soil and rock masses and groundwater conditions within a given site should be described and defined, both vertically and horizontally, before drilling. Site planning requires a reconnaissance site investigation that considers access to the drilling site and conditions for setting up the drilling equipment (**1**).[4] The extent of site characterization and specific methods used will be determined by study objectives. Study objectives also will affect the type and complexity of data collected. Sources of

---

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

TABLE 1 Well-Drilling Selection Guide

Drilling Method	Drilling Fluid	Casing Advance	Type of Material Drilled	Typical Drilling Depth, in m (ft)[A]	Typical Range of Borehole Sizes, in cm (in.)	Samples Obtainable[B]	Coring Possible	Reference Section
Power auger (Hollow-stem)	none, water, mud	yes	soil, weathered rock	<45 (150)	12.7–55 (5–22)	S, F	yes	6.2
Power auger (Solid-stem)	water, mud	no	soil, weathered rock	<45 (150)	5–25 (2–10)	s	yes	6.3
Power bucket auger	none, water (below water table)	no	soil, weathered rock	<45 (150)	45–120 (18–48)	S	yes	6.4
Hand auger	none	no	soil	<20 (70) (above water table only)	5–15 (2–6)	S	yes	6.5
Direct fluid rotary	water, mud	yes	soil, rock	>300 (1000)	5–90 (2–36)	S, R	yes	7.3
Direct air rotary	air, water, foam	yes	soil, rock	>460 (1500)	5–90 (2–36)	S, R, F	yes	7.4
DTH hammer	air, water, foam	yes	rock, boulders	<600 (2000)	10–40 (4–16)	R	yes	7.5.1
Wireline	air, water, foam	yes	soil, rock	>300 (1000)	7.6–15 (3–6)	S, R, F	yes	7.6
Reverse fluid rotary	water, mud	yes	soil, rock	<600 (2000)	30–90 (12–36)	S, R, F	yes	7.8
Reverse air rotary	air, water, foam	yes	soil, rock	>300 (1000)	30–90 (12–36)	S, R, F	yes	7.7
Cable tool	water	yes	soil, rock	<1500 (5000)	10–60 (4–24)	S, R, F (F–below water table)	yes	8
Casing-advancer	air, water, mud	yes	soil, rock, boulders	<600 (2000)	5–40 (2–16)	S, R, F	yes	9
Direct-push technology	none	yes	soil	Typical 6-7 (20-25) Maximum <30 (100)	3.8–7.6 (1.5–3)	S, F	yes	10
Sonic (vibratory)	none, water, mud, air	yes	soil, rock, boulders	<150 (500)	10–30 (4–12)	S, R, F	yes	11
Jet percussion	water	no	soil	<15.0 (50)	5–10 (2–4)	S	no	12
Jetting	water	yes	soil	<15 (50)	10 (4)	S	no	12

[A] Actual achievable drilled depths will vary depending on the ambient geohydrologic conditions existing at the site and size of drilling equipment used. For example, large, high-torque rigs can drill to greater depths than their smaller counterparts under favorable site conditions. Boreholes drilled using air/air foam can reach greater depths more efficiently using two-stage positive-displacement compressors having the capability of developing working pressures of 12 to 17 kPa (250 to 350 psi) and 14 to 21 m^3/h (500 to 750 cfm), particularly when submergence requires higher pressures. The smaller rotary-type compressors only are capable of producing a maximum working pressure of 6 kPa (125 psi) and produce 14 to 34 m^3/h (500 to 1200 cfm). Likewise, the rig mast must be constructed to safely carry the anticipated working loads expected. To allow for contingencies, it is recommended that the rated capacity of the mast be at least twice the anticipated weight load or normal pulling load.

[B] Soil = S (Cuttings), Rock = R (Cuttings), Fluid = F (some samples might require accessory sampling devices to obtain).

data that may be useful during initial site evaluation include, but are not limited to, topographic maps, aerial photography, satellite imagery, information from reconnaissance drilling, borehole geophysical-log data, geologic maps and reports, statewide or county soil surveys, water-resource reports, well databases, and mineral-resource surveys covering the proposed project area. Available reports of surface and subsurface investigations of nearby or adjacent projects should be considered and the information applicable to the current project evaluated and applied if determined reliable and beneficial. Site-specific surface geophysical surveys (**2-5**) and direct-push methods for soil and groundwater data collection (see Guide D6429 and Guide D6001) also may be useful for planning drilling locations.

5.2 Site investigations for the purpose of determining the specific placement locations of monitoring-well installations can vary greatly due to the availability of reliable site data. The general procedure, however, is as follows. First, gather factual information and data regarding the surface and subsurface conditions, then analyze the data for completeness and reliability, develop a conceptual framework or model of the site, and locate the monitoring wells based on information from the first three steps. To the extent possible, monitoring wells should be installed with an understanding of the ambient hydrogeologic site conditions. Monitoring wells often serve as part of an overall site investigation for a specific purpose, such as determining the chemical quality of the water, gaining insight into hydrochemical processes, or for predicting the effectiveness of aquifer remediation. In these cases, extensive additional geotechnical and hydrogeologic information may be required.

5.3 If the monitoring well also is to be sampled for water quality during the drilling process, the possible damage and subsequent aquifer contamination caused by drilling-fluid invasion of the borehole wall that may occur during drilling must be considered. For installation of monitoring wells designed for water-sample collection, preferred drilling methods are those that do not require the use of a drilling fluid, or if a drilling fluid is used, result in little or no drilling-fluid invasion of the borehole wall. Drilling-fluid invasion of the borehole wall normally results from the use of a poorly-controlled and improperly-designed drilling-fluid program.

5.4 Drilling methods that advance the casing as drilling proceeds are very effective methods to minimize the effects of drilling-fluid invasion of the borehole wall. Casing-advance drilling methods include, or can be used with, cable-tool drilling, hollow-stem auger drilling, reverse-circulation drilling using dual- or triple-wall drill pipe, fluid- and air-rotary drilling, rotosonic drilling methods, and driven wells. If the tendency of this method is to overream the hole, contamination may move along the casing during drilling.

5.5 Drilling methods that do not use a drilling fluid are preferable because they preclude possible aquifer contamination from such fluids. Such drilling methods that normally preclude the use of drilling fluids include hollow- and solid-stem auger drilling, hand auger drilling (only an effective shallow-drilling method when used to drill above the water table), bucket auger drilling, resonant sonic-drilling method, and cable-percussion drilling methods. Methods that normally require the use of a drilling fluid for drilling include jet-wash and jet-percussion drilling, reverse-circulation drilling, and fluid- and air-rotary drilling. In cases where drilling-fluid loss occurs during drilling, estimates of the amounts of fluid loss and depth(s) of these occurrences in the borehole should be documented. Drilling-fluid loss data may be useful in planning well-development techniques to be used upon completion of the borehole. Another important factor to be considered when evaluating this data is well-screen placement.

5.6 If drilling methods are not properly performed, poor quality samples, borehole damage, or poor quality monitoring-well installation(s) may result. It has been shown that improper drilling, particularly when drilling in unconsolidated materials (soils), can cause borehole damage. Preferential seepage paths can be formed close to the borehole by washing fine particles and creating "draining chimneys" that can be very difficult to seal (**6-8**). Drilling damages to the borehole usually are more severe in boreholes drilled in unconsolidated materials than those occurring in boreholes drilled in consolidated materials (rock). Although documentation of these occurrences is rare, it does occur. Occurrences of this nature are probably due to poor drilling-fluid control, poor drilling practice by an inexperienced driller. Damage can occur by drilling too hastily, and by use of incorrect speeds, pressures, and other variables controlled by the driller. Any drilling method using a circulating media to control cuttings removal can cause hydraulic fracturing of the drilled materials if too high of drilling rate or circulation pressure is applied.

5.6.1 Water without additives is not effective as a drilling fluid for two reasons, first, it does not have any cuttings-carrying capacity, having a Test Method D6910 Marsh-funnel viscosity of only 26 s, and secondly, it does not possess any gel-strength properties for building a mud rind on the borehole wall, allowing for borehole wall collapse, differential sticking of the drill tools to the borehole wall, and creation of "draining chimneys" due to fluid invasion and internal erosion of the borehole wall (**1, 9**). Also, water containing only natural clays should not be used as a drilling mud. This fluid mixture, containing only natural clays and water, will make only a heavy, clay-laden fluid that will not have the capacity (viscosity) to carry the drill cuttings uphole and will not make a thin mud rind on the borehole wall to inhibit its collapse (lack of gel strength). Instead, it will allow washouts of the borehole wall, fluid and clay penetration into the borehole wall, and perhaps, cause differential sticking and loss of the drill tools in the borehole. Channeling and chimneys of sand also can result in the borehole wall allowing preferential seepage paths close to the borehole.

5.6.2 When air-rotary drilling, downhole air pressures should be maintained and documented carefully. Uphole (return) air pressure(s) should be adequate to maintain cuttings removal from the borehole but not excessive enough to cause hydraulic fracturing of the materials being drilled. Such practice can result in a damaged borehole wall and the inability to form a proper seal between casing and the borehole wall in the completed installation. Borehole contamination, such as those discussed can occur (**1, 9**).

5.7 The practice of incremental drilling and sampling, using temporary casings through separate aquifers, can result in cross-contamination. To avoid or minimize the possibility of borehole cross-contamination or leakage from occurring whenever an aquitard or impermeable confining layer of material is drilled through, using any drilling method or a combination thereof, the following technique is suggested, particularly when drilling under saturated conditions. The impermeable material should be drilled into but not completely through. Casing should be installed into the impermeable material and pressure cemented/grouted into place. After the cement/grout has adequately cured, the material remaining in the casing can be drilled out. Borehole geophysical methods then can be used to evaluate the seal between the borehole annulus and the wall of the casing. After an acceptable seal has resulted, drilling completely through the confining layer can be done. Continue drilling/sampling/coring operations until the desired borehole depth has been reached. If other confining layer(s) are to be drilled in the same borehole, the above technique(s) can be followed. The next casing installed should be the next smaller size to the previously-installed casing (**9**).

5.8 Some methods that can be used in order to assess the hydraulic integrity of the borehole or a subsequent installation include the following.

5.8.1 *Indirect Method(s):*

5.8.1.1 Selected borehole geophysical logging methods (**10-12**).

5.8.1.2 Introduction of tracer(s) to the borehole combined with pumping tests (**13**).

5.8.2 *Direct Method(s)* (**6**, **7**)*:*

5.8.2.1 Pumping test(s) of the borehole.

5.8.2.2 Injection test(s) of the borehole.

5.8.2.3 Inflatable-packer testing of the borehole.

5.9 Ultimately, selection of a drilling method from several possible methods must be made only after weighing all of the advantages and disadvantages of each method against data-collection objectives. In some cases, a drilling method that minimizes the potential for subsurface contamination by the drilling process might limit the types of other data that can be collected, for example, borehole-geophysical data, from the well.

5.9.1 Geophysical surveys also should be used, when possible, to aid in the selection of a drilling method. Surface geophysical methods, such as seismic surveys and electrical-resistivity and electromagnetic-conductance surveys, can be valuable particularly when distinct differences in the properties of contiguous subsurface materials are indicated (**3**, **4**, **14**, **15**). Borehole-geophysical methods, such as fluid temperature and resistivity, natural gamma, gamma-gamma, neutron, sonic-velocity logging, caliper logging, and borehole televiewer logs (fracture logging), are useful to confirm specific subsurface geologic conditions. Borehole television logs allow a visual study of existing borehole-wall conditions, as well as viewing casing conditions in a cased borehole. Acoustic borehole televiewer logs can exhibit fracturing in the borehole. The orientation of the fractures, as well as the extent of fracture occurrence, can be determined using acoustic televiewer logs. Natural gamma logs, when used in conjunction with original driller's logs, are useful particularly for determining lithology in existing cased wells. Guide D5753 and the following references provide additional information on use of geophysical logging techniques (**4**, **8**, **10**–**11**, **16**–**17**). All of these data can play an important part in selecting a drilling method that can provide the best samples and most successful monitoring-well installation under the ambient hydrogeologic field conditions.

5.10 The advantages and disadvantages of the various drilling methods presented in this guide will vary depending on site-specific characteristics and project circumstances. Drilling depth and borehole diameters shown in Table 1 are nominal values for the method and may vary for specific cases or conditions.

5.10.1 The planning of the type(s) of drilling equipment to be used on the project should include sampling requirements and well-completion requirements consideration(s). For instance, grouting and placement of well screen(s) are common well-completion requirements, and the ability to accomplish either of these is dependent greatly on the type of equipment used. The accomplishment of satisfactory hole-abandonment procedures, as well as the ease at which any particular drilling equipment can be decontaminated also are important factors to be considered.

5.11 When using a drilling method that requires use of a drilling fluid, it is recommended that a controlled drilling-fluid program be employed in order to minimize possible drilling-fluid invasion effects on the borehole and cores obtained (**9**, **18**). Auger drilling tends to smear fine-grained sediment cuttings onto the borehole wall during the rotation of the auger flights. Cable-tool drilling can cause borehole damage by the cyclic upward and downward surging motion of the drill bit, which can force fine-grained sediment into the borehole wall. Soil compaction resulting from driving the casing also can occur in a cable-tool drilled borehole. Although reverse-circulation drilling commonly is considered a clean drilling method, invasion of fine-grained sediment into the borehole wall can occur because of the high positive hydrostatic head that must be maintained in the borehole during drilling. Also, if drilling mud or other additives are used in the reverse-circulation drilling method, borehole damage can occur. Air-rotary drilling methods also may damage the borehole by introducing air into the drilled materials or fracturing of the borehole wall if drilling air pressures are not closely monitored and are allowed to exceed the downhole pressure necessary to adequately keep the borehole free of cuttings.

5.12 Choice of drilling methods may differ depending on whether the data-collection objective is for hydrogeologic characterization or for groundwater quality sampling or not. For example, fluid-rotary drilling methods are good drilling methods to use for determining subsurface lithologic characterization because most borehole electric and sonic geophysical-logging tools require uncased fluid-filled boreholes. The same drilling methods, however, are less desirable for installation of water-quality monitoring wells because of the possible drilling-fluid effects on groundwater chemistry. Nevertheless, fluid-rotary drilling may be the method selected after considering the advantages and disadvantages of other drilling methods.

5.13 Selection of a drilling method must consider all aspects of monitoring-well installation, including casing materials and composition, screen(s), subsurface monitoring equipment and installation(s), grouting materials and placement procedure(s), as well as any other plans for well completion and development. For example, when a drilling method is used that might affect groundwater chemistry, the well development required to remove artifacts of the drilling can be intensive, time consuming, and affect water chemistry.

5.13.1 The drilling method selected must be practical logistically, and to the extent possible, minimize mechanical damage to the borehole. Local availability of a particular type of drilling rig/equipment also will be an extremely important factor to be considered before a drilling method can be selected. For instance, the availability of cable-tool rigs might be totally out of the question in some parts of the country where primarily rotary-type drilling methods are most prevalent because of the type(s) of drilling conditions in those areas. In addition, information on the geohydrology of the subsurface system might be required and can be obtained possibly by means of sampling during drilling or subsequent borehole-geophysical logging, or a combination of both methods. Final selection of a drilling method, therefore, should be made only after due consideration of all project objectives (**19**).

6. Auger-Drilling Methods

6.1 Auger-drilling methods include using hollow-stem continuous-flight augers, solid-stem continuous-flights augers, bucket augers, and hand-augers. All auger-drilling methods are limited usually to drilling in unconsolidated soils or weathered rock. Auger-drilling methods normally do not require the use of a drilling fluid during the drilling process; however, in cases where water-bearing sands or silts are drilled, the addition of water or drilling mud to the hollow-auger column may be necessary to inhibit the "blow in" of these fluid-like materials into the augers (see Guide D5784). The borehole is advanced by pushing the initial auger-column assembly below ground surface and initiating a low-velocity rotation to the auger flights or bucket-auger assembly. The lead auger section is equipped with a removable cutting head. The bucket auger, on the other hand, has hard-surfacing material around the bottom cutting edge of the bucket. As drilling progresses, auger flights or kelly rods, in the case of a bucket auger, are added to the drill stem until the desired depth is reached. The continuous auger flights carry drill cuttings to the surface.

6.2 *Hollow-Stem Auger Drilling*—The hollow-stem continuous-flight auger drilling method can be used for the installation of monitoring wells (see Practice D6151. The hollow auger flights serve as a temporary casing, which prevents caving and sloughing of the borehole wall while the monitoring-well casing is installed through the hollow auger (see Guide D5784). The hollow-stem auger-drilling method also allows for the utilization of the hollow-stem auger column as a casing for subsequent drilling activities in soils or rock (see Practice D2113). Borehole diameters up to about 55-cm (22-in.) can be drilled using hollow-stem augers. A monitoring-well casing can be installed through the hollow stem auger (auger I.D. up to 30-cm (12-¼-in.) available for insertion of casing or other instrumentation) once drilling is complete and prior to removing the augers from the borehole.

6.2.1 Soil sampling, using a split-barrel sampler, ring-lined barrel sampler (see Practice D3550), or thin-walled tube sampler (see Practice D1587), is accomplished during drilling by using a continuous sampler in the hollow-stem that advances with the auger flight or by a pause in drilling, driving, or pushing the sampler into the undisturbed material beyond the cutting head, and retrieving the sample before resuming drilling (see Test Method D1586 and Practices D1587 and D2488). The continuous auger flights carry drill cuttings to the surface. Soil samples also can be obtained during drilling, either as return by the auger flights or by pulling the augers and sampling the sediment stuck to the auger flights, but such samples are less satisfactory because the soil is disturbed and moved from the location of drilling and exposed to other soil stratum. Samples of this nature generally are not considered appropriate for chemical analysis. Groundwater samples can be obtained during drilling using a screened hollow-stem auger section. Direct-push methods also can be used in advance of the lead auger during drilling pauses to collect either fluid or soil samples or both.

6.2.2 Continuous hollow-stem soil-coring equipment consists of a rotating outer hollow-stem auger with a cutter-head bit at the bottom and a nonrotating inner sample barrel equipped with a smooth cutting shoe at the bottom (see Practice D6151). Some continuous hollow-stem auger sampling systems have a centralizer bushing mounted in the cutter head. The sampler is suspended in the hollow-stem auger column and retained in a stationary position by means of a bearing-assembly apparatus located either down the hole above the sampler assembly or located at the top of the hollow-stem auger column. The sample barrel cutting shoe is extended beyond the hollow-stem auger cutter-head bit in varying increments. The distance that the sample barrel cutting shoe is adjusted out beyond the hollow-stem auger cutting head is dictated by the stiffness of the material to be sampled (cored). The softer the soil to be cored, the greater the "lead" distance adjustment or cutting-shoe extension should be. The harder the soil to be cored, the shorter the lead-distance adjustment should be. When the sampler cutting shoe is extended beyond the hollow-stem auger, cutter-head bit the cutting edge of the sampler cutting shoe is forced into the soil ahead of the hollow-stem cutter head bit before the hollow-stem auger cutter-head bit cuts the soil away. The hollow-stem auger column and cutter-head bit rotates around the soil-coring barrel as the drill rig applies an axial force and rotation to the hollow-stem auger soil-coring column assembly.

6.2.3 *Advantages:*

6.2.3.1 Normally, precludes use of drilling fluids.

6.2.3.2 Auger drilling does not require the use of lubricants.

6.2.3.3 Continuous sampling possible during drilling using continuous sampler, split-barrel, or thin-walled samplers.

6.2.3.4 Continuous samples of groundwater can be collected during drilling, using screened auger flight(s).

6.2.3.5 The hollow-stem auger column can be used for subsequent drilling activities in soils or rock materials (see Practice D2113).

6.2.3.6 Auger-drilling equipment is relatively mobile.

6.2.3.7 Drilling is moderately fast.

6.2.4 *Disadvantages:*

6.2.4.1 Pressure equalization of water-bearing sands or silts and "blow in" of these fluid-like materials into the hollow-stem auger column can be a problem requiring use of fluid in the hollow auger to equalize the pressure head and keep the intrusive fluid-like materials from entering the hollow auger.

6.2.4.2 Soil samples returned by auger flight are disturbed, making it difficult to determine the precise depth from which the sample(s) came.

6.2.4.3 Upward vertical mixing of augered cuttings can occur.

6.2.4.4 Borehole wall can be smeared by previously-drilled clay.

6.2.4.5 Gravel pack and grout seal may be difficult to install.

6.2.4.6 Borings limited to relatively shallow depths in normal soils and soft rock.

6.2.4.7 Difficult drilling in extremely dry, fine materials, for example, playa-lake deposits.

6.2.4.8 Hollow-stem auger drilling difficult in saturated soils and soils containing very coarse gravels, cobbles, or boulders.

6.2.4.9 Hollow-stem auger does mechanically affect formation intrinsic permeability due to smear at the edge of the auger flights.

6.3 *Solid-Stem Auger Drilling*—Solid-stem continuous-flight auger drilling may be used as an alternative to hollow-stem auger drilling and other drilling methods in drilling of soil and soft or weathered rocks in which the soil generally is unsaturated, however, saturated clays drill well, and therefore, are less likely to collapse. Solid-stem auger drilling is accomplished by pushing the auger-column assembly below the ground surface and initiating a low-velocity rotation. As drilling progresses additional auger flights are added to the auger-assembly column. The continuous auger flights carry drill cuttings to the surface. Disturbed soil samples can be obtained during drilling as augered cuttings return. If the borehole remains open after removing the auger-column assembly, a monitoring well can be installed in the open borehole. The solid-stem augers drilling method often is a less-effective method to be used for installing a monitoring well than the hollow-stem augers drilling method because the solid-stem augers cannot be used as temporary casing to prevent caving and sloughing of the borehole wall. Under saturated conditions, solid-stem auger drilled boreholes usually collapse immediately upon auger removal. In some instances, if the soil(s) drilled using the solid-stem augers contain a relatively high amount of cohesive materials, such as, clayey silts, silts, etc., the borehole will remain completely open for the entire auger-drilled depth after auger removal, making it very easy to install the monitoring-well casing/instrumentation to the bottom of the borehole.

6.3.1 Soil sampling during solid-stem auger drilling using a split-barrel or thin-walled sampler only can be accomplished by pulling the auger flights from the borehole each time sample is collected. The success of the split-barrel or thin-walled tube sampling operation depends on the integrity of the borehole wall to remain open (**9**).

6.3.2 *Advantages:*

6.3.2.1 Normally, precludes use of drilling fluids during drilling.

6.3.2.2 Auger drilling does not require the use of lubricants.

6.3.2.3 Auger-drilling equipment is relatively mobile.

6.3.2.4 Drilling is moderately fast.

6.3.3 *Disadvantages:*

6.3.3.1 Soil samples may not be returned by augers.

6.3.3.2 Soil samples returned by auger flight are disturbed making it difficult to determine the precise depth from which the sample(s) came. Auger samples returned after drilling below the water table are not reliable because of the upward vertical mixing of borehole fluid and augered cuttings can occur.

6.3.3.3 Borehole wall can be smeared by previously-drilled clay.

6.3.3.4 Borehole can collapse before the monitoring well or subsurface water-quality monitoring device installation can be completed.

6.3.3.5 Gravel pack and grout seal can be difficult to install because of borehole collapse or borehole rugosity.

6.3.3.6 Borings limited to drilling to relatively shallow depths in normal soils or soft rock.

6.3.3.7 Solid-stem auger drilling difficult in saturated soils and soils containing very coarse gravel, cobbles, or boulders.

6.3.3.8 Difficult drilling in extremely dry, fine materials, for example, playa-lake deposits.

6.4 *Power Bucket-Auger Drilling*—Power bucket-auger drilling is accomplished using a power bucket auger to drill a large-diameter hole, up to about 1.25-m (4-ft) in diameter. The bucket auger is attached to a kelly bar that rotates, and the weight of the kelly advances the bucket auger into the ground. Normally, use of drilling fluids during drilling is not necessary above the water table. Bucket-auger drilling generally is limited to drilling soils, weathered, and soft rock to shallow depths of less than about 65-m (150-ft). The diameter of bucket-auger drilled wells usually range from about 45 to 120 cm (18 to 48 in.) with few being larger than 90 cm (36 in.) (**1**). Soil samples obtained by the bucket-auger drilling method are representative of the soils being drilled unless caving has occurred in the borehole. Drilling in cobbles or boulders is very difficult to accomplish because other drilling tools, such as tongs or orange-peel buckets, must be used inside of the bucket auger to remove the obstructions. Drilling below the water table in sands require the hole to be water filled. In drilling extremely permeable soils, the use of drilling-fluid additives and polymers might be necessary (**1**).

6.4.1 *Advantages:*

6.4.1.1 Normally, precludes use of drilling fluids during drilling.

6.4.1.2 Soil samples can be obtained from a bucket-auger drilled borehole using numerous types of soil-sampling devices and sampling barrels.

6.4.2 *Disadvantages:*

6.4.2.1 Borehole collapse can occur during auger drilling, particularly when borehole is advanced below the water table or drilled in poorly cohesive materials.

6.4.2.2 Borings limited to drilling to relatively shallow depths in normal soils or soft rock.

6.4.2.3 Casing cannot be advanced.

6.4.2.4 Heavy equipment required.

6.4.2.5 Kelly bar(s) normally require lubrication.

6.5 *Hand-Auger Drilling*—Hand-auger drilling is accomplished by turning a hand-auger barrel attached to short extension rods into the ground by hand until the auger barrel is full of soil. The hand-auger barrel then is removed from the borehole and the disturbed soil sample is removed from the auger barrel with a rubber-headed hammer in order to prevent tool damage. The process is repeated until the desired borehole/sampling depth is attained or until the soil will no longer stay in the hand-auger barrel. Additional extension rods, usually constructed of light-weight aluminum, are attached to the auger as drilling proceeds. The success of hand-augering depends on maintaining an open hole. Borehole collapse usually occurs once hand augering proceeds below the water table; therefore, hand augering is limited to drilling shallow boreholes in soils, for example, soil, clay, silt, sand, and organic materials (peat) that maintain cohesiveness. A monitoring well may be installed in the open hole after the hand augering is complete. A common practice of monitoring-well installation using the hand-auger drilling method is to hand auger to the water table, extract the hand-auger assembly, and then drive casing with an attached well point below the water table. A hand auger is very useful for logging lithology and obtaining an accurate estimation of the depth to the water table.

6.5.1 *Advantages:*

6.5.1.1 Normally, precludes use of drilling fluids during drilling.

6.5.1.2 Hand-auger drilling does not require the use of lubricants.

6.5.1.3 Soil samples can be obtained from a hand-auger drilled borehole. Also, numerous types of soil-sampling devices and sampling barrels can be used to obtain undisturbed samples from the open hole from any depth after first removing the hand auger assembly.

6.5.1.4 Equipment highly mobile, site accessibility usually not a problem.

6.5.1.5 Permits easy access and use in remote study location(s) where a drill rig could not gain access because of environmental concerns or other logistic problems.

6.5.2 *Disadvantages:*

6.5.2.1 Borehole collapse can occur during hand-augering operations, particularly when borehole is below the water table.

6.5.2.2 Hand-auger drilling is very slow and labor intensive.

6.5.2.3 Boreholes limited to drilling relatively shallow depths, usually less than 20 m (70 ft).

6.5.2.4 Borehole diameter limited to about 15 cm (6 in.).

6.5.2.5 Boreholes limited to drilling soils that are not cemented and do not contain large gravel, cobbles, boulders, or roots. Soils containing platy particles, such as a mica, are not easily retrieved from the borehole as they tend to slide freely out of the hand-auger barrel.

6.5.2.6 Casing cannot be advanced.

7. Rotary-Drilling Methods

7.1 Rotary drilling is accomplished by initiating rotation and applying axial pressure on the drill string and bit, while simultaneously initiating and maintaining circulation of a drilling fluid. The drilling fluid used might be made up of either water mixed with certain additives (see Guide D5783) or pressurized air (see Guide D5782) as the drilling-fluid medium. The drilling fluid is circulated down through the inside of the drill string, out through the drill bit, and back up the annulus formed between the drill string and borehole wall, forward- or direct-rotary drilling method. Cuttings from the drilling operation are carried to the ground surface by the drilling fluid. At the ground surface, the cuttings-laden drilling fluid is discharged into a pit or series of pits where the drill cuttings settle out of the drilling fluid.

7.2 The hydrostatic head of the drilling fluid in the borehole maintains a positive pressure against the borehole wall, thereby, preventing its collapse. The drilling fluid also serves to carry drill cuttings to the surface, cools and lubricates the drill stem and bit, and builds a filter cake on the borehole wall. Although the drilling fluid can prevent inflow of groundwater into the borehole and help maintain stability of the borehole wall, the drilling fluid is not intended specifically for these purposes. Common drilling fluids consist of water, mixtures of water and natural clays, guar, or bentonite, or pressured air. Drilling fluids also may have additives that modify fluid characteristics, such as barite for controlling the weight of the drilling fluid; carboxylmethylcellulose (CMC) added as a viscosifier; potassium chloride (muriated potash), added to retard clay hydration, inhibiting swelling of clays on the borehole wall and inhibiting "balling" or "smearing" of the bit; or, other additives to control drilling-fluid properties necessary for drilling under various subsurface hydrogeologic conditions (see Guide D5783).

7.2.1 Some drilling-fluid components must be added to the composite mixture before other components, consequently, an auxiliary mixing reservoir may be required to premix these components with water before adding to the mud pit (**20**). All quantities, chemical composition, and types of drilling-fluid components and additives used in the composite drilling-fluid mixture should be documented. Particular attention should be given to the drilling-fluid makeup-water source and the means used to transport the makeup water to the drilling site as potential sources of contamination to the drilling fluid. If the chemical makeup of the water is determined, the test results should be documented.

7.2.1.1 The listing and discussion of drilling-fluid additives does not imply their general acceptance for geoenvironmental exploration use. Some of the additives given previously, may impact water-quality analyses. Some readily available, but not as common drilling-fluid additives not listed previously, could cause significant contamination in a borehole or hydrogeologic unit. Also, drilling additives, which will come in contact with drinking water aquifers, should meet the requirements of the National Sanitation Foundation (NSF) Standard 60–2011 (**22**). Each additive should be evaluated for each specific application. The types, amounts, and chemical compositions of all additives used should be documented. In addition, a borehole log should document the depths where any new additives were introduced. Methods used to break revertible fluids should be documented.

7.3 *Direct-Rotary Drilling with Water-Based Drilling Fluid*—Direct-rotary drilling and sampling, using various type soil/rock sampling core barrels and devices, can be done in most soils and rocks. Direct-rotary drilling with water-based drilling fluid (see 8.1 through 8.3 and Guide D5783) is accomplished by initiating rotation and applying axial pressure on the drill string and bit while simultaneously initiating and maintaining circulation of a drilling fluid. The drilling fluid is circulated down through the drill string and the cuttings-laden return comes back up the annulus formed between the drill string and the borehole wall. Cuttings from the drilling operation are carried to ground surface by the circulating drilling fluid. At the ground surface, the cuttings-laden drilling fluid is discharged into a pit or series of pits where the drill cuttings settle out of the drilling fluid.

NOTE 1—It may be necessary to agitate the cuttings-laden drilling fluid in the circulation pit(s) by pumping or stirring to facilitate dropping the cuttings out of suspension. As long as a high gel-strength mud is in motion, it is a in viscous liquid form; however, during periods of quiescence, it becomes a semisolid. Re-agitation tends to destroy the semisolid gel and restore it to its viscous liquid form of the drilling fluid and allow the cuttings to settle out freely.

7.3.1 After the cuttings have settled to the bottom of the circulation pit(s), the drilling fluid is then recirculated as drilling progresses (**19**). Core samples of overburden soil materials can be obtained. Rock coring is accomplished by drilling the borehole through the overburden, setting the casing through the overburden into the rock, and then coring the rock through the casing.

7.3.2 The drilling fluid serves several purposes. First, it carries drill cuttings to the surface, prevents collapse of the borehole wall, prevents inflow of groundwater into the borehole, and cools and lubricates the drill stem and bit. The filter cake built up on the borehole wall by the drilling fluid tends to minimize drilling-fluid invasion of the borehole wall. Likewise, when coring, a thin filter cake is built up on the exterior of the core, thereby, preventing drilling-fluid invasion and damage to the core. Conversely, use of a poorly-designed and improperly-controlled drilling-fluid program can cause borehole, as well as soil-core damage, and infiltrated drilling fluid can be difficult to remove completely from the borehole wall and adjacent soil/rock during well development. It should be stressed, however, that using a properly-designed and controlled drilling-fluid program can greatly limit drilling-fluid invasion damage to the borehole wall or soil core. Also, the use of an unbeneficiated bentonite, as opposed to beneficiated bentonite that contains chemical additives, will eliminate drilling-fluid residues, such as, organic carbon, sulfate, chloride, binding metals, sorbing organic compounds, supporting excessive biological growth, and altering the cation exchange capacity, pH, and chemical oxidation demand of natural fluids.

7.3.3 Direct-rotary drilling can employ a casing-advance drilling method in which casing is driven slightly ahead simultaneously of the advancing bit and drill string using standard direct-rotary drilling methods. This drilling method enables drilling and coring of saturated soils that otherwise might not be possible because of borehole collapse. Casing advancement also eliminates the problem of lost drilling-fluid circulation. The use of temporary casing seals off contaminated zones, prevents overburden collapse, and minimizes drilling fluid contact with aquifers. The use of the casing-advancement method of drilling also eliminates the uncertainty of whether soil samples (cores) and groundwater samples originate from the current drill depth rather than from elsewhere in the borehole.

7.3.4 *Advantages:*

7.3.4.1 Drilling readily accomplished in both soils and hard rock.

7.3.4.2 Drilling depth essentially is unlimited for all geoenvironmental drilling and sampling purposes.

7.3.4.3 Lithologic logging using drill cuttings obtained from drilling-fluid return is moderately reliable.

7.3.4.4 Drilling is relatively fast.

7.3.4.5 Borehole normally is accessible for geophysical logging prior to installation of a monitoring well or subsurface water-quality monitoring devices.

7.3.4.6 Borehole readily can be gravel packed and grouted.

7.3.4.7 Can use casing-advancement drilling method.

7.3.5 *Disadvantages:*

7.3.5.1 Drilling fluid can alter borehole-fluid chemistry.

7.3.5.2 Lubricants used during the drill process can contaminate the borehole fluid and soil/rock samples.

7.3.5.3 Filter-cake build up on wall of borehole may prevent complete development of the well.

7.3.5.4 Location of water-bearing zones during drilling can be difficult to detect.

7.3.5.5 Drilling-fluid circulation often is lost or difficult to maintain in fractured rock, root zones, or in gravels and cobbles.

7.3.5.6 Overburden casing usually is required.

7.3.5.7 Additional equipment is required to install casing.

7.3.5.8 Difficult drilling in boulders or cobbles.

7.4 *Direct Air-Rotary Drilling* —Direct air-rotary drilling is similar to that of direct rotary drilling with water-based drilling fluid except that compressed air is used as the drilling fluid instead of a water-based drilling fluid (see Guide D5782). Direct air-rotary drilling/sampling, using various soil-sampling devices and core barrels, can be done in most soils and rock. Drilling is accomplished initiating a slow rotation and applying axial pressure on the drill string and bit while simultaneously initiating and maintaining air circulation. The air is circulated down through the drill string and the cuttings-laden air return comes back up the annulus formed between the drill string and the borehole wall. Cuttings from the drilling operation are carried to a dust collector, located at ground surface, by the upward-circulating return column of air.

7.4.1 Direct air-rotary drilling using a down-the-hole hammer (DTH) is another method of direct air-rotary drilling that normally is used for drilling in hard rock, boulders, and cobbles. In this method, a pneumatic drill rapidly strikes the rock as the drill bit is rotated slowly. The percussion effect of the DTH hammer bit pulverizes the rock, thereby, increasing the drilling rate. Normally, to prevent hammer failure and bit seizure due to operating-caused friction heating of the moving parts, the DTH hammer must be lubricated by means of an oil-injection pump. The oil-injection pump is adjusted to inject continuously a small quantity of rock-cutting oil into the air stream for lubricating the DTH hammer while drilling. The type of lubricating oil, lubricating-oil injection rate, location in the borehole of the injection, quantity of oil injected, as well as the chemical makeup of the rock-cutting oil, should be documented.

7.4.2 The air stream used in air-rotary drilling does not provide support for the borehole wall; therefore, unlike fluid-rotary drilling, air-rotary drilling relies on the integrity of the borehole wall to prevent borehole collapse. Consequently, air-rotary drilling is limited to partially lithified soil and rock units. One method of drilling is to use direct rotary with a water-based drilling fluid to drill through the unconsolidated units, then convert to direct air-rotary drilling once into semiconsolidated rock. A technique used to enhance drilling speed and cuttings removal is to add a foam surfactant to the air stream. The foam also reduces loss of air circulation into the surrounding borehole wall; however, the use of foam should be documented as it can affect the borehole chemistry.

7.4.3 Unless filtered, the intake air and the air discharged from the compressor may contain hydrocarbons that could affect water chemistry. Since most all air compressors are of the piston type, they undoubtedly will add some oil into the air stream even if HEPA filters are placed in the compressor intake port and on the discharge port. Oilless compressors are available but are not common. Also, the air stream possibly can strip volatile contaminants from the borehole wall during drilling, temporarily affecting the soil and groundwater quality. The air stream exiting the borehole can pose a health risk if the borehole is drilled in contaminated soil or rock.

7.4.4 *Advantages:*

7.4.4.1 Drilling and well installation readily accomplished in partially-lithified rock and hard rock.

7.4.4.2 Depth of drilling unlimited for all practical purposes.

7.4.4.3 Drilling in rock or soil is relatively fast.

7.4.4.4 Borehole is accessible for geophysical logging prior to monitoring-well installation.

7.4.4.5 Annulus formed between well casing and borehole wall readily gravel packed and grouted.

7.4.4.6 Well development relatively easy.

7.4.4.7 Can use casing-advancement method.

7.4.5 *Disadvantages:*

7.4.5.1 May inject water, foam, or other fluid once saturated zone is encountered in order to prevent mud rings from forming on drill rod. Drilling foam added to air stream can affect groundwater quality and should be documented.

7.4.5.2 Water-bearing zones may be difficult to detect during drilling.

7.4.5.3 Compressor discharge air may contain hydrocarbons.

7.4.5.4 The air stream can possibly strip volatile contaminants from the borehole wall during drilling temporarily affecting the groundwater quality.

7.4.5.5 Air stream exiting borehole may pose a health risk if drilling in contaminated soil and rock.

7.4.5.6 DTH hammer drilling can cause hydraulic fracturing of the borehole wall.

7.4.5.7 Overburden casing usually required.

7.4.5.8 The DTH hammer requires lubrication during operation.

7.5 *Direct-Rotary Drilling with Driven Casing*—Direct-rotary drilling in soils with simultaneously-driven casing employs standard direct air- or water-based fluid-rotary drilling methods with the addition of casing being driven simultaneously as the drilling progresses. This drilling method enables drilling and sampling of water-bearing units and overburden that otherwise might not be possible to drill because of borehole collapse. Also, the simultaneously-driven casing reduces the problem of lost drilling-fluid circulation in the borehole. By using the simultaneously-driven casing drilling method, combined with using pressured air as the drilling-fluid, it is possible to readily-identify water-bearing units and estimate aquifer yield during the drilling process. The temporary casing seals off natural zones of borehole fluid-flow and inhibits air- or drilling-fluid contact with the borehole wall, minimizes cross-contamination among aquifers, and prevents drilling-fluid invasion of the aquifers. There have been cases, however, when cross contamination has occurred along temporary casings (see 5.7). The simultaneously-driven casing method of drilling also eliminates the uncertainty regarding whether soil samples or borehole-fluid samples obtained from the borehole originate from the part of the borehole being presently drilled rather than from elsewhere in the borehole.

7.5.1 A direct-air or fluid-rotary drilling method that utilizes simultaneous casing-advancement principles is employed for overburden drilling. The method uses a pilot bit with an underreamer. The eccentric reamer drills a slightly larger borehole than the outside diameter of the casing. Threaded casing is advanced simultaneously with and immediately behind the eccentric reamer by the impact energy which is transmitted from either the DTH hammer to the casing tubes or from impact energy imparted to an upper casing drive cap from an uphole hammer system. Drilled cuttings are carried up the inside of the casing tubes using an air, air/foam (used below depths of about 15 m (50 ft)), or water-based drilling fluid. The cuttings are removed from the system through a discharge head located at the top of the drilling-fluid circulation system. Boreholes can be reamed up to slightly more than 20 cm (8 in.) in diameter and lined with casing tubes to depths of about 90 m (300 ft) using this method of drilling.

7.5.2 *Advantages:*

7.5.2.1 Drilling readily accomplished in normal soils, particularly those soils difficult to drill by other methods, such as bouldery till and coarse stratified deposits.

7.5.2.2 Temporary casing maintains stable borehole wall.

7.5.2.3 Water-bearing zones readily identified.

7.5.2.4 Yield of water-bearing units readily estimated.

7.5.2.5 Temporary casing seals off contaminated aquifers.

7.5.2.6 Problems of lost circulation during drilling are greatly minimized, however, lost circulation can still occur at or near the bit.

7.5.2.7 Minimizes sediment, air or drilling fluid contact with the borehole wall.

7.5.2.8 Minimizes cross-contamination among aquifers.

7.5.2.9 Prevents drilling-fluid invasion of the borehole wall.

7.5.2.10 Eliminates uncertainty that soil and groundwater samples are known to originate from borehole depth currently being drilled.

7.5.2.11 Cased borehole available for geophysical logging prior to installation of a monitoring well.

7.5.3 *Disadvantages:*

7.5.3.1 Equipment is not readily available and is expensive.

7.5.3.2 Extraction of casing can cause smearing of borehole wall with silt or clay.

7.5.3.3 Extraction of casing can damage well screen.

7.5.3.4 Not good for drilling in sands below water table.

7.6 *Wireline-Rotary Drilling*—Wireline-rotary drilling (see Guide D5876) is a drilling/coring process, which uses special enlarged inside diameter wireline-drilling rods with special latching pilot bits or core barrels, which are raised or lowered inside the rods with a wireline and overshot-type latching-assembly. The bottom section of rod has either a diamond or carbide coring bit and reaming shell attached to the end. The bottom rod is connected to the upper rod(s) by means of an internally-machined latching coupling that is threaded to the top of the bottom section of rod and serves to accommodate latching of either a pilot bit or a core barrel. The overshot mechanism is designed to latch and unlatch either the bit or the inner core-barrel assemblies from the latching coupling (**21**). Bit cutting is accomplished by applying a simultaneous combination of rotary and axial forces to the bit while initiating drilling-fluid circulation through the system. General borehole advancement may be performed without sampling by using either a pilot roller cone bit or drag bit until the desired depth is reached. Alternatively, the soil/rock may be sampled continuously or incrementally by replacing the pilot bit with a core-barrel assembly designed for coring either rock or soil. The pilot bit or inner core-barrel assembly can be inserted and removed at any time during the drilling process and the large inside diameter rods provide a temporary casing for borehole testing, using borehole packers, borehole geophysical-logging devices and sondes, etc., or installation of monitoring devices.

7.6.1 When drilling with fluid, the circulation generally is forward and cuttings return up the annulus formed between the borehole wall and the drill rod. This circulation pattern can be problematic in cases where advancement rate is too fast and drilling-fluid circulation is lost (possible fracturing) or where soils cave or plug the bit. Borehole damage more likely is to occur with wireline drilling due to the drilling-fluid circulation being focussed at the bit. Minimal damage occurs when circulation is monitored and maintained carefully. Often rock-core drilling applications require polymer drilling fluids, which have the ability to further penetrate the borehole wall, and consequently, seal off larger fracture systems. Drilling fluids used for drilling or coring soil deposits should be relatively viscous, usually having a Marsh-funnel viscosity greater than that of water, which is 26 s (**19**).

7.6.2 Direct-rotary wireline drilling with fluid is applicable to drilling a wide variety of soil or rock, as long as drilling-fluid circulation can be maintained. Wireline casing-advancement drilling has advantages of high penetration rates in drilling a wide variety of materials with the added benefit of the large-diameter drilling rod serving as protective casing. Some wireline systems have been adapted for drilling of soil deposits with special sample barrels or bits. Sometimes, problems with soil-drilling systems occur in cohesionless soils below the water table where sanding in of the drilling rod may prevent subsequent inner barrel or bit latching. In general, when wireline drilling and coring method(s) are used, drill rods need only to be removed when the coring bit becomes worn or damaged or if the inner core-barrel assembly or latching-bit assembly becomes sandlocked in the lead wireline-rod section and cannot be retrieved by using the overshot assembly. Boreholes drilled by the wireline casing-advancement method will usually require more well-development efforts than cable-tool drilled holes require if drilling-fluid additives are used. Wireline casing advancers may be adapted to drill and core using pressured air as the drilling fluid medium for sampling water-sensitive deposits where fluid exposure may alter the core, or in cavernous materials, or where fluid circulation loss occurs. For use of air as the circulating fluid, see Guide D5782.

7.6.3 *Advantages:*

7.6.3.1 Open large-diameter wireline drill rods allow for interval testing during pauses in drilling.

7.6.3.2 Drilling possible in gravel and cobble deposits.

7.6.3.3 The ability to drill rather rapidly through rock.

7.6.3.4 Air-rotary drilling techniques usually are employed to drill in water-sensitive materials, that is, friable sandstones or collapsible soils, may preclude rotary-drilling methods using water-based drilling fluids.

7.6.4 *Disadvantages:*

7.6.4.1 Lost circulation can be a problem when drilling in fractured, weathered, or otherwise extremely porous rock such as limestone or scoria. Polymers added to drilling fluid can invade rock fractures.

7.6.4.2 Plugging or hydraulic fracturing of the borehole wall can occur if drilling rate is too fast or if downhole circulating air pressure is allowed to greatly increase exceeding that pressure, which is adequate to clear the borehole of drilled cuttings.

7.6.4.3 Poor borehole integrity can result in normal soils if casing is not used.

7.6.4.4 If outer casing bit fails, drill string may have to be removed.

7.6.4.5 Possible volatilization of contaminants and airborne dust.

7.6.4.6 Air drilling may not be a satisfactory drilling method to be used in drilling unconsolidated, or cohesionless soils, or both, under saturated conditions.

7.7 *Dual-Wall Reverse-Circulation Drilling*—Dual-wall reverse-circulation drilling is a drilling method, whereby, pressurized air is circulated down the annulus formed between the outer and inner (dual) drill pipes/tubes which form the drill string and back up the inner of the two drill pipes/tubes (see Guide D5781). Usually, the outside diameter of the drill bit is very close to that of the inside diameter of the outer casing. Consequently, the outer casing partially or completely supports the borehole wall. A major advantage of using the dual-wall reverse-circulation drilling method over other rotary-drilling methods is that drilling is accomplished readily in soils that would otherwise collapse during the drilling process or would cave in as soon as temporary casing had been withdrawn from a borehole prior to the installation of a monitoring well or subsurface water-quality monitoring device. Also, the presence of casing in a borehole minimizes the occurrence of lost drilling-fluid circulation in porous or fractured formations.

7.7.1 The dual-wall reverse-circulation drilling method also reduces the uncertainty of the depth from which soil cuttings and borehole fluid samples have originated in the borehole.

7.7.2 *Advantages:*

7.7.2.1 Drilling readily accomplished in soil and rock.

7.7.2.2 Depth of drilling is unlimited for all practical purposes.

7.7.2.3 Stratigraphic and lithologic logging are sometimes possible from drill-cuttings samples.

7.7.2.4 Outer casing of dual-wall drilling pipe prevents borehole wall caving during drilling.

7.7.2.5 Drilling-fluid circulation loss during drilling is minimized when using dual-wall drilling pipe.

7.7.2.6 Outer casing of dual-wall drilling pipe seals off zones of contamination within the borehole.

7.7.2.7 Dual-wall drill pipe minimizes drilling-fluid invasion of the drilled soils and rock.

7.7.2.8 The dual-wall reverse-circulation drilling method also reduces the uncertainty of the depth from which soil cuttings and borehole fluid samples have originated in the borehole.

7.7.3 *Disadvantages:*

7.7.3.1 Emplacement of gravel pack and grout seal in the borehole can be difficult to accomplish.

7.7.3.2 Equipment might not be readily available and is expensive.

7.7.3.3 Extraction of casing can cause smearing of borehole wall with silt or clay.

7.7.3.4 Extraction of casing can damage well screen.

7.7.3.5 Must set a temporary casing to set a well.

7.8 *Reverse-Circulation Drilling Using a Water-Based Drilling Fluid*—Reverse-circulation drilling using a water-based drilling fluid is accomplished by applying a simultaneous combination of rotary and axial forces to the bit while initiating drilling-fluid circulation through the system. In the reverse-rotary drilling method, the drilling fluid is circulated down the annulus formed between the drill string and borehole wall, through the drill bit, and back up the inside of the drill string. Cuttings from the drilling operation are carried up the inside of the drill string by the drilling fluid. The cuttings-laden drilling fluid, subsequently, is discharged at ground surface into a settling pit or series of settling pits where the drill cuttings settle out.

7.8.1 Clear water, rather than mud, often is used as the drilling fluid. Commercially available drilling-fluid additives only are used to increase fluid density and viscosity to the point sufficient to carry cuttings to the surface; therefore, a drilling-fluid control program is of much less concern in reverse-circulation drilling than it is in fluid-rotary drilling. When the reverse-circulation drilling method is used, the user should be aware that the water used as a circulation medium can invade the aquifer, thereby, changing the native fluid chemistry of the aquifer. This occurrence should be documented. When drilling-fluid additives are used in reverse rotary drilling, the same possible problems with regard to drilling-fluid effects on the groundwater chemistry apply as for fluid-rotary drilling.

7.8.2 *Advantages:*

7.8.2.1 Drilling readily is accomplished in soils and most hard rock.

7.8.2.2 Drilling relatively is fast and for drilling large-diameter boreholes.

7.8.2.3 Borehole is accessible for geophysical logging prior to well installation.

7.8.2.4 Large-diameter borehole, if cased, permits easy installation of monitor well and subsurface water-quality monitoring devices and emplacement of gravel pack and grout in the annulus formed between the monitor-well casing and the borehole wall.

7.8.3 *Disadvantages:*

7.8.3.1 Drilling through loose cobbles and boulders may be difficult.

7.8.3.2 Large quantities of water usually are required for drilling.

7.8.3.3 Use of drilling fluids and polymeric additives can affect the borehole chemistry.

7.8.3.4 Air, if used to aid in lifting of cuttings, can affect the borehole chemistry.

7.8.3.5 Lubricants, if used during the drilling process, can affect the borehole chemistry.

7.8.3.6 Drilling equipment is large and heavy; therefore, site access may be a problem.

8. Cable-Tool Drilling

8.1 Cable-tool drilling is accomplished by repeatedly lifting and dropping a weighted drill bit suspended from a cable (see Guide D5875). The repeated dropping of the bit loosens and breaks up soil and chops rock material at the bottom of the borehole. Periodically, the drill bit is removed from the borehole and the slurry of water and cuttings at the bottom of the borehole is removed with a bailer. When drilling in normal soils, temporary casing is driven simultaneously with the drilling. After completion of the drilling, a monitoring well or subsurface water-quality monitoring device can be installed inside the casing, followed by installation of filter pack and grout and extraction of the temporary casing.

8.2 Simultaneously driving a temporary casing during drilling minimizes the potential for cross contamination of aquifers. The temporary casing seals off contaminated zones within the borehole, minimizes sediment, air or water contact with aquifers, and minimizes cross-contamination among aquifers. The method also minimizes the uncertainty of whether soil samples or borehole-fluid samples originate from the actual depth being drilled in the borehole rather than from elsewhere in the borehole. Soils may be sampled by using the sample returns from the bailer or by using a split-tube sampler (**20**).

8.3 *Advantages:*

8.3.1 Drilling possible in most all types of soil and rock.

8.3.2 Small drilling rig size enables drilling where access can be a problem with other drilling methods.

8.3.3 Use of casing maintains borehole stability.

8.3.4 A practical method of drilling through cobbles, boulders and highly cavernous or fractured rock.

8.3.5 Drilling depth to about 1520 m (5000 ft).

8.3.6 Recovery of borehole-fluid samples excellent throughout the entire depth of the borehole.

8.3.7 Excellent method for detecting thin water-bearing zones.

8.3.8 Excellent method for estimating yield of water-bearing zones.

8.3.9 Excellent method for drilling in soil and rock where lost circulation of drilling fluid is possible.

8.3.10 Minimal potential for cross contamination of groundwater because of casing.

8.3.11 Makeup water requirements when drilling above the water table relatively low 190 to 380 liter/hr (50 to 100 gal/hr) (**21**).

8.3.12 Easy installation of the well casing.

8.3.13 Allows for precise placement of a well.

8.3.14 Minimum problems arise with development of a well.

8.4 *Disadvantages:*

8.4.1 Drilling rate may be slow.

8.4.2 Heaving of unconsolidated sediment into bottom of casing can be a problem.

8.4.3 Temporary casing may cause problems with well-completion techniques, particularly, in the emplacement of effective gravel pack and grout seal.

8.4.4 Potential for cross-contamination of samples unless bits and bailers are frequently decontaminated and water and cuttings from contaminated areas are completely removed from the borehole before advancing into uncontaminated zones.

8.4.5 Penetration rates are relatively low when drilling fine-grained sediments (**21**).

8.4.6 Heavier wall, larger-diameter casing than that used for other drilling methods normally used.

8.4.7 Inability to drill open borehole when gravel-pack completion is required, except in shallow installations (**21**).

9. Casing-Advancer Systems

9.1 Casing-advancer systems (see Guide D5782) consist of casing driven by special casing hammers combined with either rotary rock bits or down-the-hole (DTH) hammers. Drilling-fluid circulation usually is routed through the bit face and up the casing, thereby, protecting the aquifers from drilling-fluid invasion and subsequent contamination of the borehole wall. Air compressors most often are used to power the casing hammer and to accomplish drilling-fluid circulation. DTH hammers use air as the circulating fluid. Fluid drilling is used less often and drilling only is accomplished with rotary rock bits. As drilling progresses, the bit is used to cut the material in preparation for casing advance. The casing can be advanced close to the bit by independent operation of the casing driver system. Some DTH hammer systems use an overreaming hammer to oversize the borehole diameter for ease of setting the casing.

9.2 Casing-advancer systems are used for high production drilling in soils, which are difficult to drill by other drilling methods and where casing is needed to maintain drilling-fluid circulation or to protect the borehole integrity. Casing-advancer systems also are used for drilling soils containing gravel, cobbles, boulders, and drilling hard rock formations. They are used for rapid installation of monitoring devices where coring is not required. The use of protective casing reduces potential exposures to overlying aquifers and allows for detailed sampling and testing of material at the base of the borehole. Generally, drill depths are 30–90 m (100–300 ft) or less, but depths of 90 m (300 ft) or more can be obtained easily in some formations. DTH-hammer systems often are combined with heavy casing hammers and can be used effectively in soils containing gravel, cobbles, or boulders, and in hard rock. Rotary rock bits using air or air-foam drilling-fluid media can be used effectively in drilling soils. When air is used as the circulating medium, it is possible to collect drill-cuttings samples using a cyclone sampling device. When a drilling foam is used, drill-cuttings samples are more difficult to collect. Fluid drill cuttings are more easily collected; however, the drill cuttings are altered during the drilling process, but limited lithologic classifications can be made because the casing allows for close-interval circulation. During pauses in drilling, the drill string can be removed and testing or sampling can be performed at the base of the borehole. In heavy gravel or cobble formations, split thick wall drive samples are attempted below the casing. In these sampling cases, recovery may be difficult and samples may contain cuttings contaminated with hammer lubricants. Synthetic lubricants have been used for lubricating DTH hammers. Air compressors most often require lubrication and traces of the lubricant often can be detected in samples. In some cases, HEPA filters can be used at the compressor intake and discharge ports. Discharge air can sometimes be monitored for volatile organic compounds. Rig engine exhaust should be directed away from compressor intakes or exhausts if sensing is used on these areas and polyaromatic hydrocarbon (PAH) detection is of concern. Oilless air compressors are difficult to obtain.

NOTE 2—Down-hole hammers require lubrication. If the investigation is to detect petroleum compounds, chemical compound specific tests (such as Gas Chromatography/Mass Spectrometry, GC/MS) may be required. Non-specific tests such as total hydrocarbon (TPH) may detect the lubricant.

9.3 During the drilling process, it is possible that aquifers can be exposed to the drilling-fluid circulation medium. The exposure of the drilled materials to the drilling-fluid can be reduced substantially by adjusting the lead distance of the bit during drilling. Fracturing may occur under high pressures if the lead bit becomes plugged with overlying cuttings caused by advancing the bit too fast. Proper drilling techniques should include maintaining proper drilling-fluid circulation and keeping the bit in close proximity of the casing.

9.4 *Advantages:*

9.4.1 Rapid hole advancement.

9.4.2 Drilling in difficult formations.

9.4.3 Incremental sampling and testing may be conducted at the base of the hole.

9.5 *Disadvantages:*

9.5.1 DTH hammers are not effective in silty and clayey soils.

9.5.2 Possible fracturing of formations is possible.

9.5.3 Heavy clay soils may require drilling with fluids.

10. Direct-Push Technology

10.1 Direct-push systems have been used to install temporary monitoring wells, and in some cases, these wells have been used for long-term monitoring during a particular program. Water sampling, discrete-interval soil sampling, and continuous soil cores to depth without the generation of cuttings can be obtained using direct-push methods. Direct-push technology often is used to refer to systems that are pushed or driven to installation depth without borehole excavation. Direct-push systems generally are small diameter ranging from 3.8 to 7.6 cm (1.5 to 3 in.). The depth of penetration by direct-push methods is controlled primarily by the physical characteristics of the soils to be sampled. Mean depths of penetration are probably 6 to 7 m (20 to 25 ft). Penetration depths of 12 to 18 m (40 to 60 ft) probably would be maximum. Penetration to depths exceeding 23 to 30 m (75 to 100 ft) are possible under amenable soil and geologic conditions. Some materials, such as hard caliche soils or soils containing cobbles or boulders, might make penetration with direct-push equipment difficult or impractical. Direct-push wells or sampling devices can be installed from the surface or advanced below the bottom of a boring. When direct-push is combined with other drilling methods for installation of a monitoring well, the previous sections on drilling method should be consulted to select an appropriate drilling method. A direct-push system can be pushed quasi-statically, hammered, or vibrated into the soil. Systems are designed for either discrete point or continuous soil-sampling events.

10.2 There are many forms of direct-push well installations. Well screens are classified as either exposed screen or protected screens (see Guide D6001). Protected screens have an advantage of protecting the screened area from groundwater exposure until the depth of interest is reached. An example of an exposed screen sampler is a wire-wound stainless-steel well point, which is driven past the bottom. Installation of temporary- or long-term monitoring wells in small-diameter hollow rods can be an alternative to installation of conventional monitoring wells installed by other drilling methods. Backfilling and sealing of a direct push well can be more difficult due to the small diameter of the equipment. Use of appropriate equipment allows for sampling and measurement of nonaqueous phase liquids (NAPL) from these monitoring wells. Direct-push monitoring wells also can be used for long-term landfill gas monitoring when properly installed. The direct-push sampling devices and monitoring wells may be used for soil-vapor extraction. The most common installations include push of a protected screen sampler to the depth of interest. The screen cover then is retracted exposing the screen to the interval of concern. The push rods can be removed and the annulus can be backfilled to seal the riser pipes or tubing. Drilling steel is available for some hydraulically-powered units, allowing penetration of up to 70-cm (27-in.) thick concrete.

NOTE 3—Some direct push well techniques can use a pre-packed well screen. This method uses larger drive rod and a pre-packed screen that can be lowered through the annulus between drive rod and riser pipe. The grout barrier and grout seal can be placed as the drive rods are withdrawn.

10.3 *Advantages:*

10.3.1 Precludes use of drilling fluids and lubricants during drilling.

10.3.2 Equipment highly mobile, site accessibility usually not a problem for small drill rigs.

10.3.3 Disturbance of geochemical conditions during installation is minimized.

10.3.4 There is minimal disturbance of drilling site because of the light-weight equipment.

10.3.5 Drilling is fast.

10.3.6 Direct-push technology does not produce drill cuttings.

10.3.7 Depending on site conditions and depth requirements, groundwater and soil samples can be collected at multiple separate locations per day.

10.3.8 Continuous cores to 1.2 m (4 ft) in length can be collected to depths of up to 15 m (50 ft) or more, depending on site conditions.

10.3.9 Well screens can be emplaced without being exposed to overlying zones that will not be sampled.

10.3.10 Direct-push equipment can be used to install air sparging and SVE and landfill gas-monitoring equipment.

10.4 *Disadvantages:*

10.4.1 Drill cuttings are not brought to land surface to allow visual examination.

10.4.2 Installation generally is limited to normal soils, such as clay, silt, sand, and gravel. Direct-push equipment is not designed to penetrate consolidated bedrock, such as limestone, slate, or granite.

10.4.3 Backfilling and sealing of a direct push well can be more difficult due to the small diameter of the equipment.

10.4.4 The small diameter drive pipe generally used precludes conducting conventional borehole-geophysical logging on the wells.

10.4.5 Exposed-type well screens can become clogged during driving making well development difficult.

10.4.6 The small-diameter direct-push monitoring wells and sampling devices are not designed to yield large volumes of water as would be required an aquifer test.

11. Vibratory Drilling

11.1 Sonic drilling, rotasonic, sonicore, vibratory or resonant-sonic drilling are some of the many names given to this dual-cased drilling system that employs the use of high-frequency mechanical vibration to take continuous core samples of overburden soils and most hard rock, and to advance casing into the ground.

11.2 Sonic drilling is an alternative to other drilling methods when difficult and varied borehole conditions occur, or continuous core sampling, or both, is necessary. The processes that result in borehole advancement are fracturing, shearing, and displacement. Drilling through cobbles, boulders, and rock is caused by fracturing of the material by the inertial moment of the drill bit. Shearing occurs in dense silts, clays, and shales provided the amplitude of the drill bit is high enough to overcome the elasticity of the material being drilled. Displacement occurs when soil material is fluidized by the vibrating drill string, and it moves away from the drill string. Very few drill cuttings are conveyed to the surface. Most of the material enters the core barrel, except for some material which are pushed into the borehole wall. As a result, the volume of drill cuttings generated during sonic drilling usually is much less than those generated from some other drilling methods.

11.3 Several features in addition to the use of vibration increases the speed and efficiency of the drilling process. The head, which combines rotation and vibration as previously discussed, is capable of pivoting 90°. This allows rapid connection of flush-threaded drill pipe by rotating a male-threaded on the head and aligning a length of female-threaded drill pipe directly to the adaptor on the head. A fully-automated, hydraulic, rotating vise/wrench allows easy breakdown of the drill-pipe connections. Once the connection is broken, the head and drill pipe is unscrewed from the head.

11.4 The sonic drilling system employs simultaneous high-frequency vibrational and low-speed rotational motion coupled with downpressure to advance the cutting edge of a circular drill string. This action produces a uniform borehole while providing continuous core samples of both overburden soils and most hard rock materials.

11.5 A sonic-drill rig advances a nominal 10- to 30-cm (4- to 12-in.) diameter core barrel for sampling and can advance up to a 30-cm (12-in.) diameter outer casing for the construction of standard and telescoped or nested monitoring wells. Well casings are to be placed in the borehole by installing smaller diameter pieces of well casing through each subsequent larger diameter piece of well casing, which is analogous to a telescope's configuration. In drilling, the core barrel is advanced ahead of the outer casing in 0.3- to 9-m (1- to 30-ft) increments, depending on the type of material being sampled, degree of subsurface contamination, and sampling objectives.

11.6 The outer casing can be advanced at the same as the inner drill rods and core barrel, or advanced down over the inner drill rods and core barrel, or after the core barrel has moved ahead to collect soil core samples and has been pulled out of the borehole. The outer casing can be advanced completely dry in most circumstances, or it can be advanced using water or air or with a drilling fluid and additives (see 8.1.2) depending upon types of materials being drilled/sampled, borehole depth and diameter, or any other project requirements.

11.7 The outer casing prevents cross-contamination while drilling and provides for controlled placement of monitoring wells and monitoring-well installation(s). After installing the monitoring well screen and riser, the well-construction materials or instrumentation, the outer casing is vibrated gently back out of the borehole. The vibration enhances the placement of the well-completion materials between the borehole wall and the monitoring-well casing.

11.8 The inner drill rods and core barrel are equipped with right-hand threads and is rotated in a clockwise direction during sampling operations. The outer casing is equipped with left-hand threads and is rotated in a counter-clockwise direction during advancement. This prevents the unscrewing of the inner drill rods and core barrel as the outer casing is advanced.

11.9 Core samples can be taken directly from the core barrel attached to the end of the drill string and extruded into a plastic sleeve, trough, or other suitable receptor. Also, core samples can be obtained in split-tube core barrel liners, which are placed in the core barrel inner tube.

11.10 In addition to advancing boreholes and installation of monitoring wells, the sonic drilling method provides the capability to collect samples using direct-push coring equipment; to sample soils, soil vapors, and perform in-situ groundwater sampling. This method can also be used to core and case angle-drilled boreholes from vertical to near horizontal.

11.11 *Advantages:*

11.11.1 The ability to obtain large-diameter, continuous and cores of almost any soil material without the use of drilling fluids, such as air or water-based fluids and additives, and with or without rotation.

11.11.2 Drilling and sampling through boulders, wood, concrete, and other construction debris.

11.11.3 The sonic-drilling system can drill and sample most softer rock, such as sandstone, limestone, shale, and slate with high percentage of core recovery.

11.11.4 Drilling can be faster than most other drilling methods, depending on depth and material drilled, with the exception of dual-wall reverse circulation drilling.

11.11.5 Uniform boreholes with a minimum of drift ideal for monitoring-well installation and corresponding well-development time.

11.11.6 Reduction of investigation-derived waste.

11.12 *Disadvantages:*

11.12.1 Rock drilling and sampling requires the addition of water or air or both to remove drill cuttings.

11.12.2 Equipment might not be readily available and is expensive.

11.12.3 Extraction of casing can cause smearing of borehole wall with silt or clay.

11.12.4 Soil may be displaced into the borehole wall during drilling.

12. Jetting and Jet-Percussion Drilling

12.1 Jet drilling is accomplished by pumping water under pressure down a small-diameter pipe fitted with a jet-wash drill bit with a wash-down bottom. The jetting action of the drilling fluid as it exits the drill bit and the drill bit itself loosen soil, which is carried by the drilling fluid up to the surface in the annulus formed between the drill string and borehole wall.

12.2 The drill string also should be rotated by hand as the jetting process is being carried on to further enhance drill bit cutting action. In cases where borehole collapse occurs, a casing can be advanced simultaneously with the jetting. Once jetting to the required depth is complete, the drill string is extracted and casing can be installed in the borehole. Jet-percussion drilling is essentially the same as jet-wash drilling except that the drill string is lifted repeatedly and dropped as drilling proceeds. This repeated up and down action further enhances the loosening of the soil caused by the jetting action of the drilling fluid. Although lifting and dropping of the drill string can be done by hand, jet-percussion drilling usually is done with equipment designed for this purpose.

12.3 Generally, large quantities of water are needed for jet-wash and jet-percussion drilling. The water used during the drilling process can affect water quality if jetting an uncased borehole because of upward vertical mixing of groundwater and geologic materials and cross contamination of groundwater along the borehole.

12.4 *Advantages:*

12.4.1 Minimal amount of equipment required.

12.4.2 Equipment is highly mobile.

12.4.3 Fast drilling in some soils.

12.5 *Disadvantages:*

12.5.1 Use of water can affect groundwater quality in aquifer.

12.5.2 Borehole can collapse before setting monitoring well if borehole uncased.

12.5.3 Effective gravel pack and grout seal may be difficult to install because of borehole collapse.

12.5.4 Large quantities of water required during drilling process.

12.5.5 Presence of gravel or larger materials can limit drilling.

12.5.6 Limited to drilling relatively shallow depth, small-diameter boreholes.

13. Keywords

13.1 drilling; environmental; groundwater; monitoring wells; site characterization

REFERENCES

(1) Driscoll, F.G. "Groundwater and Wells," 2nd ed. Johnson Filtration Systems, Inc., St. Paul, MN, 1986.

(2) American Petroleum Institute (API), "Wireline Operations and Procedures," 3rd edition, API, Washington, DC, 1994.

(3) Benson, R.C., Glaccum, R.A., and Noel, M.R., "Geophysical Techniques for Sensing Buried Wastes and Waste Migration," EPA/600/7-84/064 (NTIS PB84-198449), 1984. Also published in NWWA/EPA series by National Water Well Association, Dublin, OH.

(4) Boulding, J.R., "Use of Airborne, Surface, and Borehole Geophysical Techniques at Contaminated Sites: A Reference Guide," EPA/625/R-92/007, 1993 .

(5) "Subsurface Characterization and Monitoring Techniques: a Desk Reference Guide," Vol 1: Solids and Ground Water Appendices A and B, U.S. Environmental Protection Agency (EPA), 1993, EPA/625/R-93/003a.

(6) Chapuis, R.P., "Determining Whether Wells and Piezometers Give Water Levels or Piezometric Levels," *Symposium on Ground Water Contamination: Field Methods, ASTM STP 963*, ASTM, 1988, pp. 162–171.

(7) Chapuis, R.P., and Sabourin, L., "Effects of Installation of Piezometers and Wells on Ground Water Characteristics and Measurements," *Canadian Geotechnical Journal*, Vol 26, No. 4, 1989, pp. 604–613.

(8) Dunnivant, F.M., Porro, I., Bishop, C., Hubbell, J., Giles, J.R., and Newman, N.E., "Verifying the Integrity of Annular and Back-Filled Seals for Vadose-Zone Monitoring Wells," Ground Water, Vol 35, No. 1, 1997, pp. 140–148.

(9) Shuter, E. and Teasdale, W.E.," Application of Drilling, Coring, and Sampling Techniques to Test Holes and Wells," *U.S. Geological Survey Techniques of Water-Resource Investigations*, TWRI 2-F1, 1989. p. 96.

(10) Keys, W.S., "Borehole Geophysics Applied to groundwater Investigations," U.S. Geological Survey Techniques of Water-Resource Investigations TWRI 2-E2, 1990, p. (Supersedes report originally published in 1988 under the same title as U.S. Geological Survey Open-File Report 87-539, 303 pp., which was published in 1989 with the same title by the National Water Well Association, Dublin, OH, 313 pp.) Compliments Keys and MacCary (1971).

(11) Keys, W.S. and MacCary, L.M., "Application of Borehole Geophysics to Water Resource Investigations," TWRI 2-E1, *U.S. Geological Survey Techniques of Water-Resources Investigations*, 1971, p. 126, (Reprinted, 1990; see also Keys, 1990.)

(12) Yesiller, N., Edil, T.B., and Benson, C.H., "Ultrasonic Method for Evaluation of Annular Seals for Wells and Instrumented Holes," *Geotechnical Testing Journal*, Vol 20, No. 1, 1997, pp. 17–28.

(13) Meiri, D., "A Tracer Test for Determining Cross-Contamination Along a Monitoring Well Column," *Ground Water Monitoring Review*, Vol 9, No. 2, 1989, pp. 78–81.

(14) Claassen, H.C., "Guidelines and Techniques for Obtaining Water Samples That Accurately Represent the Water Chemistry of the Aquifer," *U.S. Geological Survey Open File Report* 82–1024, 1982, p. 49.

(15) Zohdy, A.A., Eaton, G.P., and Mabey, D.R., "Application of Surface Geophysics to groundwater Investigations," *U.S. Geological Survey Techniques of Water-Resource Investigations*, TWRI 2-D1, 1974, p.

(16) Harlan, R.L., Kolm, K.E., and Gutentag, E.D., "Water-Well Design and Construction," Elsevier, NY, 1989, p. 205 .

(17) Respold, H., "Well Logging in Groundwater Development," *International Contributions to Hydrogeology*, Vol 9, International Association of Hydrogeologists, Verlag Heinz Heise, Hannover, West Germany, 1989, p. 147.

(18) "Principles of Drilling Fluid Control," American Association of Oil Well Drilling Contractors, 1969, *American Petroleum Institute and University of Texas, eds*, Dallas, TX, p. 215.

(19) Hodges, R.E. and Teasdale, W.E., "Considerations Related to Drilling Methods in Planning and Performing Borehole-Geophysical Logging for groundwater Studies," *U.S. Geological Survey Water-Resources Investigations Report 91–4090*, 1991 , p. 17.

(20) "Drilling Safety Guide," *National Drilling Federation*, Columbia, SC, 1985 , p. 36.

(21) Nielsen, D.M. and Schalla, R., "Design and Installation of groundwater Monitoring Wells," *Practical Handbook of groundwater Monitoring* , D.M. Nielsen (ed.), Lewis Publishers, Chelsea, MI, 1991, pp. 239–331.

(22) National Sanitation Foundation, Standard 60, 2011 "Drinking Water Treatment Chemical–Health Effects".

SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this guide since the last issue, D6286–98(2006), that may impact the use of this guide. (Approved Sept. 1, 2012)

(1) Editorially revised 1.4 on SI Units.
(2) Corrected spelling of "ground-water" to "groundwater."
(3) Added SI units as standard, with inch-pound units as secondary (rationalized).
(4) Updated the National Sanitation Foundation (NSF) Standard 60 from 1988 to 2011.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the ASTM website (www.astm.org/COPYRIGHT/).