Techniques of Water-Resource Investigations of the United States Geological Survey

Chapter F1

APPLICATION OF DRILLING, CORING, AND SAMPLING TECHNIQUES TO TEST HOLES AND WELLS

By Eugene Shuter and
Warren E. Teasdale

Book 2

COLLECTION OF ENVIRONMENTAL DATA

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, *Secretary*

U.S. GEOLOGICAL SURVEY

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called "Books" and further subdivided into sections and chapters. Section F of Book 2 is on drilling and sampling methods.

The unit of publication, the chapter, is limited to a narrow field of subject matters. This format permits flexibility in revision and publication as the need arises. "Application of drilling, coring, and sampling techniques to test holes and wells" is the first chapter to be published under Section F of Book 2.

TECHNIQUES OF WATER-RESOURCES INVESTIGATIONS OF THE U.S. GEOLOGICAL SURVEY

The U.S. Geological Survey publishes a series of manuals describing procedures for planning and conducting specialized work in water-resources investigations. The manuals published to date are listed below and may be ordered by mail from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, Colorado 80225 (an authorized agent of the Superintendent of Documents, Government Printing Office).

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TWRI 8-B2. Calibration and maintenance of vertical-axis type current meters, by G.F. Smoot and C.E. Novak. 1968. 15 pages.

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Conversion factors

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meters (m)
gallon per minute (gal/min)	0.063081	liters per second (L/s)
inch (in.)	25.40	millimeters (mm)
pound, avoirdupois (lb)	453.6	grams (g)
quart (qt)	0.9464	liters (L)
pound per square inch ($lb/in.^2$)	6.895	kilopascals (kPa)

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

°F = 1.8° + 32.

APPLICATION OF DRILLING, CORING, AND SAMPLING TECHNIQUES TO TEST HOLES AND WELLS

By Eugene Shuter and Warren E. Teasdale

Abstract

The purpose of this manual is to provide ground-water hydrologists with a working knowledge of the techniques of test drilling, auger drilling, coring and sampling, and the related drilling and sampling equipment. For the most part, the techniques discussed deal with drilling, sampling, and completion of test holes in unconsolidated sediments because a hydrologist is interested primarily in shallow-aquifer data in this type of lithology. Successful drilling and coring of these materials usually is difficult, and published research information on the subject is not readily available. The authors emphasize in-situ sampling of unconsolidated sediments to obtain virtually undisturbed samples.

Particular attention is given to auger drilling and hydraulic-rotary methods of drilling because these are the principal means of test drilling performed by the U.S. Geological Survey during hydrologic studies. Techniques for sampling areas contaminated by solid or liquid waste are discussed. Basic concepts of well development and a detailed discussion of drilling muds, as related to hole conditioning, also are included in the report. The information contained in this manual is intended to help ground-water hydrologists obtain useful subsurface data and samples from their drilling programs.

INTRODUCTION

Background

Although published data are available concerning drilling and coring of wells and test holes, these data generally are incomplete in respect to the drilling performed by ground-water hydrologists and other Earth scientists. Much of the available data is a result of practical knowledge gained from the drilling of hundreds of thousands of wells for the production of oil, gas, water, and minerals. In addition to this practical knowledge, a considerable body of research relates to drillability of rock, various types of drilling rigs, and associated equipment and drilling fluids. Although this available information is vast and its quality, for the most part, is excellent, usually it does not meet particular needs of a ground-water hydrologist because a hydrologist usually in interested in very detailed information about shallow aquifers in unconsolidated materials. Unfortunately, these types of materials are the most difficult in which to core and complete representative test holes, and these materials have been the least studied and have little published data about them.

Purpose and Scope

The purpose of this manual is to describe practical aspects of drilling, coring, and sampling techniques to assist personnel concerned with collecting useful subsurface geohydrologic data, through the use of in-house drilling equipment or contract drilling. Particular emphasis is placed on techniques to obtain representative or undisturbed core samples of unconsolidated materials. Emphasis also is placed on techniques and ideas for smpling in areas where contamination by solid or liquid waste likely would be encountered. Although almost all practical drilling methods are discussed, auger drilling and hydraulic-rotary methods are emphasized because these two methods represent more than 90 percent of the drilling performed by the U.S. Geological Survey during hydrologic investigations. The U.S. Geological Survey uses those methods for installation of most test holes and observation wells. Some basic approaches to well development and detailed section on the practical aspects of drill muds and their relationship to hole conditioning also are included. A basic understanding of drilling equipment and terminology is assumed.

Acknowledgments

The authors are grateful to Mr. Arnold I. Johnson, who established the first hydrologic laboratory in the Water Resources Division 30 years ago. The laboratory performed the first in-house service drilling and sampling in the Division. The present research-drilling project evolved as a result of these earlier efforts and the greater needs for complex geohydrologic data of the U.S. Geological Survey. We wish to thank Mr. Robert R. Pemberton, U.S. Geological Survey, whose field-drilling and sampling expertise provided much of the field data and techniques explained in this report. Special acknowledgment also is given to Mr. Tom Kostick of the U.S. Geological Survey for his expert rendering of the technical illustrations by airbrush technique.

TECHNIQUES FOR DRILLING, INSTALLING, AND COMPLETING WELLS

Auger Drilling

Auger drilling is a very valuable technique for the collection of subsurface information; however, it is restricted to the drilling of unconsolidated materials or softer rocks, and it has limitations based on types of materials drilled, size of rig, diameter of augers, and expertise of the operator. Auger drilling offer means of coring, sampling, installation of observation wells and neutron moisture-meter access tubes, and other types of point-sampling devices. Hollow-stem auger drilling, particularly, offers one of the best methods available for collecting uncontaminated samples representative of shallow, unconsolidated formations. The method is unsurpassed for collecting core samples in a contaminated environment, such as around solid- or liquid-chemical-waste pits, sanitary land fills, and radioactive-waste storage areas.

Many think that, if a saturated zone is encountered in the upper part of a hollow-stem auger-drilled and sampled hole, this water will move down the auger and contaminate any samples collected in the lower part of the hole. This is not true if the cuttings are left on the auger flights using slow rotation so cuttings will not move up the hole. This mixture of cuttings has very low vertical permeability preventing downward movement of the water (table 1). In this example, a perched-water table was encountered at 29 ft and partially saturated material was encountered to 44 ft at which depth another perched zone was encountered. However, the samples collected below 45 ft were not wetted from the above perched zones.

Auger drilling is one of the best methods for collecting uncontaminated, representative samples of shallow, unconsolidated formations, particularly the hollow-stem method. We highly favor this method for sampling contaminated-environment lithologies. Auger drilling probably is the most rapid and economical method of drilling in unconsolidated sediments to relatively shallow depths. Soil profiles can be determined, and disturbed soil samples of penetrated materials can be collected from sample returns of augered materials. However, auger drilling is limited to drilling unconsolidated materials or softer rock. In materials where the auger hole remains open without caving, the hole easily can be cased after removal of the auger. Auger drilling usually is done without using air, water, or any other media to flush the hole. Cuttings are moved out of the hole and to the surface by the augering action.

Two basic types of continuous-flight augers are used for drilling: the solid-stem type and the hollow-stem type. Solid-stem augers usually are used for general reconnaissance-exploration drilling because they are more convenient to use, less complex, faster, and easier to handle than larger hollow-stem augers. Hollow-stem augers generally are used for more extensive testing and more detailed soil-sampling projects. They are used to drill and case the hole simultaneously, thereby eliminating hole-caving problems and contamination of soil samples. Also, well casing, aquifer-testing equipment, logging probes, and water- or soil-sampling apparatus can be installed directly through hollow-stemaugers.

Table 1.—Data and sample analyses from a hole drilled using a hollow-stem auger
[ft, feet; µmho/cm, micromhos per centimeter at 25°C; mm, millimeter]

Depth (ft)	NO_3—N[1]	pH	Specific conductance, µmho/cm	Soil moisture (percent by volume)	Porosity (percent)	Median grain size (mm)
0	---	8.13	127			
1	---	8.29	38			
3.5	1.1	8.70	87	3.17	47.1	0.10
4.5	1.9	8.70	95	3.53	---	---
5.0	2.6	8.30	70			
6.0	2.1	8.72	95	2.81	---	---
9.5	1.8	8.55	110			
10.5	0.5	8.85	82	6.34	47.5	9.3×10^{-2}
14.5	2.0	8.80	81			
15.5	5.7	8.62	114	8.89	---	---
19.5	0.6	8.89	75			
20.5	1.4	8.65	89	3.61	47.1	0.15
24.5	1.1	8.75	91			
25.5	0.9	8.75	80	18.38	42.6	.13
29.5	1.7	8.50	108			
30.5	2.4	8.78	90	38.39	---	---
34.5	1.3	9.15	64			
35.5	1.5	8.60	45	14.93	---	---
39.5	1.2	8.89	65			
40.5	1.2	8.95	60	21.59	44.6	0.16
44.5	5.5	8.49	124			
45.5	5.7	8.5	122	27.84	---	---
49.5	1.2	8.75	72			
50.5	.6	9.08	49	3.88	45.1	0.66
59.5	1.1	8.95	83			
60.5	.8	9.00	57	6.39	---	---
68.5	1.1	8.88	82			
70.5	.6	9.10	55	3.43	---	---
79.5	2.0	8.81	75			
80.5	1.2	8.90	64	14.72	---	---
89.5	1.5	8.55	120			
90.5	1.4	8.60	101	29.73	47.5	1.2×10^{-2}
99.5	.8	8.81	76			
100.5	.6	9.15	53	---	33.0	1.8
109.5	2.0	9.09	85			
110.5	3.6	8.85	95	27.53	---	---
120.5	4.5	7.85	69	---	---	---
130.0	2.4	8.70	75	32.9	39.35	---

[1]Milligrams nitrogen per kilogram of sample

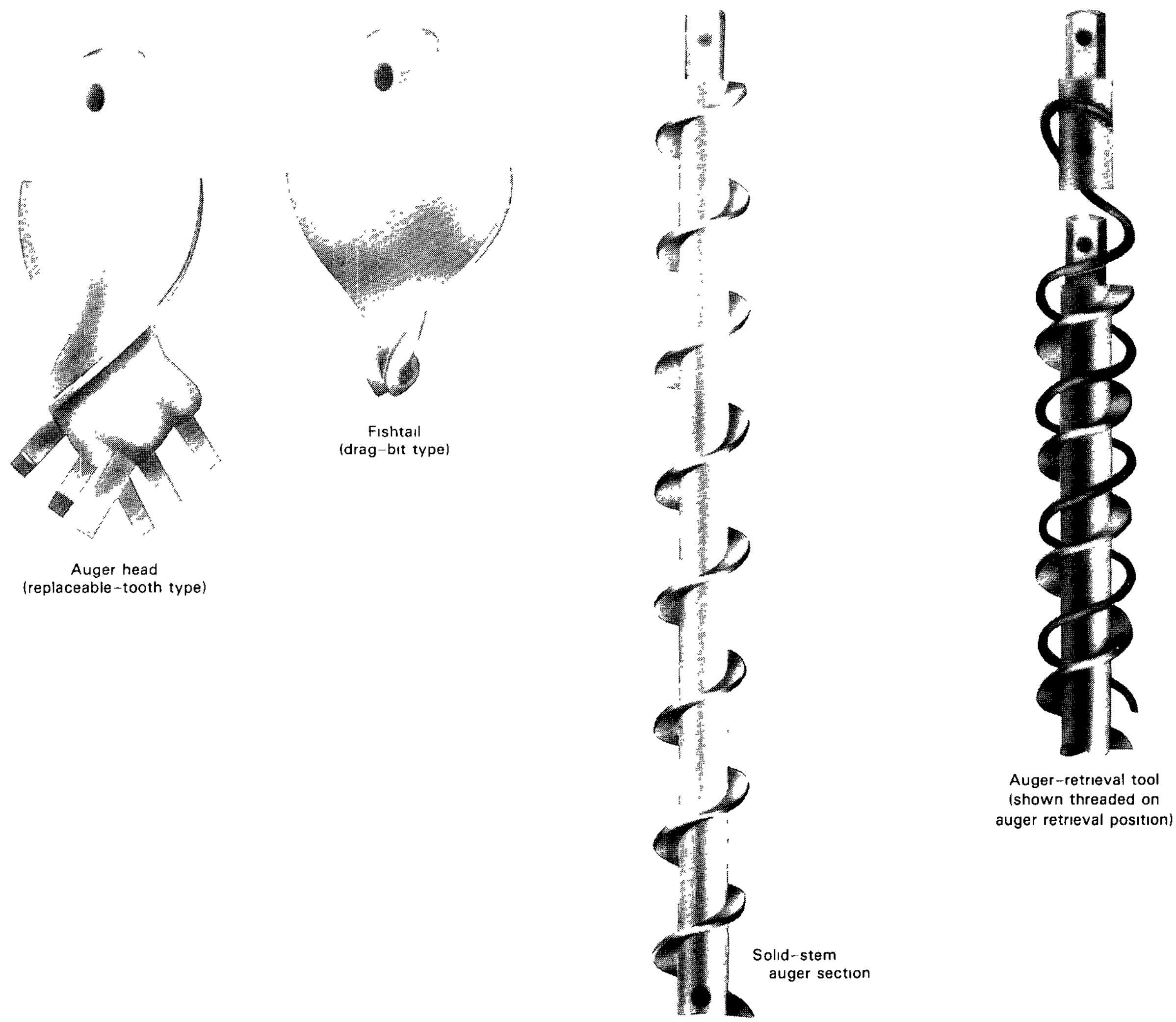

Figure 1.—Solid-stem augering tools: auger heads, auger section, and auger-retrieval tool.

Equipment and Accessories

Solid-Stem Augers

The basic equipment and accessories for solid-stem auger drilling are: lengths of solid-stem auger (usually in 5-ft lengths with auger-whorl diameters ranging from about 2 in. to as much as 12 in.), a drill head with replaceable bits, spring pins or similar means of connecting the auger sections, an auger holder or "catcher," a pointed hammer (such as a geologist's pick hammer) to drive connecting pins in or out, and an auger retriever or fishing tool. Some of these tools are shown in figure 1.

Hollow-Stem Augers

Hollow-stem augers are manufacturered in a variety of diameters, both I.D. (inside diameter) and O.D. (outside diameter), and in a variety of coupling designs. Some are made with threaded joints for coupling, and others use splined connectors with a removable, threaded set screw for transferring tensional loads. A center-rod assembly, consisting of a rod-to-cap adaptor, center rod, center-assembly plug, and a pilot bit, is used with the hollow-stem augers. Other necessary components for hollow-stem auger drilling include: a drive pin, an adaptor cap, threaded capscrews, O rings, an auger head with replaceable cutting teeth, and an auger holder.

Techniques for On-site Auger Drilling

Solid-Stem Auger Drilling

After a drill site is chosen, brush, twigs, and rocks need to be cleared from the rig area to allow safe walking and tool-handling access around the rig. Prior to spudding in the lead auger section and drill head, the immediate ground area needs to be cleared of grass and debris. A clean perimeter is established around the hole for depositing the auger returns when samples of the penetrated materials are collected. Use of low gear on the rig transmission and a moderate throttle setting usually provides sufficient safe power for drilling under any conditions. When spudding in the first few sections of augers, good practice is to rotate the augers as few turns as possible, while maintaining a firm downward pressure. This practice will start the hole straighter and decrease caving and widening at the mouth of the hole. If a faster rotational speed and less downward pressure are used, the augers tend to whip the upper part of the hole and widen it. If the hole is widened too much in the upper part, auger returns from greater depths will not be deposited at the surface but will keep falling back in the hole; if this occurs excessively, the augers will become bound in the hole. Assuming that the hole has been started satisfactorily, it is augered to the desired depth by progressively adding successive flights of augers. Hole depths that can be reached vary considerably from project to project depending on operator expertise, size and type of the rig, auger-flight diameter, pitch of the auger, the type of drill head and bits, and the materials encountered. Due to the large number of variables, setting arbitrary depth limitations for auger drilling is difficult. The industry commonly uses a depth limit of 100 ft, but holes have been auger drilled and observation wells installed to depths of 300 ft in coastal-plain sediments, using 5-in. solid-stem augers.

Hollow-Stem Auger Drilling

Hollow-stem augers usually are used for soil-sampling projects. Hollow-stem auger drilling allows drilling and casing of a hole simultaneously, thereby eliminating hole-caving problems and contamination of soil samples collected through the bottom of the auger head. The hollow-stem auger drilling and sampling method is one of the best means for collecting uncontaminated, repre-sentative, and even undisturbed samples of shallow, unconsolidated formations. This method is unsurpassed for collecting samples in a contaminated environment, such as around solid-waste pits, pesticide dumps, nitrate-contaminated zones, TNT (trinitrotoluene) spills, and radioactive-waste-disposal areas.

Hollow-stem auger holes have been drilled and drive samples collected using 7½-in. spline-connected hollow-stem augers to depths of nearly 200 ft in alluvial deposits containing gravel and even boulder zones. Some of the types of data that can be collected by the hollow-stem auger, drive-core method are shown in table 2, which also indicates the depths at which the data were obtained. With careful selection of drill tools, using proper auger-drilling techniques, results can be rewarding, and data can be obtained relatively inexpensively compared to drilling by other methods.

The actual mode of penetration using hollow-stem augers is basically no different than that previously described for solid-stem auger drilling. A major tool difference, however, is the hollow-stem auger has a center rod and pilot bit that cut the center part (3¼ in.) of the hole (fig. 2). In practice, then, both the 5-ft section of auger and center rod need to be added after each 5 ft of material have been penetrated. At any sample depth, the center rod with the pilot bit attached to it is simply withdrawn; the sampler is fastened to the center rod and lowered to the bottom of the hole for sampling. After the sample has been collected, it is returned to the surface; the pilot bit and center-assembly plug are reattached to the center rod and reset in the augers. Auger drilling can then progress to the next sampling depth where the procedure can be repeated.

Auger-Drilling Procedures and Problems

This section is intended as a guide for an inexperienced operator to some of the techniques, problems, and problem solutions in auger drilling. In pointing out the advantages of auger drilling as a fast and easy method for shallow exploration in unconsolidated materials, the authors do not mean to instill a false sense of ease in the operator. Like any other type of drilling, auger drilling posses problems, and it requires effort and expertise for successful results.

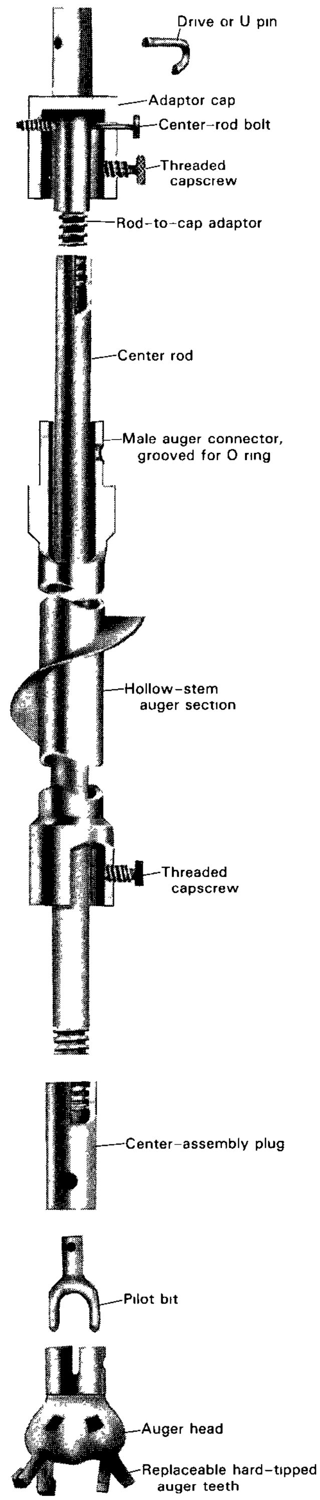

Figure 2.—Hollow-stem auger section with center-rod assembly and accessory components.

Auger Drilling in Moist or Saturated Materials

Auger drilling in moist or saturated materials usually can be done at a rapid penetration rate. However, ease of penetration, resulting in a possibly very fast drilling rate, poses more problems than advantages in auger drilling. An inexperienced operator is inclined to make a hole as fast as the auger head will penetrate the formation, even though one should not drill into formations any faster than the drill cuttings can be delivered up the auger flights to the surface. If the penetration rate exceeds surface returns of the cuttings, then trouble and lost time ultimately will result. Generating cuttings faster than they can be returned to the surface causes the cuttings to: (1) become solidly packed between the auger flights, prohibiting the newly penetrated material from moving up the auger or (2) be forced back into the hole wall if it is soft enough. Thus, the sample is not getting to the surface for lithologic identification, and a binding situation can occur later.

Assume that a typical alluvial or glacial-type material containing sand, silt, and clay zones or a mixture of these materials is being drilled. Further assume that a clay bed of a few feet thick has been encountered and the auger will make a nice bit-size smooth hole through this clay bed. Clay, particularly moist clay, is easy to distinguish when auger drilling because it has a tendency to pull the auger head in and pull down on the rig.

If a soft sand or sand-gravel mixture below this clay zone is encountered and the penetration rate of the augers is increased, many more cuttings than can be passed through the tight hole in the clay zone will be made which will create a sand lock (wedge), prohibiting any of the lower cuttings from moving up the hole. This phenomenon usually can be identified when it occurs by a sudden pull-down on the back of the rig and a noticeable laboring of the rig engine. Increasing engine power in an attempt to force some material through the restriction could result in twisting off the augers somewhere downhole. Generally, the augers can be freed by shifting the drill-rig transmission into reverse, exerting a substantial downward pressure on the auger, and slowly engaging the clutch to break loose and move the augers downward. If the augers do not come loose, try to move them slightly by alternately

Table 2.—Data from drive-core samples collected from a hole drilled using a hollow-stem auger

[ft, feet; µmho/cm, micromhos per centimeter at 25°C; mm, millimeter]

Depth (ft)	NO_3-N[1]	pH	Specific conductance, µmho/cm	Soil moisture (percent by volume)	Porosity (percent)	Median grain size (mm)
7	13.9	8.6	137			
8	8.6	8.25	46	5.67	37.9	0.41
17	9.6	8.82	84			
18	23.6	8.87	142	7.52	39.0	0.28
27	22.2	8.71	105			
28	30.0	8.59	157	2.66	32.2	0.92
37	6.7	8.80	87			
38	3.5	8.90	68	2.22	27.0	1.1
47	4.3	8.82	73			
48	2.6	9.01	50	2.47	---	---
57	2.6	8.90	71			
58	4.7	8.91	63	4.22	28.6	0.64
67	2.0	8.70	71	2.47	---	---
77	1.6	8.81	62			
78	3.3	8.51	60	3.88	36.8	0.40
87	1.5	8.75	85			
88	1.5	8.95	53	4.09	---	---
97	1.1	9.01	58			
98	1.5	8.55	118	3.18	32.7	0.93
107	1.3	8.88	79			
108	0.9	9.10	53	4.10	---	---
117	1.5	8.70	71			
118	1.2	8.90	43	3.96	39.7	0.32
127	1.1	8.81	85			
128	1.1	9.01	50	3.55	---	---
137	1.2	8.90	39	3.23	34.4	0.53
157	1.0	8.50	39	3.67	---	---
185	1.5E	8.70	77	---	---	---

[1]Milligrams nitrogen per kilogram of sample

engaging and disengaging the clutch. The augers may move only a fraction of an inch; continue the process and the augers will almost always be freed. Once the augers have been freed, reinsert them in the hole, using reverse rotation until reaching the bottom. Now, alternately raise and lower the augers, continuing reverse rotation and attempting to dislodge the material between the auger flights. Observe where the bottom is encountered by alternately raising and lowering the augers. If the material is coming off the augers, the top of the cuttings will be elevated as the operation progresses. Verify that the sand lock has been broken loose from the augers by disengaging the clutch and deadsticking the augers up through the restrictive clay zone. If the augers move freely through the previously blocked area, lower the augers to the top of the cuttings, engage the clutch in a forward gear, and slowly move the cuttings up through the tight area. When the reintroduced cuttings have been removed from the hole, continue auger drilling, remembering not to penetrate the formation at a rate that exceeds the capacity of the auger flights to carry the cuttings through the restricted part of the hole.

A similar problem that may occur while auger drilling is large gravels or cobbles locking up between the auger flights and the hole wall. This usually occurs after passing through a gravel bed. In auger drilling, particularly under saturated conditions, gravel or cobbles are not drilled but are pushed aside. During further auger drilling, either some material moving up the auger or one of the auger flights will dislodge the rock from the side of the hole. If the rock is small enough, it eventually will move to the surface; however, it can get caught between an auger flight and a hard wall section. This results in no drilling action, very similar to the previously described sand-lock problem. The best method to solve this problem is to reimbed the rock in a soft section of the hole wall in the following manner: (1) shift the rig transmission into reverse and dislodge the rock by alternately engaging and disengaging the clutch; and (2) after the rock has been dislodged, with the auger still in reverse, reinsert the auger down the hole and try to reimbed the rock in a softer wall section by alternately turning the augers one or two turns forward and one or two turns in reverse while, at the same time, imparting a slight downward thrust on the augers. This technique sounds complicated; however, experience has proven that it usually works.

The authors refer to using relatively slow revolutions per minute (usually first and second gear) during auger drilling, particularly when most auger-drilling rigs are equipped with five forward speeds. Industry literature suggests shifting to high gear and increasing the throttle setting to spin the cuttings to the surface. From experience gained by drilling hundreds of thousands of feet of holes by the auger-drilling method, we have learned that very rapid revolutions-per-minute auger drilling can result in many problems, such as enlarged holes and lost connecting pins and bolts from vibration, which results in lost augers. The higher gear ratios on power-auger transmissions may be valuable in hydraulic-rotary rock coring, but they are not appropriate for auger drilling in unconsolidated material. Even when auger drilling in saturated conditions, rapid auger drilling will only accomplish the pumping out of gigantic mounds of caved or viscous sands from some unknown depth. An appropriate method for auger drilling in moist or saturated materials is to use a moderate throttle setting with the rig transmission in first or second gear; exert enough pressure on the hydraulics to penetrate the formation at no faster rate than cuttings can be transported up the auger flights; and log the hole by feel of the drilling action, along with geologic observation of the returned cuttings, remembering that these cuttings are a mixture of penetrated lithologies. Cuttings returned to the surface, when auger drilling below the water table, can come from any place in the hole and are meaningless for sequential lithologic interpretation.

In the process of auger drilling under saturated conditions, the auger penetrates sand, silt, and clay layers, and rind or filter cake will form on the wall of the hole and will prevent loose materials from falling off the wall or large caving areas from forming. The hole then can be successfully cored and an observation well installed if the above-described augering procedures are followed.

Auger Drilling in Dry Materials

General problems encountered and possible solutions, such as for sand and gravel locking mentioned in the previous section, are also possible during auger drilling in dry materials. However, one particular problem is poorly understood and requires special attention. When auger drilling in nearly dry lake beds (playa deposits) or similar type sediments (commonly found in the arid western part of the United States), heat is generated in the drilling action through friction of the material trying to move up the auger flights in a dry and close-tolerance hole. The materials actually bake on the augers and auger head to a consistency that cannot be penetrated; the auger head teeth are unable to cut the material, and the material will not move up the auger. The hole wall is so competent that the material being cut by the teeth has no place to go, and penetration refusal is reached. Most operators assume they have hit rock, because it feels and sounds like rock (a screeching and grating sound emanates from the hole).

Remove the auger when this situation occurs, and clean the lower few whorls of the auger if they are completely covered with this baked material, which is so hard that it may have to be removed with a geologist's pick or chisel. When the augers are reinserted in the hole, drilling will progress until enough heat is generated to result in a repetition of the problem. Note how to recognize and remedy this problem. When this baking-on occurs, a semihard obstruction forms around the augers that functions like a brake band. A sudden change in the sound of the engine on the rig would indicate this problem; the engine labors and might even stall. Disengage the clutch immediately and stop the auger rotation; notice the backlash in the augers at this time from the torque imposed on them. Relieve the pull-down tension and cautiously and slowly reverse the augers' direction, thereby unscrewing them from the tight material. Continue this procedure until the lower flights of augers are free from the obstruction; then resume drilling at a moderate speed and advance the augers slowly back into the material, allowing the auger teeth to break up the cakey zone of sediments and transport them up the auger flights. If necessary, pour several gallons of water into the hole around the augers, as they are rotating, to cool and break up these sediments and free the augers for drilling. However, prior to pouring any water down the hole, check with the person in charge of the drilling program to see if the water is going to have any deleterious effect on later sampling for moisture content. If augering with a hollow-stem auger, one technique for destroying this baked-on material is: remove the center-assembly plug and lift the auger about 5 ft; pour in enough gravel (1- to 1½-in.-diameter, crushed preferred) to fill the bottom 5 ft of the hole. Reinsert the center rod and center-assembly plug and slowly drill into the gravel; the gravel has a tendency to remove the baked material from the auger. Try any or all of these techniques depending on hole conditions. If none of these techniques is successful in dislodging the caked or baked-on plug at the auger head or between the auger flights and the auger will not penetrate, remove the entire string of augers and remove the material that caused the obstruction, repeating this technique whenever necessary.

Although the authors stress slow rotational speed of the auger for drilling moist or saturated formations, we also must emphasize it for dry materials because faster rotational speed increases the heat generated by friction, and heat is the major problem here. For example, a problem encountered in drilling dry lake-bed materials and solutions to the problem follow: An experienced auger-drill operator was attempting to drill and collect drive-core samples at 5-ft intervals to a depth of 100 ft. After destroying three clutches on the rig to reach a total depth of 50 ft in several days, the operator was sure the materials were too hard for auger drilling. However, because of a critical need to obtain the core samples, another extremely knowledgeable operator was sent to assist in the operation. His observation was that the operator was drilling at a far too rapid speed, resulting in a high-heat baking of the materials on the auger. His first recommendation was to drill the hole using first gear, with the throttle set at a fast idle. The result, using his suggested method, was a 1-day completion of a 100-ft hole, collecting drive-core samples every 5 ft.

Drill Response in Various Lithologies

The following discussion lists some reactions of a drill to various lithologies penetrated with ease or difficulty, that may help an operator determine what type formations he is drilling in.

1. Sands: Relatively easy drilling, smooth auger rotation, and fast penetration rate. If sands become dense, penetration rate decreases and the back of the rig may lift slightly.

2. Sands and gravel: If sands and gravel are encountered below the water table and the gravel-size is small (1-in. diameter or less), a slight vibration may be felt as the auger teeth encounter the gravel. As gravel size increases, the chatter or vibration of the auger increases. If this lithology is encountered above the saturated zone, the vibration is much more pronounced.

3. Silts and silty clays or clay silts-dry (playa-lake deposits): Slow auger rates (particularly in indurated material) may cause considerable chatter of augers; cuttings may become extremely hot; and a screeching sound may be caused by auger rotation. Rig engine will labor or even stall from the augers binding in the hole. Very few or no cuttings are returned to the surface. Remedial steps may have to be used if penetration is to be successful.

4. Silts and silty clays or clay silts-wet (playa-lake deposits): Smooth, fast auger penetration. Augers may dig in in moist clay-silt formations and pull down if auger penetration is too fast. Cuttings may come to the surface shaped as cohesive balls or cones of various sizes. Cutting returns to the surface may occur erratically or not at all in some instances. If these materials are completely saturated, the penetration rate increases, and cuttings returned to the surface are the consistency of a milkshake.

5. Clays-dry: Auger drilling characteristics are similar to those of dry silts.

6. Clays-moist: Easy penetration. They will exert a definite pull-down on the back of the rig if penetration rate is too fast. If penetration rate is not too fast, the material will stick between the auger flights. Slower penetration will result in the cuttings returning to the surface with a texture like ropey modeling clay. If the clay is completely saturated and sticky, it will adhere to the augers, resulting in no returns.

7. Caliche, friable soft sandstone, and siltstone: If these materials are dry, they will cause a chattering similar to gravel and will also have a tendency to cake on the auger, similar to dry silt. If they are saturated, they will have characteristics similar to tightly compacted sands.

8. Boulders: When large boulders are encountered, a pronounced chattering and hammering of the augers occurs with a high-pitched screeching of the auger teeth as they try to cut the rock.

Retrieval of Lost Augers

Nearly everyone operating an auger-drilling rig for any length of time eventually is going to lose an auger down the hole. Several methods exist for fishing and retrieving lost augers; these methods may or may not be successful depending on the condition and equipment available for conducting the operations. The usual cause for loss of an auger is that someone forgot to put in a coupling pin or the pin has lost its temper from metal fatigue and is vibrated out. Or, in the case of hollow-stem auger coupling, someone did not put in the threaded capscrew or forgot to tighten it. If these omissions occurred and the auger drilling progresses, when the augers are retracted, the auger flights are separated. On some occasions, welded upper or lower shanks of the augers simply part from weld or metal fatigue. Whatever the reasons for separation, some of the auger is left in the hole and needs to be retrieved. One or more of the following fishing and retrieval methods should be successful. The first question that is asked when auger separation occurs is: What happened? The only answer is: Pull the remaining auger to examine it. Assume that, after auger drilling with a 4½-in.-diameter solid-stem auger and returning it to the surface, the bottom shank is still in place. Then, the problem is that the U pin either was not put in, was inserted backwards, or somehow came out. The first step, prior to the fishing attempt, is to use a sounding weight to see if any cuttings are in the hole that have buried the top of the 1⅝-in. hex shank on the top of the auger. If cuttings or caved material are on top of the lost augers at the time of sounding, first remove this material by using a wash pipe and washing the sloughed material out of the hole.

If the top of the auger can be sounded, proceed with the fishing operation. Carefully lower the recovered sections of the augers back down the hole without rotating them, until they come in contact with the augers in the hole (the fish). The hex connectors unlikely would be aligned, so attempt to align them by exerting a very light downward pressure with the rig hydraulics while, at the same time, slowly turning the drive spindle (with a pipe wrench if possible). When the mating hex shanks are aligned, the augers will drop slightly. As soon as this occurs, stop any rotation. Now, slowly begin retrieval operation by lowering the hydraulics until the augers are butted tightly together. The augers are now reconnected, but no U pin is in them so they cannot be merely pulled out. However, they can now be screwed out of the hole. Shift into reverse gear, begin slowly rotating the auger, and decrease pressure on the hydraulics at a rate equal only to the upward thrust exerted by the augers. This upward thrust will try to lift the back of the rig; this can be seen to occur, so it is not difficult to keep the hydraulic retraction rate equal to that of the reversing augers. After the augers have been reversed out to the point where the U pin was missing, set the augers down on the auger holder and insert a connecting pin.

If the connecting bolt was lost when drilling with hollow-stem augers, the same procedure for getting back onto the fish, and then reversing the augers out to retrieve them, would be applicable. The only difference in solving this problem when drilling with the hollow-stem auger would be in that instance where cuttings filled the hole above the lost auger. Instead of using a wash-out pipe, simply connect to the top of the hollow-stem auger and flush through it to remove the cuttings.

Use of Auger-Retrieval Tool

A special tool is manufactured for retrieval of a lost auger; this tool (fig. 1) is a "corkscrew" device manufactured of high-tension spring steel, designed to turn onto the lost auger, with the whorls of the retrieval tool matching those of the auger. If the weld of an auger section breaks, either the top shank of one auger or the bottom shank of another, there is no connection such as described in the preceding section to attach to for unscrewing the auger from the hole. The kind of break can only be determined after first removing the string of augers that is still attached to the rig. Remove this part of the auger as carefully as possible to not leave any cuttings on top of the lost auger. Assume, in this instance, that the problem is not a lost bolt or U pin but rather an actual parting of a weld and the auger broken in two. The simple "reconnection and unscrew from the hole" method cannot be used. After removal of the auger, sound the hole to see if it is open to the fish by addition of other auger sections. This reinsertion of the retrieval tool needs to be accomplished very carefully because it has a very close tolerance fit to the size of the hole previously cut by the bit, and (as discussed before) a rind commonly will be on the hole wall that corresponds to the diameter of the augers that are slightly less than bit diameter. When the retrieval tool is started in the hole, lower it without rotation whenever possible. However, if resistance is encountered, rotate the tool very slowly and, with a minimum downward pressure, try to auger the rind or other obstacle material up past the whorls of the retrieval tool. Reversing the rotation of the auger while trying to get the retrieval tool down the hole will cause a lot of material to fall to the bottom and, as a result, the retrieval tool might not reach the lost auger. If the retrieval tool reaches the lost auger, you will feel a contact. The next step is to screw the retrieval tool onto the lost auger until the connection is tight. Then, try to retrieve the augers that were lost in the hole by first attempting to rotate the augers without pulling up on them; use first gear at a moderate power rate, no more than 1,000 r/min on the engine tachometer. If the auger rotates at this time, something similar to sand locking, or a boulder lodging between an auger flight and the hole wall, has occurred to break the auger.

If the augers will not rotate, exert a 1,000- to 2,000-lb downward thrust with the rig hydraulics while, at the same time, alternately engaging and disengaging the clutch to break loose whatever is binding the augers. If this does not loosen the locked auger, push down on the augers as hard as possible without lifting the rig wheels off the ground, but do *not rotate the* augers. If any downward movement is achieved at all, alternately apply up and down thrust with the rig hydraulics, being careful not to pull up too hard (2,000 to 3,000 lb) or the coil spring of the retrieval tool may break or straighten. If any up and down movement of the augers occurs, eventually they should break loose to a point where they can be removed from the hole by deadsticking. If the pull becomes too difficult, rotate the augers slowly in a forward gear if possible. Do not pull or torque the augers so hard that the retrieval tool breaks, leaving it on the top of the lost auger. If this occurs, another retrieval tool cannot be connected to the last auger and the string of tools probably are irretrievable. If the above method is unsuccessful in loosening the augers, the retrieval tool needs to be reversed off the lost auger and returned to the surface.

The decision to proceed will depend on the cost of the tools in the hole versus the estimated cost of retrieval by complicated procedures, in time, money, and effort. If only a few sections of hollow-stem auger are in the hole, such as four sections plus the bit, the equipment cost is more than $1,100 at current prices (1988). Assuming a 50 percent chance of recovery, more than several days in attempted recovery cannot be invested or recovery cost may exceed the recovered equipment cost. If 15 sections of hollow-stem auger plus auger head are stuck in the hole, the equipment cost is about $3,700. Then, as many as 6 or 7 days in recovery attempts could be invested.

Auger Retrieval Using Wash-Over Method

Sand locking or boulder lodging at some place on the auger may prevent recovery of the auger sections by the fishing tool. These obstacles must be removed before the augers can be freed, probably by a combination of washing and drilling over the augers. If there isn't any wash-over pipe on hand, contact local drilling firms to see if they have the correct size wash-over pipe (7 in. for 6¼-in. auger) available on a rental basis. If the rig has a mud pump and rotary capability, attempt the drilling-over method. We have used flush-joint, collarless casing successfully, although standard 7-in. collared casing also has been successfully used for this drill-over procedure. First, assemble the necessary components: (1) enough pipe to overdrill to the bottom of the lowermost auger section; (2) one cross over sub that mates from the kelly sub to the pipe; (3) one 7-in. collar torch cut in a sawtooth pattern, with hard-facing weld applied to the sawteeth for use as a bit;

and (4) one 20-ft joint of pipe, cut and threaded into two 5-ft and one 10-ft joints. Now, construct a mud pit to the approximate dimensions of 3-ft wide by 6-ft long by 5-ft deep; fill it with a mixed drilling fluid using 50-s (seconds) viscosity, high-yield bentonite. A fluid discharge pit needs to be cut from the top of the auger hole to the mud pit for fluid return.

Start the drill-over washing procedure. Connect the sawtooth cutting collar to one of the 5-ft sections of pipe and couple this section of pipe to the kelly sub. With the suction hose in the mud pit, engage the mud pump and, as soon as fluid comes out of the bottom of the pipe, rotate the pipe slowly while, at the same time, exerting just enough hydraulic downward pressure to force the pipe down the hole. The saw-tooth cutting collar will have to shave off some of the wall as the auger bit cut only a 7¼-in. hole. Note: Initially, no drill fluid will return to the mud pit because the existing auger hole will have to be filled with drill cuttings and fluid before any return can come back up the outside of the pipe. If the kelly is long enough, advance the bottom cutting bit to at least 20 ft, pull the kelly back, and remove the 5-ft section of pipe and sawtooth collar bit. Now, screw the sawtooth bit onto the 20-ft joint of pipe and set this back into the hole. Reattach the kelly sub and continue drilling and circulating drilling fluid as before. Some rigs may be equipped with a kelly that is too short to drill ahead far enough to use 20-ft pipe joints for each succeeding connection. However, in the list of equipment were 5-ft and 10-ft joints of pipe. By using combinations of these shorter joints with a shorter kelly, the pipe can be advanced to a depth such that, when the pipe is pulled back and the shorter joint removed, a 20-ft joint can be added and the string dropped back into the hole and again enable you to recouple the 20-ft joint. With this combination of subjoints, 20-ft pipe joints can be used even if the rig is equipped with only a side-delivery water swivel in the 5-ft-plus hydraulic ram movement. Be very careful in penetration rate and torque applied to the pipe. Standard casing, particularly threads, are not made to withstand much abuse and, additionally, whatever torque is applied to the threads with the rig later has to be uncoupled, using pipe wrenches and manpower. If the problem that caused the augers to break was a sand-lock, it may not be felt on the way down. If it was gravel or boulder wedging, however, it will definitely be felt, and patience is needed when drilling them out because the hard-faced bit is not a hard-rock bit. When the bottom of the augers has been reached, flush the hole for several minutes to remove as many cuttings from the hole as possible while, at the same time, building a filter cake on the wall of the hole that will keep any sand or rock from falling back into the hole.

Now, slowly remove the wash-over drill pipe from the hole. Each time a section of drill pipe is removed, pour or pump in an equal quantity of drill fluid to replace the volume displaced by the removal of the pipe to maintain a positive fluid head inside the hole to support the filter cake and prevent recaving of sand, and so forth. After the entire string of wash-over pipe has been removed, recouple the spiral auger-retrieval tool and the necessary 5-ft sections of auger to reach the broken-off section; screw the retrieval tool onto the lost auger (as previously described); and, in almost all instances, the lost augers can now be removed from the hole. As mentioned in a previous section, using the drilling-wash-over method may be too expensive to retrieve a few sections of auger, but it may be well worth the effort in recovering a string of tools worth several thousand dollars. As an indicator of retrieval cost, a 100-ft wash-over needs to be completed in about 1 day; add that cost to the pipe and tools needed for the retrieval attempt to assess the cost of the operation.

Auger-Drilling Precautionary Measures

The following precautionary measures are discussed to decrease the chance of losing augers in operator-controllable situations:

1. When solid-stem augers are used, check the spring-type U pins carefully. If they fit extremely loosely in the augers, they need to be tightened by hammering the U closed until they have to be driven into the auger-flight connection hole. Inspect the pin for any hairline cracks that might have developed along the U bend; if any cracks exist, discard the pin.

2. When the U-pin connector is installed in the augers, make certain that the pin is driven in with the spring part of the pin facing to the right or in the direction of normal auger rotation. If the pin is installed incorrectly (in the opposite direction of normal auger rotation), rocks and soil will be forced under the pin while drilling, causing it to fall out in the hole resulting in lost tools.

3. When either hollow-stem augers or solid-stem augers are used, thoroughly inspect the box ends and pin ends of the augers before putting them on the drill string and drilling with them. Generally, cracks will develop in the steel or in the end-attachment welds from metal fatigue and torque stress imparted to the auger while drilling. If any metal or weld failure is apparent, set the auger aside until it can be repaired. If information needed by the project requires the extra depth obtainable by using one or two faulty or questionable augers, connect these augers last, near the top of the hole where they can be observed. If they do break, the result will not cause a loss of tools downhole because the break or failure will occur near or just below land surface. If this happens, dig down to the break, attach a clevis or cable sling around the remaining augers, and retrieve the augers with the sandline.

4. When hollow-stem augers are used, always inspect the welds around threaded inserts. If indications of cracks or weld failure are visible, repair them before using. If the auger-connecting capscrew does not start or thread easily into the threaded insert by using only the fingers, retap the insert to remove any burrs. If the capscrew still refuses to start readily, check the capscrew and redress threads with the die or small file. Do not force it to thread with a wrench.

5. When connecting hollow-stem augers that do not butt together correctly (box and pin connection), inspect the internal keys in the box end and the keyways in the pin end. Periodically, these become burred and distorted during tight or chattering auger-drilling conditions, and they require dressing with a small file to make the augers go together smoothly. Also, inspect the nonthreaded bolt hole in the pin end of the auger for any bulging or bolt-hole elongation. Dress any internal or external bulge around the hole with a file to facilitate ease of auger coupling and ease of center-rod assembly removal (it would tend to hang up on the internal bulge). If the bolt hole appears extremely elongated, replace the pin end.

6. Before using capscrews to connect the hollow-stem auger flights, clean the threads thoroughly with a wire brush. Use a 12-gauge shotgun cleaning brush (wire type) to clean dirt and grit out of the threaded insert holes before threading the capscrew into it. Lubricate threads slightly with a light oil to prevent rusting; water needs to be used as a lubricant during drilling.

7. When drilling in gravels with a hollow-stem auger, if excessive chattering of the augers occurs, apply some nonhardening Permatex or similar material to the capscrew threads to prevent the capscrews loosening and falling out in the hole because of chattering vibrations.

In addition to drilling holes by the auger method for determining lithology and taking core samples, completing the hole as a temporary or permanent observation well for the purpose of collecting water samples also usually is desired. The following sections describe some of the many ways of installing well points in both solid-stem and hollow-stem augered holes.

Installation of Well Casing and Screen in Solid-Stem Augered Holes

The major problem with installing observation wells in a solid-stem augered hole is getting the screen or screened well point down through the caved material that usually results (particularly below the water table) when the augers are removed from the hole. The simplest method for installing a screen through caved or bridged material is: Couple a screened-drive point (fig. 3) to the bottom of a 21-ft section of whatever diameter of steel pipe is needed for the well, and lower it into the hole, adding whatever number of additional joints of pipe are needed until a point is reached at which the well point and pipe, by its own weight, will no longer penetrate the caved material. In many instances, the drive point can be pushed through the caved material by using rig hydraulics to push it to the required depth. If the caved material consists of relatively dense clean sand and the point cannot be pushed through, use the drive hammer ordinarily used for drive-core sampling. Note: If a drive hammer is used, the use of a drive-rod-to-pipe coupling will not damage the pipe threads. Although this is the simplest method for installing a screened-drive point through caved material, it is the least preferred method because the screen can be plugged with fine particles as it passes through the caved-saturated material. The hydrostatic head outside the screen will try to equalize to that inside of the pipe; this action may completely plug the screen slots resulting in a slow or nonresponsive observation well. Try to alleviate this problem by pouring water into the pipe, keeping it as full as possible to maintain a higher hydrostatic head inside the pipe than the hydrostatic head outside the pipe.

Two more appropriate methods for installing a screened well point through caved material, both requiring a pump and water supply, are:

1. Sound the test hole to determine elevation of the filled-in material, and insert the drive point to a depth of a few feet above that point. Now, couple the pump-discharge hose to the top of the well pipe and pump in clean water at a rate of 20–25 gal/min through the drive-point screen, while, at the same time, lowering the pipe and screen. This water will wash the material away from the drive-point screen so that it does not become plugged; at the same time, it will provide a lubricated annulus for the pipe to follow. Now, the only resistance to penetration is located in the bottom few inches of the tapered drive point; this resistance is usually overcome by the weight of the pipe. If resistance from either dense, clean sand or possibly some gravel that has bridged the hole is encountered, preventing penetration of the point, spud the point through the problem zone by alternately lifting and dropping the pipe string with the sandline winch. A drive point usually can always be driven through caved material by using this wash-in method; also, the screen will be clean and responsive to water-level changes in the aquifer (into which it has been installed).

2. Another method of installing a screened well point through caved material is using a so-called jetting point (fig. 4). These points are equipped with a spring-loaded ball-check valve that keeps material from coming into the screen from the bottom, while allowing pumping through the bottom of the screen for washing away material in the hole. The jet-type well point will allow wash-through in almost any restrictive conditions in the hole. It is particularly valuable used in conjunction with plastic-pipe well installations because no driving or abusive methods need to be used to penetrate the caved material.

Either of these two washing methods offers a good means of installing well points through caved materials in a solid-stem auger hole, and they offer the best possibility for providing an adequately responding observation well. One additional technique can be used to assure that the wells will be responsive to head changes in the aquifer. When required depth of the screen is reached, increase the pump discharge and vigorously flush the screen (a pressure exceeding 80 lb/in.^{2} may break the pipe if

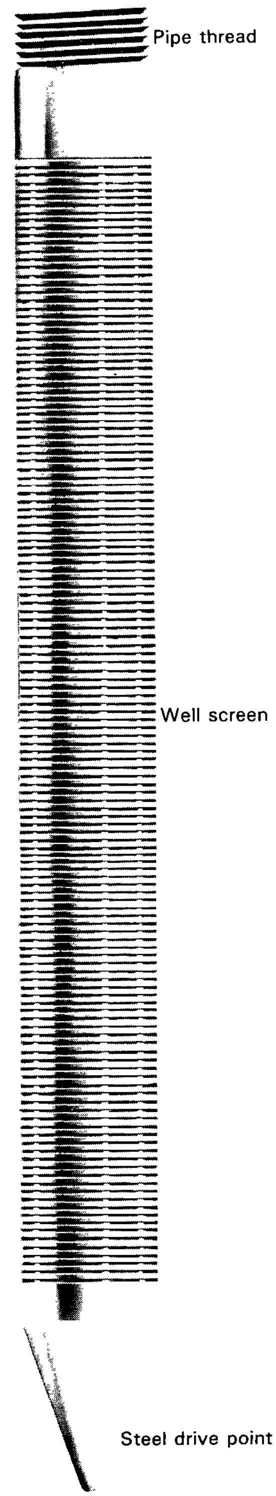

Figure 3.—Well-screen and drive point.

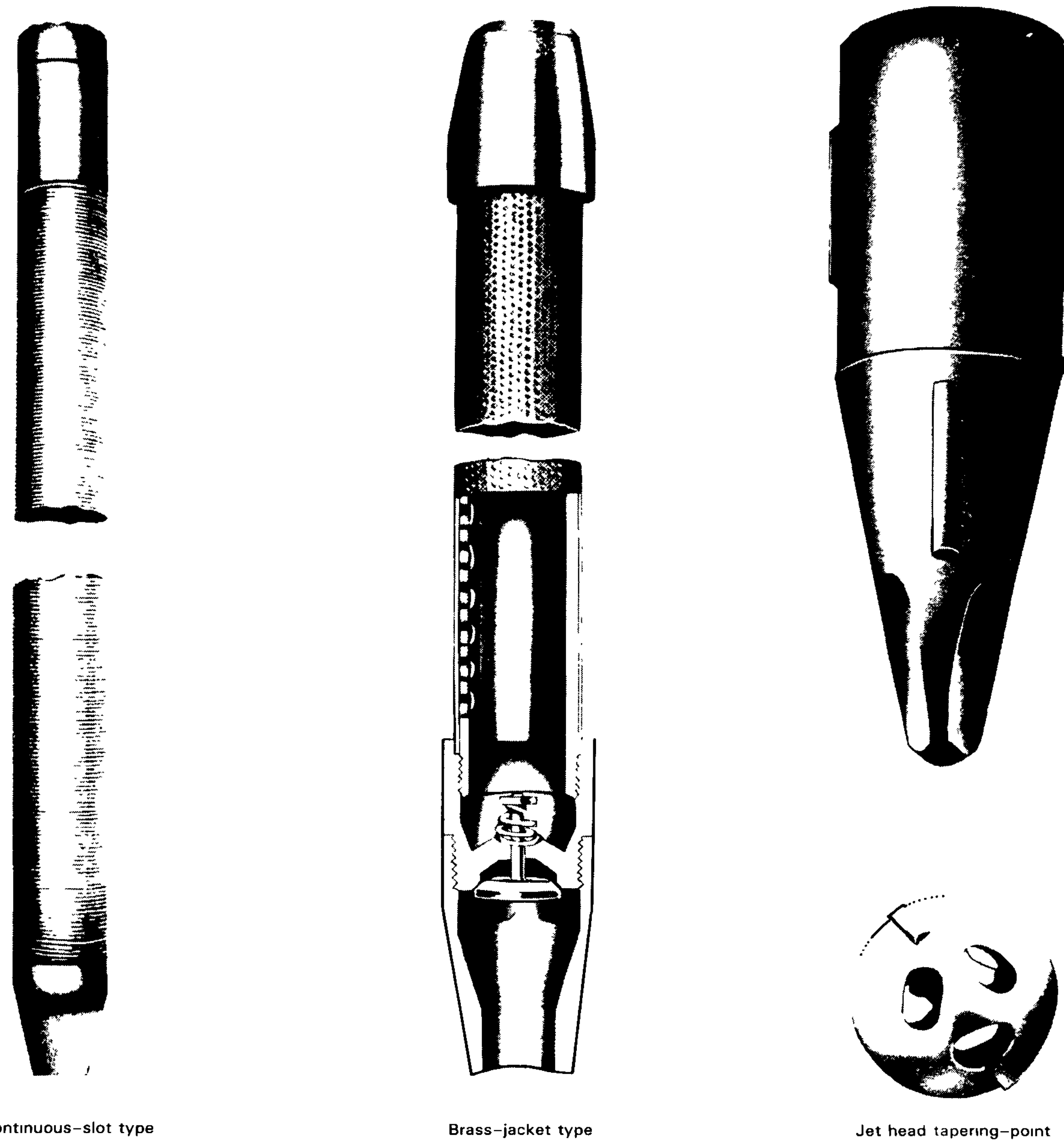

Figure 4.—Types of self-jetting well points.

plastic pipe is used). Do this for several minutes, and, as the screen flushes out, sediment around it will be agitated and lifted; shut the pump off and let the agitated cuttings resettle. Coarser cuttings will settle back first, resulting in a coarser sand pack around the screen. This continual gradational settling of finer materials out above the screen will lessen the possibility of vertical movement of water within the borehole.

Drilling-in of the screen is one additional method of installing well points and screen through caved material in auger holes. This method has special application in holes with a considerable quantity of dense sand or gravel bridging, through which the well point or screens cannot be pushed or driven, particularly where no means of water flushing is available. First, weld on either cutting blades or a gravel-removal spiral to the bottom of the screened points (fig. 5). These blades or spirals are constructed to open the hole to a point greater than the diameter of the screen, providing some protection to the screen, while at the same time providing room for (succeeding) pipe collars.

Lower the well screen on 21-ft joints of steel pipe into the hole until the dense caved material or gravel bridge is reached. Use 5-ft joints of pipe, coupled to the auger drive, by a 1 5/8-in. hex to male pipe-thread adaptor; slowly and carefully drill the screen in. Take special drilling care if large gravels are encountered because they can tear the screen; if large gravels are encountered, rotate the pipe very slowly. The drill wings or spiral tend to push the gravels back into the softer materials in the hole; however, some of them will move up beside the screen. If this occurs, too fast rotation and penetration rate can result in serious damage to the screen. If the auger is equipped with a side-delivery water swivel or some other means of water delivery, use it to aid in lubrication during installation, as well as keeping the screen slots open. Water can also be poured in the pipe to maintain a positive head inside the pipe as previously described. Although this method requires care because of the chance of screen damage, it can be successful; screens as large as 6 in. in diameter have been installed to considerable depths using the method.

Installation of Well Casing and Screen in Hollow-Stem Augered Holes

Installation of a screened well point through a hollow-stem auger is easier than the installation of a screened well point in a caved solid-stem auger hole. Assume a situation where the aquifer to be screened with a screened well point has been auger drilled using one of the methods to keep cuttings from coming up inside the auger, described on pages 57 to 58. Also, suppose a drive-core sample has been taken at the bottom of the hole to verify that it is the desired aquifer material. Proceed with a simple method that will usually result in the installation of a very clean, responsive observation well. Lower the pipe with screened drive point attached to the bottom of the hole. If the method for holding out fill-in of the auger by caving materials was the hollow-stem auger filled with viscous fluid technique (see p. 57 to 58), the viscous fluid needs to be pumped out of the hole by attaching a discharge hose to the top of the pipe and pumping clean water through the screen. After flushing, disconnect the hose; fasten a pipe to the drive-hammer-rod connection and, through the use of the drive hammer and cathead, drive the screened well point into the aquifer material. Another excellent method of installing well points through a hollow-stem auger, where viscous sand fills up the inside of the hollow-stem auger, is described in a written communication by P. A. Lutin, A. E. Coker, and R. R. Pemberton (1967). The following quoted material from the communication provides the essential concept.

> The desired length of casing was measured from the tip of the well point and the plastic pipe was cut with a knife.
>
> The length of plastic pipe plus the well point was such that with a plastic adaptor, coupling, and 5-foot section of galvanized iron pipe, the total length of the assembled casing exceeded the depth of hole by about 2 feet, thereby leaving a 2-foot section of galvanized iron pipe above the land surface.
>
> In some areas of Florida, drilling in the unconsolidated sediments above the limestone bedrock was troublesome because quicksand continuously filled the hole. When quicksand was encountered, a spare coil of plastic pipe was unrolled and fitted with a wash head, and the effluent end of the pipe was inserted through the auger stems to wash the hole free of sand. The spare plastic wash pipe could be removed and the assembled plastic well casing inserted in the sand-free hole in a matter of seconds.
>
> After the well casing had been installed, the auger was removed, the hole backfilled, and the-section of steel pipe was cemented in for stabilization. It should be noted that flexible plastic pipe is used for this method of installation.

If installation of observation wells in hollow-stem auger holes is to be accomplished in the open hole or at some depth other than through the bottom of the auger, then the methods described on pages 13 to 16 are applicable.

Throughout the description of installing observation wells in auger-drilled holes, the authors have stressed the importance of keeping the screens clean so that the well will respond quickly and accurately to water-level changes in the aquifer. A poorly responsive observation well will provide erroneous data. Any observation well or water-sampling point that is installed should be checked immediately to ensure that it is open and responsive to the aquifer by running a slug test to determine specific capacity, or, if some means of pumping the well is available, it can be checked for yield. If the well point is not adequately responsive, remedial

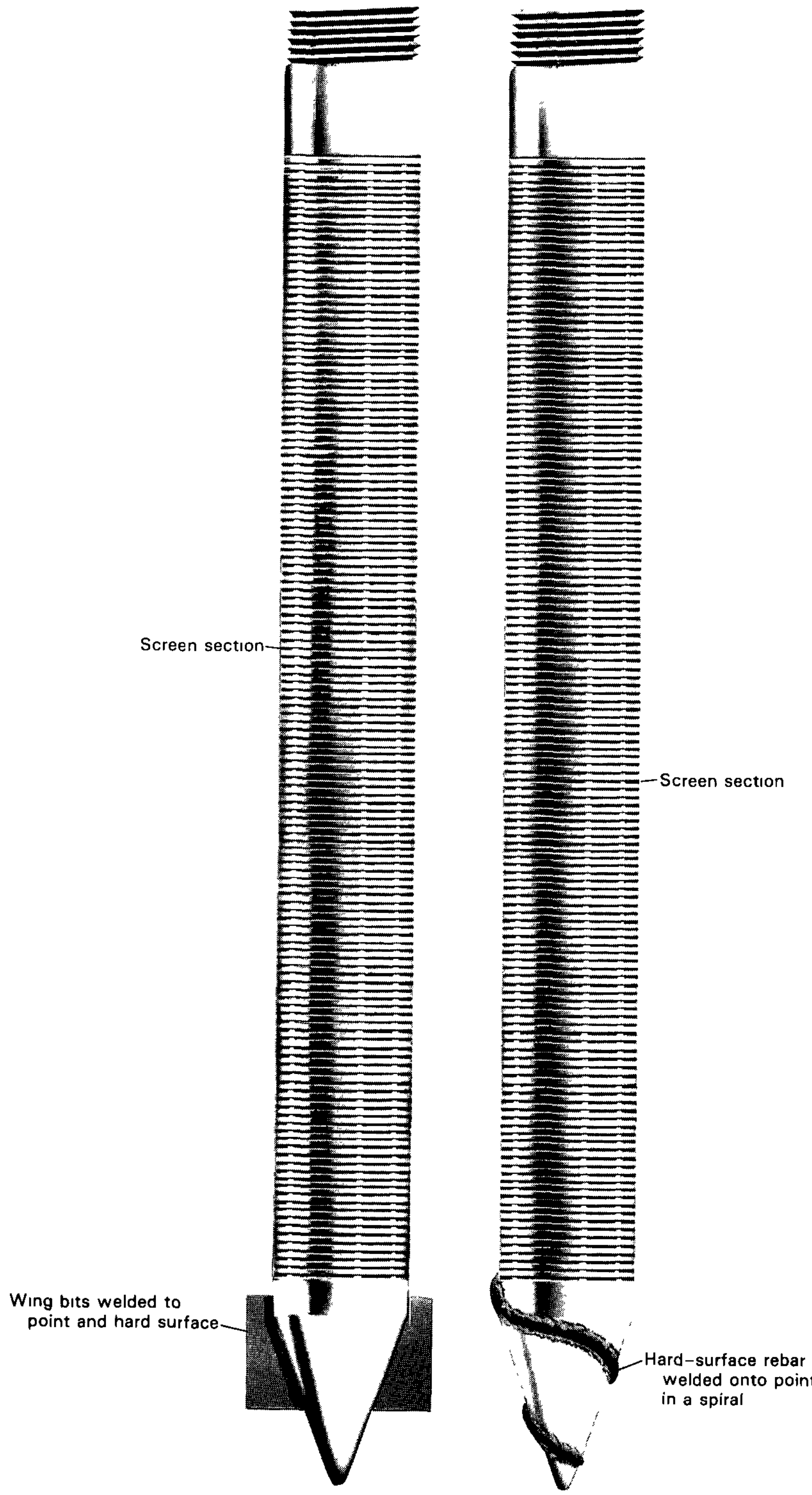

Figure 5.—Drilling drive-point-type well screens.

development procedures must be used to correct the problem. Methods for development of small-diameter wells are described beginning on page 85.

Hydraulic-Rotary Drilling

Applications of Hydraulic-Rotary Drilling

A high percentage of holes drilled for oil, gas, and mineral exploration is drilled by the hydraulic-rotary method as is an ever-increasing number of standard test holes and water wells. Although the cutting samples from hydraulic-rotary-drilled holes are usually not any more contaminated than those obtained from cable-tool drilled holes, and water wells drilled by the hydraulic- or mud-rotary system require more development effort, the method is still gaining in popularity because it is economical. In drilling unconsolidated sediments and hard rock, other than cavernous limestones and basalts where circulation cannot be maintained, the hydraulic-rotary method is a faster and usually more economical drilling method than the cable-tool method. The Water Resources Division of the U.S. Geological Survey uses the hydraulic-rotary method for a high percentage of its contract drilling of test holes. However, the kinds of data and quality of data that should be available from this type of drilling are often not obtained, so this section of this manual offers some remedial techniques.

A basic but detailed description of drilling mud is provided to assist the reader in understanding this very important aspect of hydraulic-rotary drilling. Mud control, particularly in shallow test-hole drilling and in the installation of water wells, is the most important factor to be considered in hydraulic-rotary drilling. Mud control is of paramount importance in hole control and conditioning of the hole for later geophysical logging because borehole-geophysical logs must be run in a rotary-drilled hole to get maximum data from the hole. In addition, mud control is of vital importance in the drilling of water wells (both observation and production); a proper filter cake must be formed on the wall to prevent harmful invasion of mud into aquifers. The mud must later be removed from the aquifer in the development process of the completed well.

The petroleum industry drills into producing zones that may be orders of magnitude less permeable than many of the shallow ground-water aquifers with which the U.S. Geological Survey is concerned. Yet petroleum companies design elaborate mud programs maintained by mud engineers to prevent invasion, while many other persons involved in ground water almost totally ignore the problem. The purpose here is to emphasize the importance of mud control in the proper collection of samples from mud-rotary-drilled holes, as it has great significance in mud-rotary coring (see p. 37).

Equipment and Accessories

The basic equipment and accessories of a hydraulic- or mud-rotary drill are: a derrick and hoist, a mechanically or hydraulically operated pull-down and holdback system, and a revolving table through which slides a square or fluted kelly that turns the drill pipe and allows it to move downward as it is turned. The string of drill pipe is usually equipped with heavy drill collars at the lower end to provide weight and stability to the drilling tools. A cutting tool or bit attached to the bottom end of the string of pipe and a pump forces drilling fluid through a water swivel and down through the string of drill pipe. The entire system is engine powered.

Methods of Drilling

Drilling is accomplished by circulating fluid through the bit, while rotating and lowering the string of drill pipe. The bit cuts and breaks up the material as it penetrates the formation, and the fluid picks up the materials generated by the cutting action of the bit. This fluid, with cuttings contained, then flows upward through the annular space between the drill pipe and drill hole carrying the cuttings to the ground surface, thus clearing the hole. The string of drill pipe and bit move downward, deepening the hole as the operation proceeds. After the drilling mud reaches the surface, it flows through a ditch or affluent pipe to a settling pit where the cuttings settle to the bottom. Cuttings are sometimes run through a shale shaker for removal of the larger particles. From the settling pit, the fluid overflows into the main pit, from which it is picked up through the suction hose of the mud pump and recirculated through the string of drill pipe.

The following three articles are suggested as references for those readers who want further reading on the subject: "Rotary Drilling

Handbook" (Brantly, 1961); "Ground Water and Wells" (Universal Oil Products, 1966); and "Water Well Technology," (Campbell and Lehr, 1973).

Drilling Mud

Three general types of drilling fluids are: (1) water with either native clays or commercial, high-yield bentonites added; (2) mud-laden, oil-base mixtures; and (3) air. Mud-laden, oil-base muds have no applications in drilling for ground-water investigations; and air, as a drilling fluid, is discussed on page 29.

Drilling mud serves to: (1) remove the cuttings generated by the cutting action of the bit from the bottom of the hole; (2) cool the bit and lubricate the bit bearings if the bit is the roller-cone type; (3) build a filter cake on the hole wall preventing fluid loss in mud invasion of penetrated formations; (4) support and prevent caving of the wall of the hole; (5) control the formation pressures of water or gas preventing these fluids from coming into the hole; and (6) lubricate the string of drill pipe as it rotates in the hole. These purposes are not listed in any order of importance.

Many problems encountered in mud control result from a lack of understanding of the terms used in describing drilling muds. For example, many people think of viscous mud as a weight property of the mud instead of a property of mud thickness (fig. 6). However, a viscous mud actually can be only slightly heavier than water; conversely, a heavy mud might be low in viscosity. These differences are important when considering desired purposes of the drilling mud in a drilling program. In general, use the lightest weight drilling mud possible considering the formation pressures and caving problems that may be encountered. The lighter weight muds will result in shallower invasion of permeable zones, thus permitting easier development of the aquifer upon completion of the well.

Unfortunately, many drillers feel that by keeping the drilling fluid thin, less damage and aquifer invasion by the mud will occur. However, this often is not the case and the reverse is true, because thin or low-viscosity muds containing 10–15 percent solids by weight may be composed mostly of heavy sands, and considerable invasion of the aquifer and washing of the hole wall will occur prior to the buildup of a filter cake. Also, a heavier, thicker mud cake will eventually form from filtration. An example of loss of hole control from using a thin native mud as compared to using a prepared viscous mud, is demonstrated in figure 7. Observe where the difference in the borehole rugosity is shown in the comparison of caliper logs of two holes drilled close together in the semi-unconsolidated Ogallala formation in western Texas.

The process that resulted in the two radically different holes drilled in the same lithology is shown in figure 7. Initially, the hole was to be used as a combination injection-production well, and the proposed procedure for completion was to drill through a 40-ft-thick aquifer (from 105 to 145 ft), install a screen through the entire thickness of the aquifer, case the hole to surface, and cement the annulus from the top of the screen to the surface. The screened aquifer was to be developed by the natural sand-pack method, using the bailing-surging-bailing, high-velocity jetting, and additional bailing method. No mud program was designed for the drilling of Hole 1. The drill contractor expressed assurance that, from prior experience in drilling, the use of clear water as a drilling fluid would soon result in the formation of an adequate drilling mud composed of a mixture of the water and natural clays contained in the formation. Unfortunately, this did not occur; enough natural clay was never encountered in the upper part of the hole to form a lightweight, viscous mud. As a result, the native drilling fluid rapidly washed out the loosely consolidated sand zones, and total circulation of drilling fluid was lost. Circulation was not restored even though circulation-loss materials were used. An attempt was made to cement off the zones of lost circulation and complete the hole as planned. Although the drill contractor was able to fill the hole up above the top lost-circulation zone, drilling out of the cement resulted in the bit breaking out of the cemented hole, and total circulation was again lost. After drilling blind (no circulation of fluid or cuttings to the surface) for a short interval, the hole was abandoned.

Prior to the start of drilling of Hole 2, a high-yield bentonite mud mixture with a marsh-funnel viscosity of 60-s and a weight of 8.55 lb/gal (pounds per gallon) was made. The hole was drilled through the previous zones of lost circulation, with no circulation loss and a minimum of fluid loss through filtration. Caliper logs of the two holes (fig. 7) dramatically demonstrate improved hole conditions resulting from the design and utilization of a

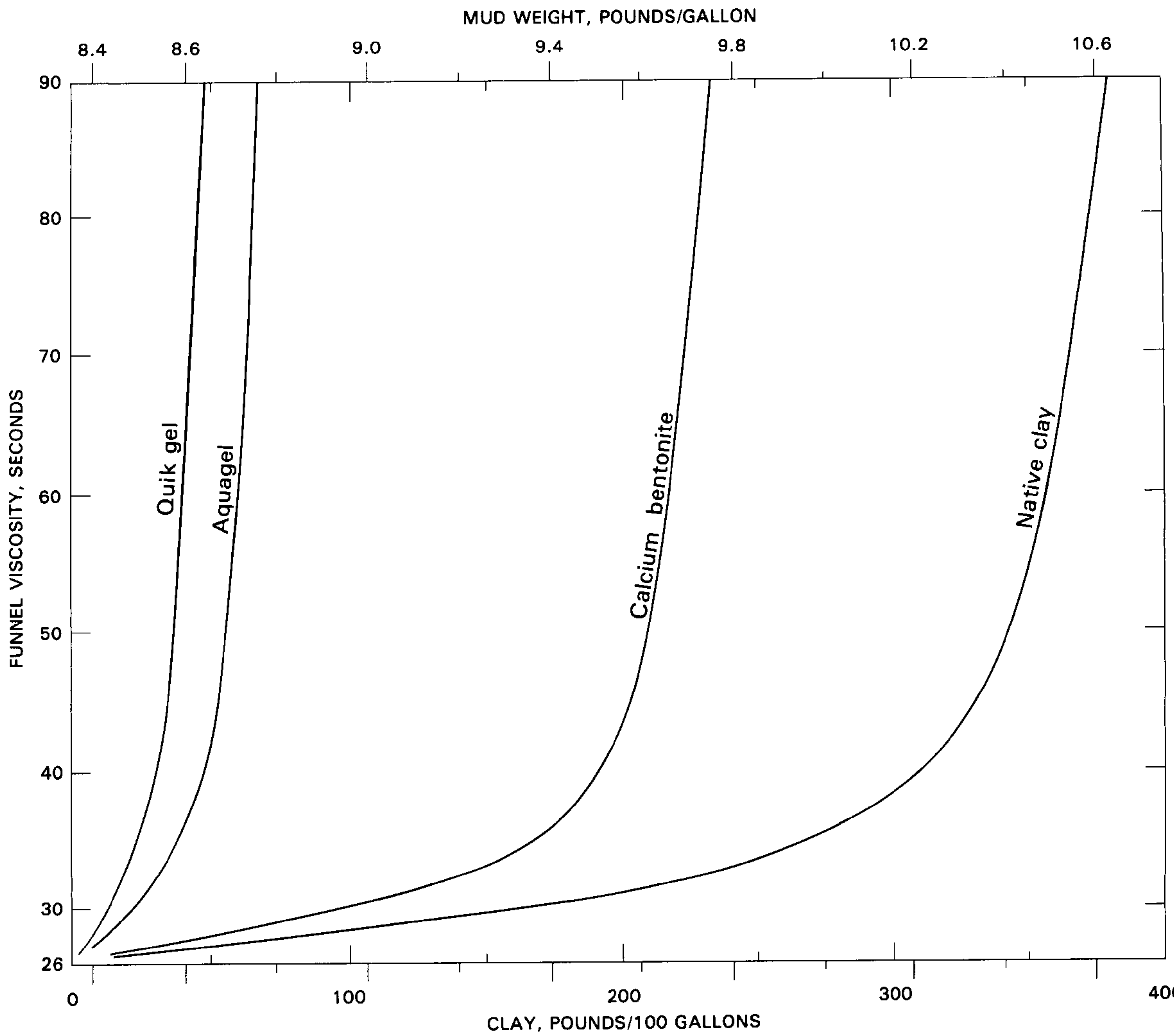

Figure 6.—Comparisons of mud weight versus funnel viscosity for various clays.

controlled mud program. The time to stop lost circulation and wash-out problems when drilling in unconsolidated granular materials is prior to start of drilling when the mud program is designed. Many examples of poor borehole conditions that result from the use of an improperly prepared drill mud are available, as demonstrated in figure 7. However, this example was used to emphasize the importance of proper mud control.

Instruments for Field Monitoring of Drilling Muds

Many types of instruments are used to measure various properties of drilling muds. The following three—Marsh-funnel viscometer, mud balance, and sieve and funnel for sand-content set—are basic instruments that one should use before and during the drilling process so that mud control can be regularly monitored during all phases of the drilling.

Viscometer

The Marsh-funnel viscometer is a funnel-shaped container, 6 in. in diameter at the top and 12 in. long. A 10-mesh screen, fitted across one-half of the top, removes foreign matter and large cuttings from the drilling mud. To determine the viscosity of a drilling mud, pour 1 qt of the drilling fluid into the funnel while holding a finger over the outlet spout. Then, simultaneously remove the finger from the

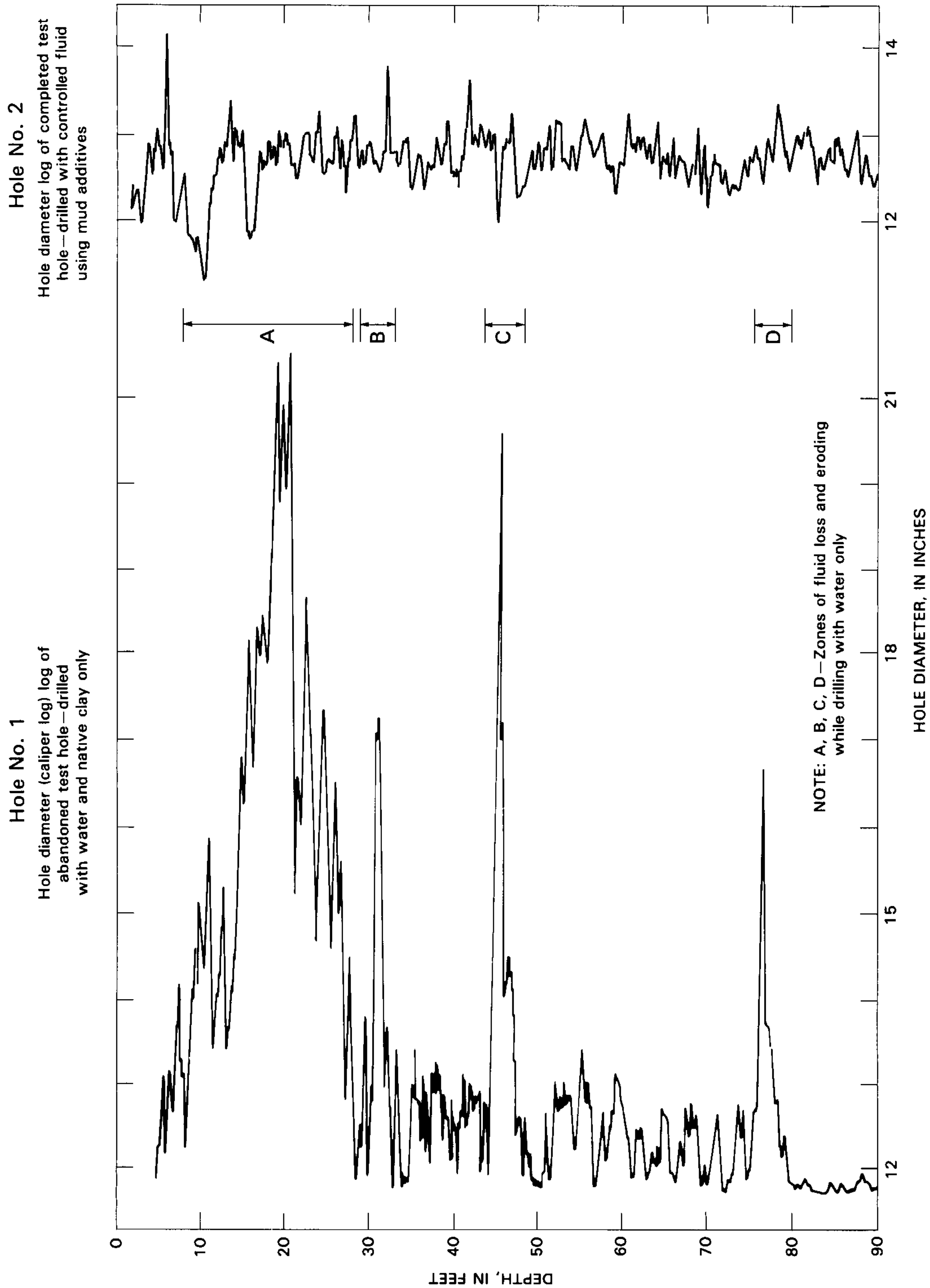

Figure 7.—Hole-rugosity differences caused by using improper drilling-fluid control in one of the holes.

spout and start a stop watch. When all the drilling mud has flowed out of the funnel, stop the watch and record the viscosity in seconds. Note: The Marsh-funnel viscosity of water at 70°F is 26-s; a mud viscosity of 50-s is a viscosity approximately double that of water.

Measurements obtained from the Marsh-funnel viscometer are influenced by gelation rate and density, which vary the hydrostatic head of the column of drilling mud in the funnel. An excellent, practical description of viscosity changes due to density changes, when the Marsh funnel is used, is provided in "Ground Water and Wells" (Universal Oil Products, 1966, p. 223) and is quoted in the following paragraph.

> Water shows a Marsh-funnel viscosity of 26 seconds. A good drilling mud weighing about 9 pounds per gallon usually shows a Marsh-funnel viscosity in the range of 35 to 45 seconds. If the mud picks up sand that increases its weight to 10 pounds per gallon, the Marsh-funnel viscosity may decrease to 35 seconds or less, even though its real vicosity when free of sand may be 43 seconds. The greater density of the sand-laden mud causes it to flow from the funnel faster.

In contrast, when increased mud weight is the result of picking up native clay from the ground-up cuttings, the Marsh-funnel viscosity is likely to be much higher than 43 seconds.

Mud Balance

The mud balance is a simple device that measures density of the drilling mud in pounds per gallon. The device consists of a balance beam with a fixed cup for holding a fraction of one gallon of drilling mud on one end and a sliding counterweight on the graduated arm of the balance beam. To measure the density of the drill fluid, fill the cup to capacity; seat the lid into the top of the cup, resulting in the squeezing of some mud out through the vent hole in the top of the lid; wipe off any excess mud that is on top of the lid or the sides of the cup; then move the balance rider until the instrument is balanced. Read the indicator and record the density directly in pounds per gallon. Frequent density tests will disclose any changes taking place in the unit weight of the drilling fluid.

Sand-Content Set

The sand-content set consists of a 200-mesh sieve and a graduated cone-shaped tube. To measure the sand content of the mud, pour 100 cm^3 (cubic centimeters) of drill mud onto the sieve and wash the drilling mud through the screen, using a clean-water wash. Flush the sand that is retained on the screen into the graduated cone-shaped tube and read the sand content directly in percentage by volume. Regular sand-content determinations should be performed because: (1) heavy sand content, particularly in a thin mud tends to invade aquifers resulting in a thick filter cake opposite any permeable zones, (2) heavy sand content settles out rapidly in a low gel-strength mud during drilling pauses, resulting in stuck drill pipe, and (3) excessive sand content is abrasive to pump parts and the string of drill pipe. Sand contents as high as 5 percent can be tolerated in drilling muds having proper viscosity and weight; however, when drilling in aquifer materials, sand content should be kept low.

High-Yield Bentonite Clays

High-yield bentonite clays are used to manufacture drilling muds that are high in colloidal content and gel strength. Colloids are composed of particles ranging in diameter from about 0.5 microns to 0.005 microns. Colloidal content and gel-strength properties are two extremely important components of a drilling mud. Highly colloidal clay has the ability to become hydrated with many times its own weight of water, forming a suspension that occupies a volume many times greater than that of the original solid resulting in the yield of a low-solids, high-viscosity drilling mud. It also results in a drilling mud having good filtration properties; that is, it will deposit a thin filter cake of low permeability on the wall of the hole, allowing a minimum of fluid to pass into the formation (see fig. 8 for thickness of solids and mud cake for various clays). The rapid formation of a low-permeability filter cake on the borehole wall is important whenever mud-rotary methods are used for drilling ground-water-test wells, production wells, and for coring of unconsolidated formations.

In addition to rapid filter-cake buildup properties, colloidal materials also provide a gelling function. Gel strength is that property of the drilling mud that permits drill cuttings to remain in suspension when drilling operations are halted. As long as a high gel-strength mud is in motion, it is in a viscous liquid form; however, during periods of quiescence, it becomes a semisolid. Reagitation will quickly

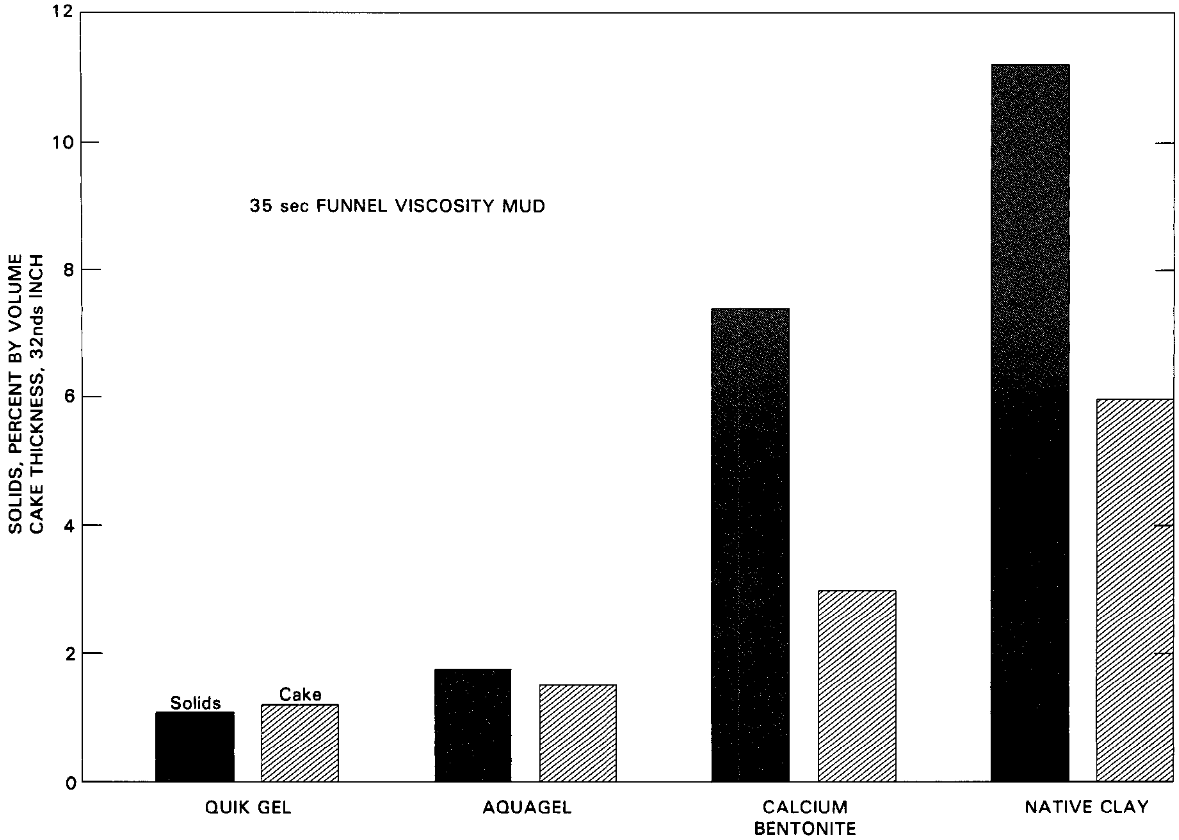

Figure 8.—Cake thickness of solids for various clays.

destroy semisolid gel and restore it to its viscous liquid form. Mixing drilling muds that have too high a gel strength can be overdone, because the mud velocity slows whenever the mud flows into the larger reservoir areas of the mud pit. When this slowing occurs the mud tends to gel, preventing the cuttings from settling out. However, some agitation of the mud in the pits by pumping and stirring can alleviate this problem.

Problems Encountered in Hydraulic-Rotary Drilling

Bit-Swabbing Damage

Surging and swabbing are methods of destroying the filter cake opposite an aquifer, allowing the aquifer materials to fall in against the screen or gravel pack. Unfortunately, they also are undesirable phenomena that occur quite frequently during the drilling process and are very harmful to the bore-hole. Accidental swabbing during drilling occurs because of mud-control difficulties resulting in high fluid loss opposite permeable zones, consequently causing the formation of thick filter-cake buildup opposite these permeable zones (particularly if the sand content of the mud is too high and the drill operator has failed to recognize the problem as the string of drill pipe is being removed from the hole). The density of the drilling mud will increase and the viscosity of the drilling mud will decrease as sand content increases resulting in a thicker filter cake on those sections of the hole opposite permeable zones. Whenever the drill string is removed from the hole, these less-than-bit-diameter rinds have to be removed to allow passage of the drill collars and bit. The problem begins when the drill collars and bit are pulled through the less-than-bit-diameter rind zones and a mud pack forms on the bit creating a swab or surge block. If the operator is not aware of this surging-swabbing effect, a bridged or caved hole will result. The bridging and caving of the hole occurs very rapidly, particularly if the drill string is removed from the hole very quickly or is dry. As the bit is removed from the hole at too fast a rate, the bit acts as a swabbing tool and pulls off the thick filter-cake section opposite a permeable sand (fig. 9). The forces of hydrostatic head in the formation, plus the total or partial vacuum occurring at the bottom of the bit-swab, are imparted against the momentarily resulting dewatered or negative head zone inside the hole, causing the permeable section to pump into the hole. These pumped-in cuttings either bridge or cave in the hole or settle to the bottom of it.

The hole-control-damage problem is illustrated in figure 9. How can this be prevented? Some remedial or preventive steps to alleviate the problem can be taken; however, the remedial measures require time and effort, resulting in added drilling costs. The first step is preventive and consists of close monitoring of the mud program. Proper drilling-mud control will usually prevent or minimize filter-cake buildups. However, it is not certain that smaller-diameter filter-cake rings do not exist at some points in the hole, and it must be assumed that they do.

Two methods exist for removal of the drill pipe from the hole to minimize the swabbing effect that will ruin the hole for borehole-geophysical logging and sampling techniques:

1. Remove the string of drill pipe from the hole at a relatively slow rate to minimize differences in hydrostatic head between the formation and the hole. Equalization of these pressure forces can only be accomplished if the inside of the drill string is vented to the atmosphere, allowing a completely unrestricted movement of fluid out of the pipe and bit so no changes in differential pressure occur between the fluid inside the hole and the formation. Pulling a string of drill pipe without a means for keeping the inside of the drill pipe open to the atmosphere (by using holes in the side of the pulling swivel or a regular water swivel) is referred to as dry pulling. However, if a vented string of drill pipe is pulled so fast that the mud cannot run out of the bit fast enough to keep the hole filled, bit-swabbing damage to the hole will still occur. A momentary differential pressure of a positive nature in the formation will occur (the amount of the pressure depends on the distance that the string of drill pipe is below the saturated zone), and this positive pressure will attempt to cave the hole. Never permit the drill-rig operator to repeatedly lower the string of drill pipe and run at tight spots in the hole when trying to remove the string of drill pipe because that would damage sections of the hole and would necessitate extensive flushing and redrilling to get back into the hole.

2. If borehole-geophysical logging or sampling methods are to be used that require no damage or bridging of the hole occur during removal of the string of drill pipe, the method of circulation during pulling should be used. This is a slow method, but it usually guarantees success in preventing damage to the drill hole upon removal of the string of drill pipe. Maintain circulation at a slow rate through the string of drill pipe at all times when it is being pulled. This guarantees that no great differential pressures will develop between the formation and drill hole; also, circulation will prevent buildup of muds and sands on the bit that make it act like a swab. These methods lengthen time needed to remove the string of drill pipe from the hole and may increase the cost of drilling, but the increased value of data afforded will be worth the extra effort and added cost. However, in most cases, the added time for tripping in and out of holes less than 2,000-ft depth is not a large factor in overall costs.

Borehole-Geophysical Logging

Borehole-geophysical logging is a method for continuously sampling lithologic and hydrologic parameters penetrated by the drill. The authors do not discuss any of the techniques of borehole geophysics in the manual. These techniques are fully explained in "Application of borehole geophysics to water resources investigations" (Keys and MacCary, 1971). Our reasons for mentioning borehole geophysics is that it is a very valuable sampling method and should be included in the planning stages of a drilling program; much of our discussion on mud control and hole conditioning is oriented toward conditioning the hole for gaining optimum data results from borehole-geophysical logging. In support of the need for proper mud control and hole conditioning in relationship to borehole-geophysical logging, the following is quoted from Keys and MacCary (1971, p. 20):

> Drilling a hole generally disturbs the fluids and pore spaces in the environment to be measured. Rotary drilling with mud probably causes the greatest disturbance in the environment near the borehole. In rotary drilling, a natural or artificial mud is circulated down the drill stem to bring the

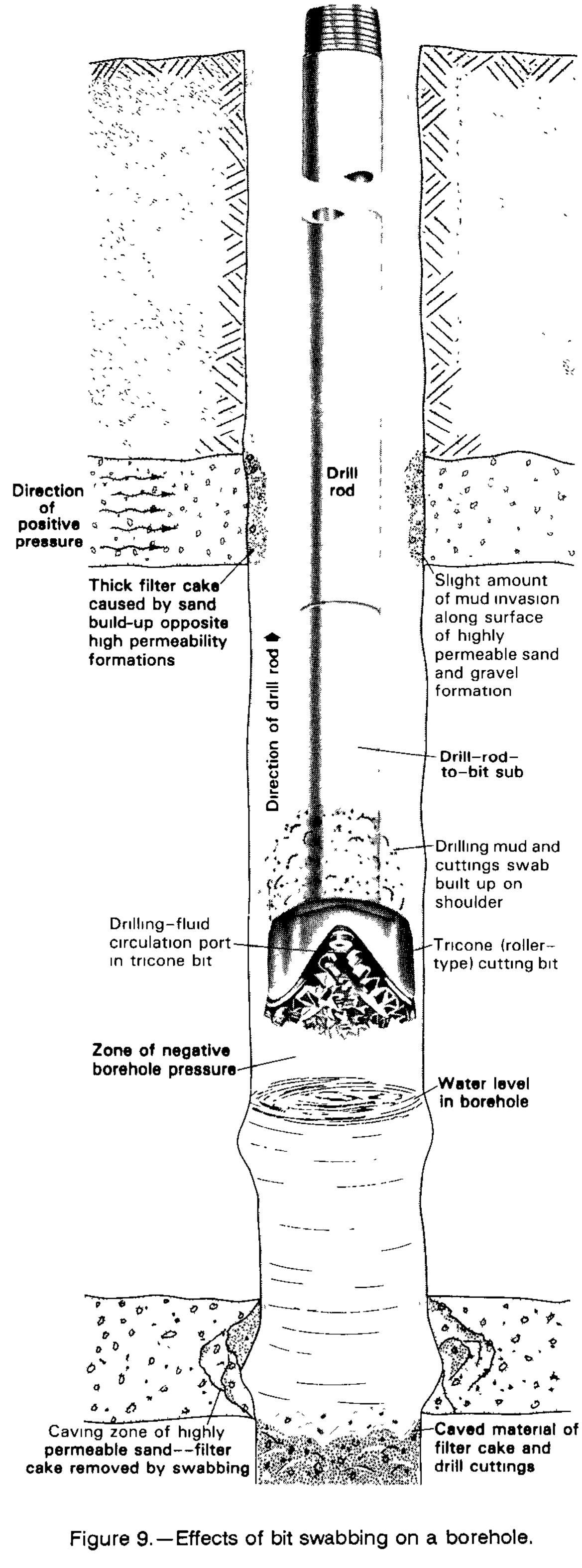

Figure 9.—Effects of bit swabbing on a borehole.

cuttings back to the surface. The mud also keeps the hole open, cools the bit, lubricates the drill stem, coats the wall of the hole to reduce fluid loss, and serves as an electrical-coupling medium necessary for many logging operations. Because the pressure of the mud column exceeds the hydrostatic pressure in the formation being penetrated by the bit, the mud filtrate invades the rock adjacent to the borehole and displaces the native fluids away from the hole. During this process, many of the particles suspended in the mud are filtered out and form a mud cake or filter cake on the wall of the hole. The invaded zone and mud cake may introduce unknown and, in general, undesirable factors in log interpretation.

The effects of drilling also have a positive aspect. Thickness of the filter cake and thickness of the invaded zone are sometimes related to the hydraulic properties of the aquifer system. In addition to the type of mud, the differential pressure, and the length of time an aquifer has been exposed to mud, the porosity and permeability of sediments will also determine the depth of invasion. In most oil fields, if all other factors are equal, the low-porosity sediments will generally be invaded deeper than the high-porosity sediments. The most obvious reason for this apparently anomalous relationship is that there is a greater volume to fill in high-porosity formations. Further, the permeability of the mud cake is generally lower than the permeability of the rock so that the mud cake and differential pressure become the factors that control the rate of filtration. In contrast, thicker invaded zones were found to occur in aquifers rather than in confining beds in shallow, poorly consolidated sediments. A complete discussion of invasion characteristics is beyond the scope of this manual, and reference should be made to Doll (1955).

Drilling and sampling operations, including good mud control, need to be designed to cause the least possible disturbance to the borehole if geophysical logging is to be done. In addition, the hole ought to be conditioned so lightweight logging tools can be lowered to the bottom of the hole. This may require complete replacement of the drilling mud that was used in the drilling process with a clean drilling mud. It may also require the method of circulating out of the drill pipe, explained on page 24 so there will be no caving or bridging of the hole as these tools are removed.

Installation of Well Casing and Screen

After the hole has been drilled to the desired depth by the hydraulic-rotary method, it is ready to be cased and screened. However, if the hole is drilled in a competent hard rock, it might be desirable to complete the well in open hole and not set casing and screen. Whatever the final method of well completion, the completed hole preparation procedures are quite similar.

When the desired hole depth has been attained, circulation of the drilling fluid is continued until all the drill cuttings have been flushed from the hole. Final flushing of the hole with a freshly prepared, low-viscosity drilling mud is advisable. By so doing, most of the fine, sand-sized cuttings still remaining in suspension in the drilling mud can be allowed to settle out in the mud-circulation pit instead of settling to the bottom of the hole.

After the hole has been flushed, the drill pipe is removed using either of the methods previously discussed to prevent bit-swabbing hole damage. The well screen and casing are then set and sealed in the clean, drilling-fluid filled hole; the drilling fluid is pumped out, and the well is developed using the appropriate well-development techniques.

Cable-Tool Percussion Drilling

The cable-tool percussion method of drilling is one of the oldest drilling methods known. Its first recorded use was in China about 600 B.C. for percussion drilling of relatively shallow brine wells. Cable-tool percussion drilling is still a very versatile tool for obtaining good subsurface geohydrologic data when used for test-hole drilling; and this method probably is used to install more water wells than any other method. Although the Water Resources Division, U.S. Geological Survey, does not own or operate any cable-tool rigs they are used extensively in contracting for relatively shallow test holes in both hard rock and unconsolidated formations. A very brief and basic description of the method is given, and some methods for taking cores in cable-tool drilled wells is presented in this manual to provide the hydrologist with more than just cutting samples from the hole. Many articles describe the cable-tool method in detail; we refer those readers who plan to use the method for contract-test drilling to two specific references: "Ground Water and Wells" (Universal Oil Products, 1966, chap. 11) and "Water Well Technology" (Campbell and Lehr, 1973, chap. 4).

Applications of Cable-Tool Percussion Drilling

Drilling test holes and water wells by the cable-tool method is an old and reliable method. Cuttings returned by the bailer and evaluated in conjunction with a competent cable-tool driller's log provide a good description of the drilled lithologic materials. This method, used also in conjunction with drive-core samples, can provide accurate subsurface information. Collecting water samples from a cable-tool drilled hole when using the drive-casing mode is unsurpassed. Unfortunately, specifications are usually not written adequately to ensure that the maximum data are obtained from a cable-tool drilled hole. For instance, specifications might be written that do not call for drive-core sampling, thin-walled Shelby-tube sampling, or even a collection of water samples from the aquifers drilled. These data are relatively easy to obtain in the process of the drilling in drive-casing method of cable-tool drilling, but they are impossible to obtain after the well has been completed. Also, various geophysical-logging methods are available that can provide information on water quality in an uncased hole, but none exist that can provide data or water quality once the casing has been installed. Only radiation-type logging devices can be used in a cased well; for instance, the natural gamma log can provide information on grain-size distribution. The quality of data and types of data needed and the method by which these data are to be obtained should be carefully considered prior to writing the final contract of drilling specifications.

Also, in writing specifications, do not restrict the drilling contractor. A set of recently reviewed specifications specified that "a cable-tool hole be drilled and a 6-in. casing driven to a depth of 725 ft, a 20-ft length, 4-in.-diameter screen installed using the casing pull-back and swedging method." The restrictive aspect of this specification was that the drilling contractor would have to accomplish this by using a single string of 6-in.-diameter casing; no telescoping of casing was allowed. Ultimately, the skin friction on the outside of the 6-in. casing would become so great that it could not be driven to the specified depth of 725 ft but would break in the attempt. Drilling and driving a specified diameter casing to a given depth is done by starting out with a larger casing (12-in.) and going with it to refusal; then reducing to 10-in.-diameter casing, and drilling and driving it to refusal. This telescoping of casing is continued as a method for reaching final depth at the specified diameter. The writer of drilling specifications should contact drilling contractors in the area of interest for professional input on local conditions to complete a well in that area.

Equipment and Accessories

A complete string of drilling tools for cable-tool drilling consists of a set of rope sockets, set of drill jars, a drill stem (for added weight), and a drill bit. The drill jars have no function in the initial drilling process; they are included in the drilling tools as a precautionary measure and would be used under the following problem conditions:

1. If drilling was performed in an uncased hard-rock hole, and vibration resulting from the bit striking the bottom of the hole caused a piece of rock to fall out of the wall of the hole on top of the drill bit, it might be impossible to pull the drill bit out of the hole with the wireline hoist. If this occurs, the drill cable would be slacked off to allow the jar links to open to their full length. Then, on the upstroke, the jars would impart a blow to the tools below. Repeating this jarring procedure would break the rock that had fallen in on top of the drill bit, thereby freeing the drilling tools and drill bit.

2. When drilling in unconsolidated materials using the cable-tool method, it is common practice to drill ahead of the casing a few feet to facilitate later driving of the casing. Occasionally, when this method is used, gravel or boulders will fall in and lock up the bit; here, the jars would be used as described above to obtain the same results.

Methods of Drilling

The cable-tool drilling method is relatively simple; the drilling-tool string is alternately raised and dropped through the use of a spudding arm, with the drill string suspended by left-lay drill cable. Drilling is accomplished without letting the cable go completely slack when the bit strikes bottom, maintaining some pull and stretch on the cable. The elasticity and lay of the cable permits, through the cable swivel, a few degrees turn of the bit each time the drilling tool string is raised and lowered, allowing the cutting section of the bit to strike a new section of the hole on each drop. Turning the bit is necessary if a round hole is to result; otherwise the well would be concave-oval shaped like the bit. In drilling practice by the cable-tool method, water, sometimes with mud added, is poured into the hole, so that the cuttings generated by the action of the bit can form a slurry and remain in suspension, allowing the bit to strike undrilled rock instead of material that has already been cut. These slurried cuttings periodically have to be bailed out of the hole; otherwise their viscous nature restricts the free fall of the drilling-tool string, resulting in a slower penetration rate.

If cable-tool drilling is performed in competent rock, no casing is used in the drilling operation, because the hole wall will not collapse and cave in. However, when cable-tool drilling is performed in unconsolidated formations, casing has to be driven to support the hole wall and prevent caving. The basic procedure for drilling and driving casing in unconsolidated material follows:

A section of heavy-wall drive casing is equipped with a sharpened cutting shoe and is driven to the bottom of the hole (the cutting shoe will have to shave off a section of the wall). The bit assembly is then run to the bottom of the hole, water is poured in, and the drilling is resumed. After the hole has been drilled to about 5 ft below the casing (depth will usually depend on the driller's assessment of the competency of the material), the bit assembly is removed from the hole, the slurried cuttings are bailed out, the drive clamps are reattached to the drill stem, and the casing is once again driven to the bottom of the hole. In very soft formations, the driller may drive the casing beyond the point at which the hole has been drilled, water can be poured in the casing to form a slurry with the drilled cuttings, and the material can be bailed out. This procedure of drilling, bailing, and driving the casing can continue to considerable depth. After the water table has been reached, it is usually no longer necessary to add water for creating slurry.

Installation of Well Casing and Screen

There are so many different ways of installing well screens by using the cable-tool method (that is, casing pulled back, bailed down, wash-in, etc.) that they will not be described in this manual. For excellent examples and descriptions of the methods, the reader is referred to "Ground Water and Wells" (Universal Oil Products, 1966) and "Water Well Technology" (Campbell and Lehr, 1973).

Air-Rotary Drilling

Air-rotary drilling has become an increasingly popular method for drilling test holes and wells. Air was first used as a drilling circulating medium as early as the late 1800's. Extensive test drilling for uranium during the 1950's caused the air-rotary drilling industry to gain considerable momentum in the drilling field. It was not without its problems, however, and the high cost of compressors made the method too prohibitive for use by many drilling contractors. As more research was conducted in the field of air-rotary drilling and greater capacity air compressors were developed, the method became economically more feasible.

Applications of Air-Rotary Drilling

The air-rotary method of drilling is a particularly effective method to use when drilling hard rock. Penetration rates are generally faster and drilling costs lower than using other conventional drilling methods for drilling these materials. Bottom-hole percussion tools and bits are most often used for this purpose.

Air-rotary drilling is often preferred over hydraulic-rotary methods for drilling wells in highly fractured and cavernous rock aquifers where the loss of costly drilling fluids is a problem. However, this type of drilling environment requires large volume compressors and drilling foam to remove the cuttings from the hole and accomplish the drilling. The drilling additives used in air-rotary drilling to prevent lost circulation in the rock are not usually as detrimental through plugging of the aquifer as many other conventional hydraulic-rotary drilling muds.

Equipment and Accessories

The basic air-rotary drilling rig is equipped essentially like a drilling rig used for conducting hydraulic-rotary drilling, with the major exception being that the standard mud pump is replaced by a compressor and compressor-cooling assembly. An air-rotary drilling rig is also equipped with a fluid-injection pump that is capable of delivering fluid volumes ranging between about 6 and 20 gal/min. Like a mud-rotary drilling rig, an air-rotary drilling rig has a derrick and hoist, a pull-down and hold-back system, and a revolving rotary table and kelly system to turn the drill pipe. The drilling-tool string consists of sections of drill pipe, drill collars to provide weight and stability to the string of drill pipe, and a cutting tool or bit that is attached to the bottom end of the string of drill pipe and collars. The entire system is engine powered.

Methods of Drilling

The methods of drilling with air are basically the same as those methods used for hydraulic-rotary drilling. Air is used instead of a drilling mud as the circulating medium to cool the bit and remove the bit-drilled cuttings from the hole. The injection pump is used in conjunction with the air compressor to aid in the removal of sticky, wet cuttings from the hole; otherwise they tend to accumulate on the drill pipe and also plug the bit. Drilling foam, polymers, and other drilling additives can be mixed with the injection fluid to stabilize the hole wall and aid in the removal of drilled cuttings from the hole.

The minimum annular air velocity required to adequately clean the cuttings from a hole (drilling with dry air) is about 3,000 ft/min. The annular velocity of air can be calculated as follows:

$$AV = \frac{\text{cfm} \times 144 \text{ in.}^2/\text{ft}}{\text{area of annulus (in.}^2)}$$

where AV = annular velocity,
cfm = cubic feet of free air per minute.

If drilling foam or other gel additives are injected considerably lower air velocity and annular pressure are required to lift the cuttings from the hole. For a more detailed overview of the air-rotary drilling method, see "Water Well Technology" (Campbell and Lehr, 1973, p. 121–136).

Borehole-Geophysical Logging

If the hole is to be geophysically logged upon completion of drilling, it must be properly conditioned beforehand. Regardless of the drilling methods or type of drill used to make the hole the criteria necessary for conditioning the hole prior to logging are basically the same. The drilled cuttings have to be removed and the hole wall stabilized to prevent caving or bridging if open-hole logs are to be run in the borehole before casing is set. Borehole swabbing can also occur in an air-rotary-drilled hole because of mud buildup formed on the bit and the formation of mud rings on the drill pipe. Therefore, when the drill pipe is removed from the hole to facilitate logging, it should be done with care.

Installation of Well Casing and Screen

The borehole is first flushed of all drilled cuttings. This can be accomplished by circulating air, air mist, foam, and (or) polymers in the hole until it is clean and no bridging or caving occurs. The drill pipe is then carefully removed from the borehole and the casing and screen are set in the open hole and sealed in place. After the installation is completed, the well is developed as necessary.

Reverse-Circulation Drilling

The method of reverse-circulation drilling was designed primarily for drilling large-diameter production wells in unconsolidated formations. The practical minimum diameter (about 16 in.) for drilling holes by the reverse-circulation method almost precludes its being used for test-hole drilling. However, this method provides the best cuttings samples of any drilling method because of the large intake capacity of the bit (5 in. or more); this method also provides fast delivery of cuttings to the surface because of high ascending velocities (can be several hundred feet per minute) of the drill cuttings and fluid. Therefore, reverse circulation is an excellent drilling method for obtaining cutting samples. For those readers interested in the method, comprehensive descriptions are provided in "Water Well Techology" (Campbell and Lehr, 1973) and "Ground Water and Wells" (Universal Oil Products, 1966).

TECHNIQUES FOR CORING

Hydraulic-Rotary Coring

Hydraulic-rotary coring is commonly referred to as diamond drilling. The name seems to fascinate people, possibly because it was originally used to