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Standard Guide for Selection of Drilling and Direct Push Methods for Geotechnical and Environmental Subsurface 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 geotechnical and environmental soil and rock borings ~~and the installation of monitoring wells and other water-quality monitoring devices.~~for sampling, testing, and installation of wells, or other instrumentation. It does not address drilling for foundation improvement, drinking water wells, or special horizontal drilling techniques for utilities.

~~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.~~

1.2 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. Soil and rock sampling in drill holes is addressed in Guide D6169. Pertinent guides and practices addressing specific drilling methods, equipment, and procedures are listed in Section 2. Guide D5730 provides information on most all aspects of environmental site characterization.

1.3 The values stated in either SI units or inch-pound units (given in brackets) are to be regarded separately 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. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with the 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.~~

1.4 This guide does not purport to comprehensively address all ~~of the~~ methods and the issues associated with drilling for geotechnical and 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~~ these methods 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,~~revisions. Therefore, users should consult with manufacturers or producers prior to specifying program requirements.

1.5 ~~*Pertinent guides addressing specific drilling methods, equipment and procedures are listed in*~~ *This standard does not purport to address all* ~~*2.1. A comprehensive list of guides, methods, practices, and terminology for drilling is contained in Guide*~~ *of the safety concerns, if any, associated* ~~*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.*~~*with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

[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.

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

1.5.1 Drilling operators generally are required to be trained for safety requirements such as those of construction and environmental occupational safety programs dictated by country, regional, or local requirements such as the US. OSHA training programs. Drilling safety programs are also available from the National Drilling Association (NDA4U.com) or other country drilling associations.[2]

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.*

1.6 *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.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D420 Guide for Site Characterization for Engineering Design and Construction Purposes
D653 Terminology Relating to Soil, Rock, and Contained Fluids
D1586D1452 Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of SoilsPractice for Soil Exploration and Sampling by Auger Borings
D1587 Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes
D2113 Practice for Rock Core Drilling and Sampling of Rock for Site Exploration
D2488 Practice for Description and Identification of Soils (Visual-Manual Procedures)
D3550D3740 Practice for Thick Wall, Ring-Lined, Split Barrel, Drive Sampling of SoilsMinimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction
D5088 Practice for Decontamination of Field Equipment Used at Waste Sites
D5092 Practice for Design and Installation of Groundwater Monitoring Wells
D5608 Practices for Decontamination of Sampling and Non Sample Contacting Equipment Used at Low Level Radioactive Waste Sites
D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater (Withdrawn 2013)[4]
D5753 Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging
D5778 Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils
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 Groundwater 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

[2] "*Drilling Safety Guide*," National Drilling Federation, Columbia, SC, 1985, p. 36.
[3] 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.
[4] The last approved version of this historical standard is referenced on www.astm.org.

D6429 Guide for Selecting Surface Geophysical Methods
D6910 Test Method for Marsh Funnel Viscosity of Construction Slurries
D6914 Practice for Sonic Drilling for Site Characterization and the Installation of Subsurface Monitoring Devices
2.2 *Geotechnical Sampling, In situ Testing, and Instrumentation in Drill Holes:*
D1586 Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils
D1587 Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes
D2573/D2573M Test Method for Field Vane Shear Test in Saturated Fine-Grained Soils
D3550 Practice for Thick Wall, Ring-Lined, Split Barrel, Drive Sampling of Soils
D4403 Practice for Extensometers Used in Rock
D4428 Test Methods for Crosshole Seismic Testing
D4719 Test Methods for Prebored Pressuremeter Testing in Soils (Withdrawn 2016)[4]
D6519 Practice for Sampling of Soil Using the Hydraulically Operated Stationary Piston Sampler
D6598 Guide for Installing and Operating Settlement Platforms for Monitoring Vertical Deformations
D6635 Test Method for Performing the Flat Plate Dilatometer
D7299 Practice for Verifying Performance of a Vertical Inclinometer Probe
2.3 *Sampling, Testing, and Installations in Drill Holes:*
D4700 Guide for Soil Sampling from the Vadose Zone
D4044/D4044M Test Method for (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers
D4050 Test Method for (Field Procedure) for Withdrawal and Injection Well Testing for Determining Hydraulic Properties of Aquifer Systems
D4630 Test Method for Determining Transmissivity and Storage Coefficient of Low-Permeability Rocks by In Situ Measurements Using the Constant Head Injection Test
D6282 Guide for Direct Push Soil Sampling for Environmental Site Characterizations
D6724/D6724M Guide for Installation of Direct Push Groundwater Monitoring Wells
D6725/D6725M Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers
D6907 Practice for Sampling Soils and Contaminated Media with Hand-Operated Bucket Augers
D7242 Practice for Field Pneumatic Slug (Instantaneous Change in Head) Tests to Determine Hydraulic Properties of Aquifers with Direct Push Groundwater Samplers
D7352 Practice for Volatile Contaminant Logging Using a Membrane Interface Probe (MIP) in Unconsolidated Formations with Direct Push Methods
D7648 Practice for Active Soil Gas Sampling for Direct Push or Manual-Driven Hand-Sampling Equipment
D8037 Practice for Direct Push Hydraulic Logging for Profiling Variations of Permeability in Soils

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of ~~general~~ common technical 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*—*in drilling,* 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.~~

3.2.2.1 *Discussion—*

The flats or splines of the kelly bar engage the rotary table so that the rotation of the rotary table turns the kelly bar, which in turn, rotates the drill pipe and the rotary bit.

3.2.3 *mud rings, n*—*in drilling,* 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.~~

3.2.3.1 *Discussion—*

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,*~~ *bucket, n—in drilling,* 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 1998 edition of this standard was written solely for selection of drilling methods for environmental applications and specifically for installation of groundwater monitoring wells. The second revision was made to include geotechnical applications since many of the advantages, disadvantages, and limitations discussed extensively throughout this document also apply to geotechnical design use such as data collection (sampling and in-situ testing) for construction design and instrumentation. Besides installation of monitoring wells (D5092, D6724/D6724M), Environmental investigations are also made for sampling, in-situ testing, and installation of aquifer testing boreholes (D4044/D4044M, D4050).

4.2 There are other guides for geotechnical investigations addressing drilling methods such as in Eurocode **(1, 2)**[5], U.S. Federal Highway Administration, (**3, 4**), U.S. Army Corps of Engineers, (**5**), and U.S. Bureau of Reclamation (**6, 7**). An authoritative Handbook on Environmental Site Characterization and Ground-Water Monitoring was compiled by Nielsen **(8)** which addresses drilling methods in detail including the advent of Direct Push methods developed for environmental investigations. Two other major drilling guides have been written by the National Drilling Association (**9**) and from the Australia Drilling Industry Training Committee **(10)** and these guides are user for the drillers.

4.3 ~~The~~Table 1 ~~selection of particular method(s) for drilling monitoring wells (see~~lists sixteen classes of methods addressed in this guide. ~~Table 1)~~The selection of particular method(s) for drilling/push boring 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~~ drilling/push boring methods available and the applications, advantages, and disadvantages of each with respect to determining ~~groundwater chemistry and other hydrogeologic properties data.~~geotechnical and environmental exploration.

4.3.1 On Table 1, practically all methods allow for coring, but some are much more efficient than others. Some drilling systems such as hollow-stem augers or wireline coring allow for practically continuous coring with minimal time for switching barrels while other drilling methods require the whole drilling equipment be removed from the hole. A prime example is the rate of rock coring using fluid rotary and conventional core barrels versus wireline rock coring. Wireline line rock coring is fast with long continuous runs whereas fluid rotary requires more "trip time" to add and remove shorter length core barrels using drill rods. Table 1 delineates methods where coring is possible, and in general, by either continuous (c) or incremental (i) sampling.

4.3.2 Sampling for environmental contaminants in soil, unconsolidated formations or groundwater often requires special considerations. In many environmental applications the use of drilling fluids (air, water, mud or foam) is often discouraged or even prohibited as these fluids may dilute the analytes of interest or even introduce analytes of concern not previously present (see 5.4).

4.4 This guide ~~can be~~ is most often used in conjunction with Guide D6169~~.~~ on soil and rock sampling because sampling is the primary activity during drilling/push borings. 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~~well installations (see Practice D5092). Practices on hollow-stem auger (D6151) and sonic drilling (D6914) were written for both geotechnical and environmental purposes and address sampling methods. Practice D2113 on rock core drilling includes sampling methods.

4.4.1 This guide covers direct push methods that are only used to make open holes for testing and sampling. This most often accomplished using dual tube systems and using the tubes for access of the subsurface for water sampling, D6001, soil sampling (D6282), well installation (D6724/D6724M, D6725/D6725M) and aquifer testing (D7242).

4.5 *Predominant or Typical Drilling/Push Boring Methods Used for Geotechnical and Environmental Applications:*

4.5.1 *Geotechnical Investigations in Soils (unconsolidated deposits)*—The most commonly used drilling methods for geotechnical exploration are fluid rotary drilling when groundwater is present. Hollow-stem auger drilling is also frequently used especially in arid regions where introduction of fluids is to be avoided in unsaturated soils.

4.5.2 *Environmental Investigations in soils (unconsolidated deposits)*—Most of these investigations are focused on soil contamination or, groundwater quality investigations so introduction of drilling fluids is not desirable and methods which generate minimal waste are highly favored. Direct Push methods were developed because they develop minimal investigative derived waste (IDW). Sonic methods are frequently used and generate minimal IDW but large cores. Hollow-stem augers and fluid rotary are used yet they generate large amounts of IDW.

4.5.2.1 At most environmental sites hazardous contaminants are present in the subsurface. Because of this fact any drill cuttings or drilling fluids returned to the surface should be properly handled, contained and stored (drums or roll-off bins, etc.) for sampling and laboratory analysis. Laboratory analyses may be required to verify that hazardous contaminants are not present above regulatory action levels prior to proper disposal. If concentrations of hazardous chemicals in cuttings or waste drilling fluids exceed regulatory action levels the waste may require treatment before disposal or may need to be properly disposed in a hazardous waste landfill. Review pertinent regulations before drilling/push boring to maintain compliance. The generation of contaminated waste

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

TABLE 1 ~~Well-Drilling~~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~~
Drilling Method	Drilling Fluid	Casing Advance	Type of Material Drilled	Typical Depth, in m [ft][A]	Typical Range of Borehole Sizes, in cm [in.]	Samples Obtainable[B]	Coring Possible (see 4.3.1)[C]	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 (Hollow-stem)	none, water, mud	yes	soil, weathered rock	<45 [150]	12.7-55 [5-22]	S, F	Yes(c)	6.2
~~Power auger (Solid-stem)~~	~~water, mud~~	~~no~~	~~soil, weathered rock~~	~~<45 (150)~~	~~5–25 (2–10)~~	~~s~~	~~yes~~	~~6.3~~
Power auger (Solid-stem)	none	no	soil, weathered rock	<45 [150]	5-25 [2-10]	S	Yes(i)	6.3
~~Power bucket auger~~	~~none, water (below water table)~~	~~no~~	~~soil, weathered rock~~	~~<45 (150)~~	~~45–120 (18–48)~~	~~S~~	~~yes~~	~~6.4~~
Power bucket auger	none, water (below water table)	no	soil, weathered rock	<45 [150]	45-120 [18-48]	S	Yes(i)	6.4
~~Hand auger~~	~~none~~	~~no~~	~~soil~~	~~<20 (70) (above water table only)~~	~~5–15 (2–6)~~	~~S~~	~~yes~~	~~6.5~~
Hand auger	none	no	soil	<20 [70] (above water table only)	5-15 [2-6]	S	Yes(i)	6.5
~~Direct fluid rotary~~	~~water, mud~~	~~yes~~	~~soil, rock~~	~~>300 (1000)~~	~~5–90 (2–36)~~	~~S, R~~	~~yes~~	~~7.3~~
Direct fluid rotary	water, mud	yes	soil, rock	>300 [1000]	5-90 [2-36]	S, R	Yes(i)	7
~~Direct air rotary~~	~~air, water, foam~~	~~yes~~	~~soil, rock~~	~~>460 (1500)~~	~~5–90 (2–36)~~	~~S, R, F~~	~~yes~~	~~7.4~~
Sonic (vibratory)	none, water, mud, air	yes	soil, rock, boulders	<150 [500]	10-30 [4-12]	S, R, F	Yes(c)	8
~~DTH hammer~~	~~air, water, foam~~	~~yes~~	~~rock, boulders~~	~~<600 (2000)~~	~~10–40 (4–16)~~	~~R~~	~~yes~~	~~7.5.1~~
Direct-push technology	none	yes	soil, weathered rock	Typical 15-30 [50-100] Maximum 60 [200]	3.8-15 [1.5-6]	S, F	Yes(c)	9
~~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~~
Air rotary, Casing-advancer	air, water, mud	yes	soil, rock, boulders	<600 [2000]	5-40 [2-16]	S, R, F	Yes(c)	10.3
~~Reverse air rotary~~	~~air, water, foam~~	~~yes~~	~~soil, rock~~	~~>300 (1000)~~	~~30–90 (12–36)~~	~~S, R, F~~	~~yes~~	~~7.7~~
Reverse circulation, air rotary	air, water, foam	yes	soil, rock	>300 [1000]	30-90 [12-36]	S, R, F	Yes(i)	12
Reverse circulation, fluid rotary	water, mud	yes	soil, rock	<600 [2000]	30-90 [12-36]	S, R, F	Yes(i)	12.3
~~Cable tool~~	~~water~~	~~yes~~	~~soil, rock~~	~~<1500 (5000)~~	~~10–60 (4–24)~~	~~S, R, F (F–below water table)~~	~~yes~~	~~8~~
Cable tool	water	yes	soil, rock	<1500 [5000]	10-60 [4-24]	S, R, F (F–below water table)	Yes(i)	13
~~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~~
Jet percussion	water	no	soil	<15.0 [50]	5-10 [2-4]	S	no	14
~~Jetting~~	~~water~~	~~yes~~	~~soil~~	~~<15 (50)~~	~~10 (4)~~	~~S~~	~~no~~	~~12~~
Jetting	water	yes	soil	<15 [50]	10 [4]	S	no	14

[A] ~~Actual~~Actual achievable drilled depths will vary depending on the ambient geohydrologic conditions existing at the site and size of ~~drilling~~ drilling/push boring 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~~[250 to 350 ~~psi)~~psi] and 14 to 21 m^3/h ~~(500~~[500 to 750 ~~cfm),~~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)~~[125 psi] and produce 14 to 34 m^3/h ~~(500~~[500 to 1200 ~~cfm).~~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~~Soil = S (Cuttings), Rock = R (Cuttings), Fluid = F (some samples might require accessory sampling devices to obtain).

[C] I = Incremental sampling, C = continuous sampling.

drill cuttings and fluids significantly increase the potential for worker exposure to hazardous contaminants. Review pertinent regulations (such as OSHA 1910.120, etc.) to maintain compliance with worker safety and monitoring requirements.

4.5.3 *Rock, Weathered Rock, and Coarse Cobble Boulder Drilling*—Wireline rock coring is used in competent rock and results in the best core recovery. For coarse grained unconsolidated deposits and weathered bedrock samples are very difficult to recover and, rotary air drill through drive casing advancers are often used and require larger drills. Larger sonic drills can also drill and recover rock and boulder formations.

4.5.4 Sonic drilling methods have increased in use for both geotechnical and environmental explorations. The method offers very rapid continuous coring with the ability to drill difficult formations with large diameter equipment.

4.5.5 Shallow hand auger (D4700) is used for both disciplines but in most cases hand applications are used as part of initial site surveys prior to drilling/push boring or just for characterization of shallow soil sampling. Hand auguring is very labor intensive and has almost been abandoned in favor of using direct push equipment.

NOTE 1—The reliability of data and interpretations generated by this practice is dependent on the competence of the personnel performing it and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 generally are considered capable of competent testing. Users of this practice are cautioned that compliance with Practice D3740 does not assure reliable testing. Reliable testing depends on several factors and Practice D3740 provides a means of evaluating some of these factors.

Practice D3740 was developed for agencies engaged in the testing, inspection, or both, of soils and rock. As such, it is not totally applicable to agencies performing these field practices. Users of this test method should recognize that the framework of Practice D3740 is appropriate for evaluating the quality of an agency performing drilling. Currently, there is no known qualifying national authority that inspects agencies that perform this test method. There is training and certification for drillers that are normally required for critical installations such as water well drilling (NGWA, NDA).

5. Program Planning and ~~Drilling~~ Drilling/Push Boring Considerations

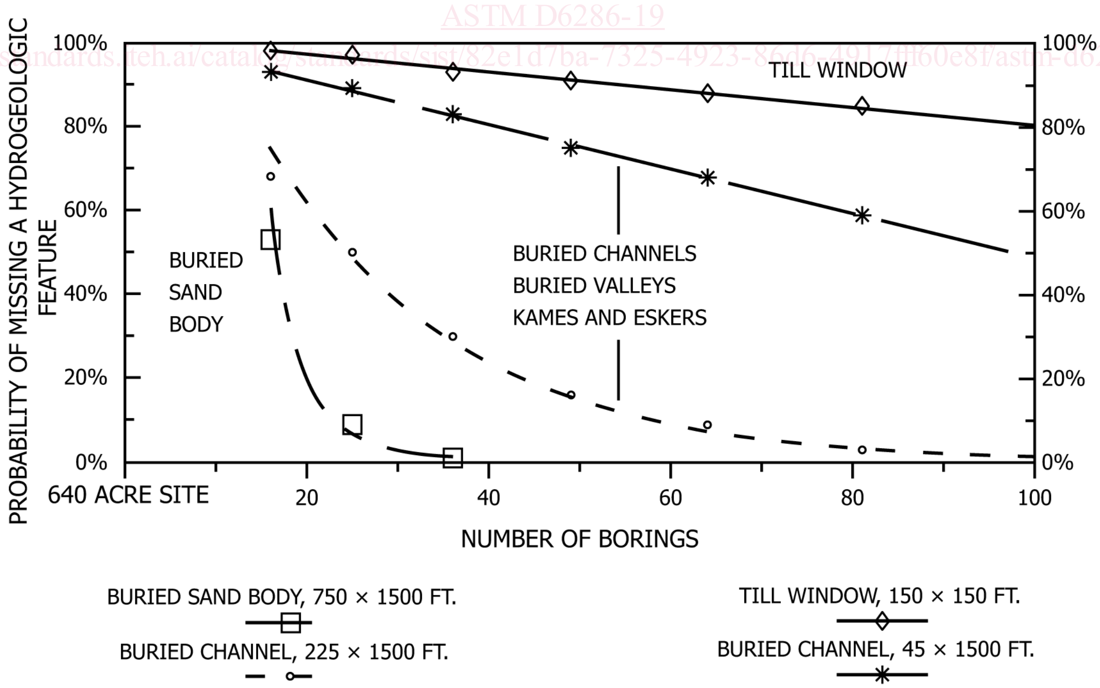
5.1 All factors affecting both surface and subsurface environment at a specific site requires professional judgment and must be considered by the geologist/hydrologist or experienced driller before a ~~drilling~~ drilling/push boring method is selected. ~~Significant~~ Development of a Conceptual Site Model (CSM) of 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~~ drilling/push boring equipment (**~~1~~1-8**). 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 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,~~ drilling/push borings, 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~~At any site review ~~(~~nearby,~~2-5~~) ~~and direct-push methods for soil and groundwater data collection (see Guide~~ available borings and discuss drilling/push boring methods with local contractors experienced with the geologic conditions.~~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~~Once the desk studies and field reconnaissance are performed, onsite explorations are normally phased using subsurface screening methods to refine the CSM before final selection of drill hole locations. Site-specific surface geophysical surveys (D6429) ~~**can**~~**(11-15),** ~~vary greatly due to the availability~~direct-push soil or water sampling (D6282, D6001~~of reliable site data.~~), hydraulic profiling (D8037 ~~The general procedure,~~), cone penetrometers (D5778 ~~however, is as follows. First, gather factual information and~~), dynamic cone penetrometers, or solid stem power augers (D1452 ~~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~~) can be performed in grid patterns across the site to refine the stratigraphy of the geology at the site and may detect problem areas for targeting with drilling/push boring and sampling. Surface geophysical methods, such as seismic surveys and electrical-resistivity imaging and electromagnetic-conductance surveys, can be valuable particularly when distinct differences in the properties of contiguous subsurface materials are indicated **(16, 17).**~~the water, gaining insight into hydrochemical~~ When free product petroleum fuels are present in the subsurface, membrane interface probe (D7352 ~~processes, or for predicting the effectiveness of aquifer~~), or high-resolution fluorescence logging with induced fluorescence or optical image probes can be used to identify depths and locations to target for sampling by drilling/push boring methods **~~remediation.~~(18, 19~~In~~).**~~these cases, extensive additional geotechnical and hydrogeologic information may be required.~~

5.2.1 The odds of detecting certain critical geologic features of interest on large sites are greatly improved using screening methods prior to drilling/push boring and can be used to reduce the amount of expensive drill holes. Fig. 1 shows the number of drill holes and the probability of detecting several types of geologic features at a 260 ha [640-acre, 1 square mile] site (**8**). Without screening methods using geophysics and low-cost probing or drilling/push boring methods, some geologic features could be totally missed even with 100 drill holes. Further, the screening methods can be used to reduce the amount of drill holes and target them on critical layers.

5.3 *Geotechnical Considerations—*~~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~~ Drilling/push boring activities for geotechnical investigations include sampling (both disturbed or intact for laboratory testing), in situ testing, and installation of monitoring ~~wells designed for water-sample collection, preferred drilling methods are those that do not~~devices such as piezometers (observation wells), or inclinometers (see ASTM procedures cited in 2.2~~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~~). Ideal drilling/push boring methods often are dictated by soil or rock types and the likelihood of the method to disturb soils ahead of the drilling operation, but more importantly is the presence of groundwater. Fluid rotary drilling predominates in humid areas with shallow groundwater, whereas in arid areas, the hollow-stem auger is more commonly used. With unsaturated soils in arid regions it may not be desirable to use fluid drilling methods that could wet soil samples prematurely ahead of laboratory testing of samples. A common drilling/push boring test is the standard penetration test (D1586 ~~and improperly-designed drilling-fluid program.~~) and only certain drilling/push boring methods are suitable. When drilling in hydraulic structures such as dams and levees, drill methods should be selected that minimize the potential for hydraulic fracturing (see 5.6.2). Air drilling should not be used in impervious cores of dams and levees.

~~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,~~



The probability of finding many types of subsurface geologic features using borings alone is fairly low. The use of supportive studies such as surface geologic mapping, aerial photo interpretation, and surface and borehole geophysics can greatly improve the chances of successfully mapping the subsurface. Without a complete and accurate map of the subsurface, site models can be misleading.

FIG. 1 Probability of Finding Geologic Features Using Only Drill Holes on a Large Site (8)

~~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.~~

5.4 *Environmental Considerations*—~~Drilling~~ Environmental drilling/push boring is primarily for the collection of samples and installation of groundwater monitoring wells (see standards listed in 2.3). An authoritative reference for well drilling and installation can be found in groundwater and wells **(20)**. Environmental considerations include preservation of sample representativeness for chemical contamination, aquifer integrity, and reduction in waste (IDW). Drilling/push boring 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~~fluids are most often used and measures are taken given in 5.4.1 ~~(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~~below. Direct push and sonic methods using no fluids and generate minimal waste (IDW) and provide the borehole wall protection with casings. Direct push equipment has the potential to perform many different in-situ tests as drilling progresses (2.3 ~~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~~). Groundwater monitoring wells using drilling/push boring methods in this standard are designed and installed in accordance with D5092 ~~to be used upon completion of the borehole. Another important factor~~and direct push wells are installed with accordance with ASTM D6724/D6724M ~~to be~~and D6725/D6725M ~~considered when evaluating this data is well-screen placement.~~ for prepacked wells.

5.4.1 If the monitoring well also is to be sampled for water quality during the fluid 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. Drilling-fluid invasion of the borehole wall normally results from the use of a poorly-controlled and improperly-designed drilling-fluid program. Drill fluids are designed to coat and partially penetrate the wall of the drill hole to stabilize the boring. Water used as a drilling fluid or to prepare drilling muds must be tested to verify it is clean and free of the contaminants of interest or other potential contaminants not present at the site. Often, municipal water is chlorinated and as such could contain trihalomethanes which are regulated contaminants in groundwater.

5.4.2 The project manager should review the project work plan, sampling plan and quality assurance plan prior to selection of the drilling/push boring method(s) to be used at the facility under investigation to assure the proper drilling and sampling practices are used to meet specified project requirements. While some drilling/push boring practices may be more time efficient if they yield non-representative samples then the resulting geological, water quality and analytical results may be inaccurate and misleading for the purposes of an environmental investigation. This could result in the development of an inaccurate (CSM) and remediation action, and significant lifetime cost increases to achieve site closure for contaminated facilities.

5.4.3 *Dry Drilling/Push Boring Methods Preferred*—Drilling/push boring methods that do not use a drilling fluid are preferable because they preclude possible aquifer contamination from such fluids. Direct push methods for monitoring well installation minimize or preclude the use of drilling fluids. Other 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 crucial factor to be considered when evaluating this data is well-screen placement.

5.4.3.1 *Use of Dry drilling/Push Boring Methods Below the Water Table*—Dry drilling/push boring methods such as direct push, sonic, and hollow-stem augers all suffer from problems when used below the water table, especially in sands which are the target aquifers for testing or well placement. Sand below the water table can be unstable and heave into the casings. In these cases, and if permitted, in the work plan water may have to be added to stabilize water levels in the boring (5.4.1). The alternative is to retract casings which may have further disturbance to the base of the boring. Any borings with casing left overnight will likely fill with groundwater to the level of the groundwater table and provisions may have to be made to remove this water via bailing or air lifting prior to well installation or resumed sampling if required in the work plan. Alternately, the water in the casing may have to remain and create a balance with the existing aquifer during the resumption of drilling activities.

5.4.4 *Use of Cased Methods*—Drilling/push boring methods that advance the casing as drilling proceeds are very effective methods to minimize the effects of groundwater migration along the casing and can maintain seal across multiple aquifers. Dual tube direct push equipment, sonic drilling, casing advancer methods (10.3) and reverse circulation all advance casings continuously during the drilling process. Hollow-stem augers provide a stable inner casing but allow mixing of soil and water on the auger flights. Incremental open hole drilling and sampling such as fluid rotary drilling may require telescoped casing (5.4.4.1) to seal off multiple aquifer zones separated by confining units.

5.4.4.1 *Sealing Across Aquifers in Open Hole Drilling – Telescoping*—The practice of incremental open hole drilling/push boring and sampling in uncased borings, 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/push boring 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 with the use of centralizers. After the cement/grout has adequately cured, the material remaining in the casing can be drilled out. Borehole geophysical methods (see D5753) 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 (**21**).

5.4.5 Casing advancers are often used in coarse grained deposits and weather bedrock. If the tendency of this method is to over ream the hole, contamination may move along the casing during drilling. Air rotary drilling should not be used for most environmental investigations, especially when Volatile Organic Compounds (VOCs) are under investigation or contaminants effected by changes in Oxidation Reduction Potential (ORP) are under investigation. Air rotary drilling can strip VOCs from the formation and groundwater resulting in low biased analytical data for environmental investigations. Additionally, air rotary drilling can and has contaminated formations with compressor oils or VOCs present in the local ambient atmosphere. Air rotary drilling can also fracture the surrounding ground mass if circulation is lost.

5.4.6 Ultimately, selection of a drilling/push boring 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/push boring 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 (5.9), from the well. 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

5.4.7 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/push boring 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.

5.4.8 The planning of the type(s) of drilling/push boring 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 drilling/push boring equipment can be decontaminated are also important factors to be considered. It is standard procedure to have to clean equipment prior to entrance and exit from the site as well as decontamination of sampling and installation equipment during drilling operations using procedures given in D5088 and D5608.

5.5 *Drill Hole Diameter*—Drilling depth and borehole diameters shown in Table 1 are nominal values for the method and may vary for specific cases or conditions. Drill hole diameter is probably the most important consideration for selection or drilling/push boring methods.

5.5.1 *Geotechnical Considerations*—Drill hole diameter directly affects sample quality with larger diameters yielding higher quality samples using most all sampling methods, disturbed or intact. The majority of geotechnical work requires a minimum borehole inside diameter of 100 mm [4 in.] for soils. Intact sampling of soils for laboratory testing are greatly improved by using 150 mm [6 in.] boreholes (D1587). For rock coring, NQ3 is often used for mineralogical investigations but the larger HQ3 and PQ3 size yields better cores and allows for water testing.

5.5.2 *Environmental Considerations*—The diameter of the borehole and the well casing for conventionally drilled filter packed monitoring well should be selected so that a minimum annular space of 2 in. [50 mm] is maintained between the inside diameter of the casing and outside diameter of the riser to provide working space for a tremie pipe (Practice D5092). Special procedures in D6724/D6724M and D6725/D6725M address methods to place groundwater monitoring wells in small diameter direct push equipment with much smaller annulus. Generally, environmental sampling does not require physically intact samples where larger diameters are required. Direct push equipment has now reached capabilities with double tube system that exceed 100 mm [4 in.] inside diameters but often are used in smaller sizes.

5.6 *Drilling – Damage by Poor Drilling Procedures – Hydraulic Fracturing:*

5.6.1 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 (**22-24**). 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.

5.6.2 *Hydraulic Fracturing*—Geotechnical drilling for water retaining hydraulic structures such as dams or levees should be carefully selected to avoid potential for hydraulic fracturing. Drilling methods using fluids or air have potential to hydraulically fracture soils if poor drilling practice or the formation leads to circulation blockage. For water retaining structures dry drilling methods such as hollow-stem augers or sonic drilling are preferred and fluid and especially air drilling are to be avoided. Air drilling has been banned in impervious cores of dams (**25**).

5.7 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.*Drilling Methods – Fluid/Water Drilling:*

5.7.1 Fluid/water drilling methods are commonly used for geotechnical boreholes and are often preferred for these drilling programs. Conversely, fluid drilling is typically avoided when possible for environmental borings and monitoring well installations. Drilling fluids can significantly impact the water quality of the test or installation location causing bias in basic water quality parameters such as specific conductance, dissolved oxygen, pH and ORP conditions. Accurate determination of these parameters can be vital to understanding the contaminant degradation processes occurring in the aquifer and to designing an effective remediation program. Additionally, drilling fluids can dilute the observed concentration of hazardous contaminants present at the facility or accidentally add contaminants to the formation exacerbating the existing problem. The use of drilling fluids should be avoided for environmental borings when possible.

5.7.2 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 (**126, 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 upholeup-hole 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.

5.7.3 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 theusing 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 **completed(26).** installation. Borehole contamination, such as those discussed can occurAuger drilling tends to smear fine-grained sediment cuttings onto (the**1**, **9**).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.

5.7 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.

5.8 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.*Drilling Methods – Air Drilling:*

5.8.1 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 in Sterrett and Shuter can occur with air drilling (**20**, **21**). When exploring for volatile organic contamination during an environmental assessment air-rotary drilling can result in loss of analytes from the borehole and surrounding formation. The use of air rotary drilling can significantly impact water quality parameters such as dissolved oxygen and ORP potential as well as change the redox state of sensitive dissolved metals and metal complexes. This can make the determination of ambient aquifer geochemistry conditions difficult or impossible. Accurate measurement of these parameters and dissolved species can be critical for understanding contaminant degradation and development of an effective remediation program at environmental sites.

5.9 *Geophysical Logging of Boreholes and Borehole Condition Evaluations:*

5.9.1 The purpose of the drilling may be for geophysical logging, or, the condition of the borehole can be evaluated using geophysical logging. The proposed geophysical logging may require a certain drilling method. For example, suspension logging requires a drill fluid filled borehole. Geophysical logging is often performed in rock core holes for better determination of rock mass properties.

5.9.2 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 (**14**, **24**, **27-30**). 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 Some methods that can be used to assess the hydraulic integrity of the borehole or a subsequent installation include the following.

5.10.1 *Indirect Method(s):*

5.10.1.1 Selected borehole geophysical logging methods (**27**, **31**, **32**).

5.10.1.2 Introduction of tracer(s) to the borehole combined with pumping tests (**8**, **33**, **Note 2**).

5.10.2 *Direct Method(s)* (**22**, **23**)*:*

5.10.2.1 Pumping test(s) of the borehole (D4044/D4044M).

5.10.2.2 Injection test(s) of the borehole (D4050).

5.10.2.3 Inflatable-packer testing of the borehole (D4630).

5.11 ~~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~~ The drilling/push boring method selected must be practical logistically, and to the extent possible, minimize mechanical damage to the borehole. Additionally, for environmental explorations the drilling/push boring method should have minimal impact to the chemical conditions in the borehole and surrounding formation to assure that representative samples can be obtained. Local availability of a particular type of drilling rig/equipment also will be an extremely important factor to be considered before 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.~~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, hydrogeologic parameters might be required for the investigation 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 (**28**).

~~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).~~

5.12 *Borehole Installation Sealing or Sealing for Abandonments:*

5.12.1 *Annular Sealants*—Guidelines for sealing Geotechnical boreholes were recommended by Luttnegger and DeGroot (**34**). This report gives recommendations for both bentonite and cement grouts and use of bentonite pellets or chips. The materials used