CHAPTER 7
Well-Drilling Methods

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Johnson Screens

This chapter discusses drilling methods that are appropriate for installing water wells. (For a discussion of which methods are most appropriate for sampling, see Chapter 3.) A variety of drilling methods exists due to the occurrence of a wide range of geologic conditions—from hard rock (e.g., granite, dolomite) to unconsolidated sediments (e.g., alluvial sand, gravel). Specific drilling methods are dominant in certain areas because they are effective and provide cost advantages. No single drilling method is best for all geologic conditions, and the methods and equipment capabilities vary as widely as the application requirements can.

Also described in this chapter are basic drilling principles, some applications, and the practical limits of major drilling methods for various geologic conditions. Additionally, a master table (Table 7.2) that summarizes the advantages and disadvantages of each drilling method is included at the end of this chapter.

DIRECT CIRCULATION METHODS

Air and Mud Rotary Drilling

The direct rotary drilling method was developed to increase drilling speeds and to enable drillers to reach greater depths in most formations (Figure 7.1). A borehole is drilled by rotating a bit attached to the lower end of a string of drillpipe. Cuttings are removed by continuous flow of air or other fluid in the annular space between the borehole and drillpipe. At the surface, settling pits or mechanical equipment extract the cuttings, allowing clean drilling fluid to be recirculated downhole. When using air drilling, cuttings are deposited on the ground or in a collection system and the circulating air goes into the atmosphere.

Figure 7.1. Tophead drilling rig (Schramm, Inc.).

Two drilling methods use air as the primary drilling fluid—direct air rotary and downhole air hammer. In air rotary drilling, air alone lifts the cuttings from the borehole. A compressor provides air that is piped to the swivel hose connected to the top of the kelly or drillpipe. When forced down the drillpipe, the air escapes through small ports at the bottom of the drill bit thereby lifting the cuttings and cooling the bit. The cuttings are blown out through the top of the borehole and collect at the surface around it. Injecting a small volume of water or a water and surfactant (foam) mixture into the air system controls dust, lowers the temperature of the air, and cools the swivel.

Use of air drilling is practical only in semi-consolidated or consolidated materials. It is the preferred flushing medium, however, because penetration rates are greater, no cleaning of the flushing medium is required before its re-introduction into the borehole, and no coating of the borehole occurs.

Air and mud rotary rigs use two different methods to rotate the drill string, either a table-drive or a tophead drive. On tophead rigs (*see* Figure 7.1), rotation is provided by a hydraulically driven gearbox which travels up and down the mast. The drill string is connected directly to the rotation unit therefore a kelly is not required. Tophead rigs provide excellent control of the drill string during penetration and retraction. A table-drive rig supplies power to the drillpipe through a kelly bushing located on the table (Figure 7.2). The components of the direct-rotary drilling machine are designed to serve two functions simultaneously: operation of the bit and continuous circulation of the drilling fluid. Both functions are indispensable in cutting and maintaining the borehole.

Cuttings are ground finely enough that the uphole velocity of the air is sufficient to lift them to the surface. Foam enhances the lifting capacity of the air which enables larger cuttings to be removed, thus increasing the drilling rate and reducing air loss to the formation. Suggestions for appropriate uphole velocities and the use of various drilling-fluid additives can be found in Chapter 8.

Drilling bits similar to those designed for drilling with water-based fluids also can be used when drilling with air. Field tests of various bit sizes have shown that the penetration rate often is faster and the bit life is longer when air is used (as compared with the use of water-based drilling fluids). Figure 7.3 lists the formations drilled effectively by carbide- and steel-tooth bits in air rotary drilling.

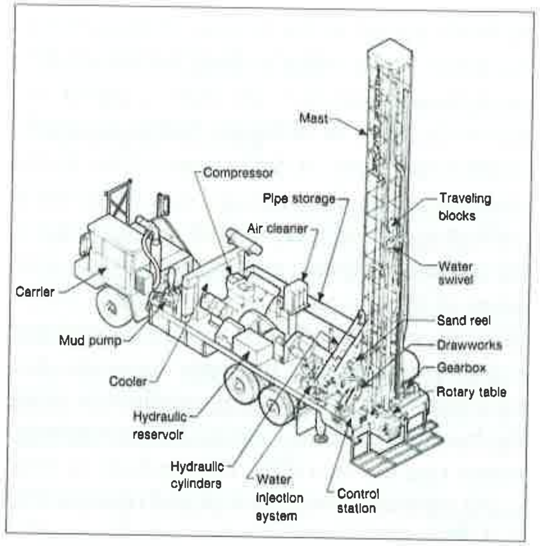

Figure 7.2. Schematic diagram of a truck-mounted direct rotary rig, illustrating the important operational components.

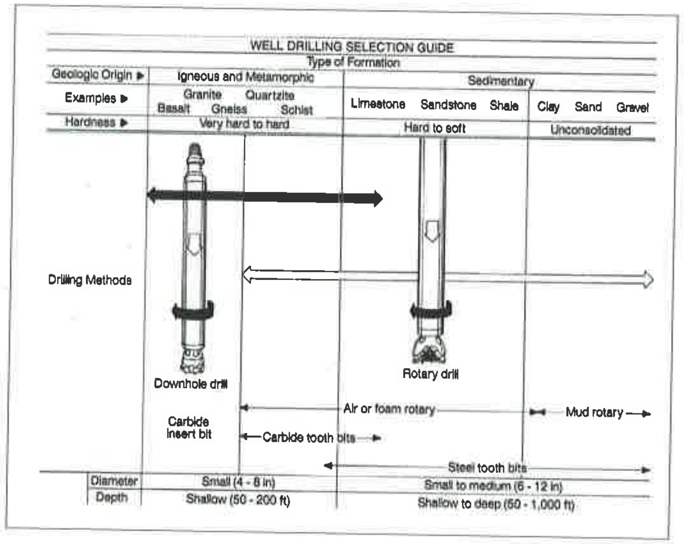

Figure 7.3. Guide for the use of bit types in air-drilling systems.

In direct circulation rotary drilling, generally two types of bits are used—the drag bit and the roller-cone bit. Drag bits (Figure 7.4) have short cutting blades that are faced with durable metal and are cleaned and cooled by jetting drilling fluid down the faces. These bits cut rapidly in sand, clay, and some soft-rock formations, but they do not work well in coarse gravel or hard-rock formations.

Figure 7.4. Drag bits are used in rotary drilling for fast penetration in unconsolidated or semi-consolidated sediments (Torquato Drilling Accessories).

A special type of drill bit—polycrystalline diamond compact (PDC)—has synthetic diamond discs on the cutting faces. These bits can drill formations that are too soft or too sticky for conventional diamond bits, and formations that are too hard for conventional drag bits and which previously were drilled using tricone roller bits or downhole hammer (DTH) bits (*see* Figure 7.5).

Figure 7.5. Photograph of a PDC bit (Torquato Drilling Accessories).

Roller-cone bits perform a crushing and chipping action, making it possible to drill harder formations. The number of teeth on each roller cone used depends on the difficulty of the drilling—the bit should have more teeth on each cone as a rock becomes harder and more difficult to drill. The rollers commonly have either hardened-steel teeth (Figure 7.6) or tungsten-carbide inserts of varied shape, length, and spacing. Roller bits are available to cut materials ranging from soft clays to particularly dense and abrasive formations such as dolomite, granite, chert, basalt, and quartzite. For drilling particularly dense or abrasive formations, roller cones that have carbide buttons (instead of teeth) are used. These are termed button bits (Figure 7.7).

Figure 7.6. Roller-cone or other cone-type bits are preferable for drilling into consolidated rock.

Figure 7.7. Button bit (Atlas CopCo).

When borehole enlargement is necessary, reamers (Figure 7.8) and underreamers are used. A reamer is used to straighten, clean, or enlarge a borehole. Underreaming enlarges the borehole beneath the casing with a bit that can be expanded at the desired depth, so that a larger hole can be drilled. Underreaming often is practical when use of a filter pack is desired but drilling the entire borehole at the larger diameter is cost-prohibitive. Utilizing pre-pack screens, such as the Johnson Screens Muni-Pak™, is becoming a popular option in place of performing underreaming. (See Chapter 9 for a discussion of Muni-Pak™ screens.)

Figure 7.8. Roller-cone borehole reamers.

A conventional drill string consists of the bit, drill collar(s), and the drillpipe; table-drive rigs also include the kelly (Figure 7.9), but no kelly is used on a tophead rig. Both tophead and table-drive rigs also can use stabilizers or reamers in the drill string. Selection of the bottom-hole assembly depends on the physical conditions of the geologic materials. Drill collars are heavy-walled drillpipe used to add weight and stiffness to the lower part of the drill string to facilitate borehole straightness and optimum penetration rate. Table 7.1 presents representative data (in U.S. customary units) on recommended sizes of drill collars. Such stabilizers are important for maintaining a borehole's straightness.

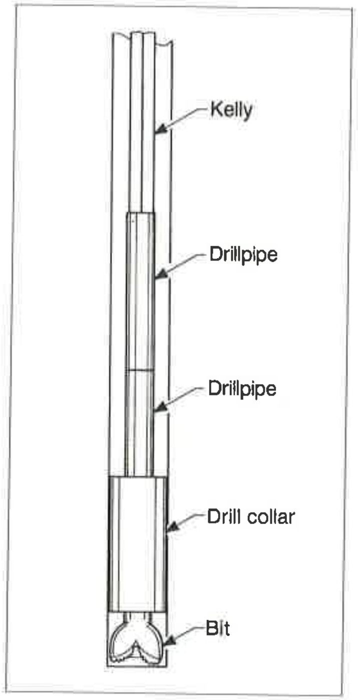

Figure 7.9. Typical drill string for a direct rotary rig operation.

Table 7.1. Ideal Size Range for Drill Collars

Hole Size (in)	Casing Size to be Run (OD in)	Calculated Ideal Drill-Collar Range (in)		API Drill-Collar Sizes Which Fall in the Ideal Range (in)
		Min	Max	
6⅛	4½	3.87	4.75	4⅛, 4¾
6⅛	4½	3.75	4.87	4⅛, 4¾
6¾	4½	3.25	5.12	3½, 4⅛, 4¾, 5
7⅞	4½	2.12	6.12	3⅛, 3½, 4⅛, 4¾, 5, 6
	5½	4.22	6.12	4¾, 5, 6
8⅜	5½	3.72	6.50	4⅛, 4¾, 5, 6, 6¼, 6½
	6⅝	6.40	6.50	6½
8½	6⅝	6.28	6.72	6½, 6¾
	7	6.81*	6.75	6¾
8¾	6⅝	6.03	7.12	6¼, 6½, 6¾, 7
	7	6.56	7.12	6¾, 7
9½	7	6.81	7.62	6, 6¼, 6½, 7, 7¼
	7⅝	7.50	7.62	7⅝†
9⅞	7	5.43	8.00	6, 6¼, 6½, 6¾, 7, 7¼, 7¾, 8
	7⅝	7.12	8.00	7¼, 7¾, 8
10⅝	7⅝	6.37	8.50	6½, 6¾, 7, 7¼, 7¾, 8, 8¼
	8⅝	8.62*	8.50	8¼
11	8⅝	8.25	9.62	8¼, 9, 9½
12¼	9⅝	9.00	10.12	9, 9½, 9¾, 10
	10¾	11.25*	10.12	10
13¾	10¾	9.75	11.25	9¾, 10, 11
14¾	11¾	8.75	12.00	9, 9½, 9¾, 10, 11, 12†
17½	13⅜	11.25	13.37	12†
20	16	14.00	14.75	14†
24	18⅝	15.50	16.75	16†
26	20	16.00	19.50	16†

* In these instances, the equation used to calculate the ideal minimum drill-collar size produces an anomalously high value. See Woods and Lubinski (1954) for a complete discussion on how to determine the best collar size for a specific diameter borehole.

† Not API standard-size drill collar.

(Drilco 1979)

Drillpipe is seamless tubing that usually is 20 ft (6.1 m) to 30 ft (9.1 m) long, however other lengths are available. It is manufactured with a tool-joint pin on one end and a tool-joint box on the other (Figure 7.10). To reduce the power required for the pump, drillpipe diameter should hold friction losses in the pipe to acceptable levels. For efficient operation, the outside diameter of the tool-joint should be about two-thirds the size of the borehole diameter; however this ratio might be impractical for boreholes that are larger than 10 in (254 mm).

In table-drive machines, the kelly constitutes the uppermost section of the drill string. It passes through and engages the rotary table, which is driven by hydraulic or mechanical means. A heavy thrust bearing between the two parts of the swivel carries the entire weight of the drill string while allowing the drillpipe to rotate freely. In tophead drive rotary machines the rotational unit moves up and down the mast; energy is obtained from a hydraulic transmission unit powered by a motor-driven pump.

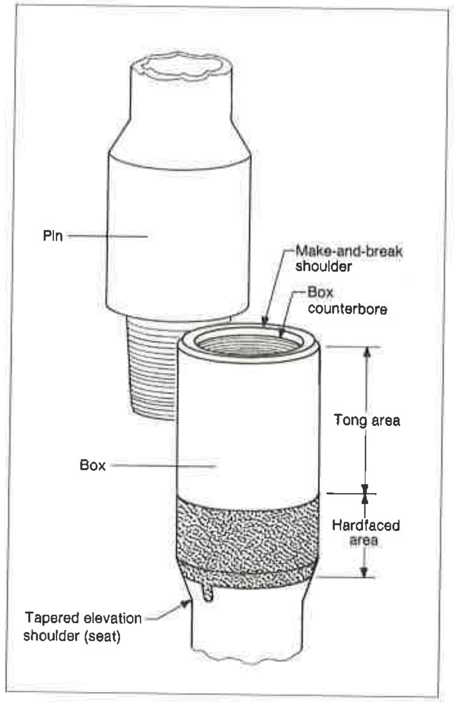

Figure 7.10. Drillpipe is heavy-walled seamless tubing with tool-joint pin and box-end fittings.

For shallow boreholes—those less than 250 ft (76 m) deep—pull-down pressure can be applied to the bit. In deep direct-rotary drilled boreholes, drilling professionals must hold back (suspend) part of the drill-string weight from the swivel to avoid placing excessive weight on the bit. Drill bit manufacturers can recommend the optimum pressure that an individual bit should receive for ensuring maximum cutting rates.

Drilling fluid (mud) control is essential to efficient rotary drilling. For drilling to proceed efficiently, there must be proper coordination of the borehole size, drillpipe size, bit type, pump capabilities, and drilling-fluid characteristics that all are based on the geologic conditions at the site. In water-well applications, drilling fluids range from air and freshwater to engineered water-based solutions containing special additives for viscosity, density, and solids control. Maintaining optimum uphole velocity is critical for proper borehole cleaning. (See Chapter 8 for a discussion of standard drilling fluids.)

The essential functions of a drilling fluid are to:

- Carry the cuttings from the bottom of the hole to the surface;
- Support and stabilize the borehole wall to prevent caving;
- Seal the borehole wall to reduce fluid loss;
- Cool and clean the drill bit;
- Allow cuttings to separate from the fluid at the surface; and
- Lubricate the bit, bearings, mud pump, and drillpipe.

The hydraulic pressure that typical drilling muds exert against the formation being drilled is greater than the static formation pressure, thus there can be overbalance (invasive) damage to the formation. The overbalanced fluid pressure depends primarily on the density of the drilling mud. Control of drilling-fluid properties during all phases of well construction minimizes both the frequency of occurrence of such damage and the time required to alleviate it. Experience and knowledge of drilling-fluid additives are essential for minimizing formation damage while maintaining borehole control.

Underbalanced Rotary Drilling

In underbalanced drilling programs the objective is to have a lightweight borehole fluid that ideally exerts a hydrostatic pressure equal to or less than the static formation pressure, which eliminates the invasive effects of drilling fluid that cause formation damage. This practice is gaining popularity in locations where it can be applied because it increases penetration rates, reduces lost-circulation problems, minimizes differential sticking, shortens development time, and reduces borehole damage. The use of underbalanced drilling also is popular in the oil industry, where it involves equipment and techniques that are more sophisticated than those required in the water-well industry, because formation pressures can far exceed those normally found in water-well drilling. The rate of return for underbalanced wells, however, typically is greater than for wells drilled using other methods.

Figure 7.11 illustrates the differences between overbalance and underbalanced drilling techniques. Example (A) shows underbalanced drilling, where the fluid pressures are less within the borehole than they are in the aquifer. This situation leads to minimized borehole damage. Example (B) shows a typical drilling situation where fluid pressures in the borehole exceed formation pressures; in this scenario a mudcake develops.

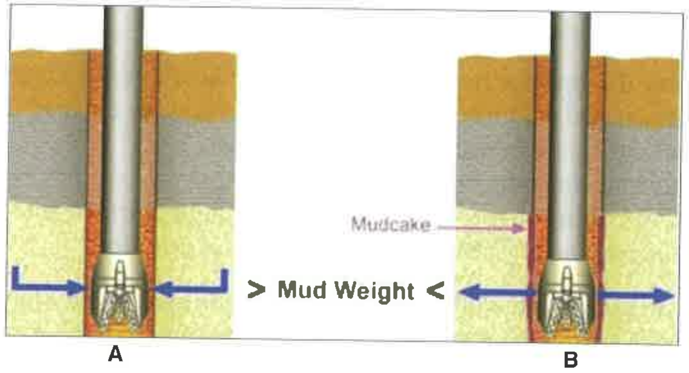

Figure 7.11. Differences in fluid migration with (A) and without (B) underbalanced drilling (www.rigzone.com).

A typical situation is where the static water level is below the land surface. This situation requires the addition of air or foam to reduce the fluid density sufficiently and enable drilling in a balanced or underbalanced state unless the well is flowing. Balanced drilling methods include air rotary and reverse rotary. Caution should be exercised with air injection and the possibility of increased corrosion to the drillpipe or tooling. A common example of underbalanced drilling in the water-well industry is air rotary (drilling with air or foam injection). Underbalanced drilling conditions do not build filter cake (*see* Chapter 8) because negative differential pressure encourages flow into the borehole and not out into the formation.

Downhole Hammer Drilling

Another air rotary drilling method is the downhole hammer system. A pneumatic drill at the end of the drillpipe rapidly strikes the rock while the drillpipe slowly is rotated. A hammer is constructed from alloy steel and heavy tungsten-carbide inserts that provide the cutting surfaces. Rotation of the bit helps to insure even penetration and straighter holes—including when drilling in extremely abrasive or resistant rock types. The penetration rates for drilling in hard rock are greater than those obtained by other drilling methods. Hammer bits in sizes of 5 in (127 mm) and 6 in (152 mm) are most common, with sizes of up to 24 in (608 mm) also available. Cuttings are removed continuously so the bit always strikes a clean surface, which makes the air-hammer method highly efficient.

Compressed air must be supplied to the hammer at a pressure of at least 100 psi (690 kPa). The most common pressure on modern rigs used primarily for air drilling is 350 psi (2,415 kPa), with pressures sometimes as great as 500 psi (3,450 kPa). To remove cuttings effectively, the volume of flushing air must be adequate to maintain the upward velocity in the annulus between the drillpipe and the borehole at a minimum of 3,000 ft/min (915 m/min), as determined by the following equation (in U.S. customary units).

$$V_r = \frac{183.34 \cdot cfm}{(D)^2 - (d)^2} \tag{7.1}$$

Where:

V_r = annulus velocity (ft/min);

cfm = cubic ft free air per min;

D = hole diameter (in); and

d = outside drillpipe diameter (m).

A downhole hammer is extremely effective in penetrating dense, resistant formations such as basalt, quartzite, and granite.

When a conventional downhole hammer is used in dual-wall drilling, air is forced down the inside of the hammer and out through the ports. The air passes up around the outside of the hammer shaft into a special crossover sub and then into the inner casing (Figure 7.12). When a reverse circulation downhole hammer is used in dual-wall drilling, cuttings exit the bottom of the borehole through a hole in the face of the bit. The cuttings are carried through the center of the downhole hammer and into the center tube of the dual-wall pipe; from there, compressed air carries the cuttings to the top of the borehole.

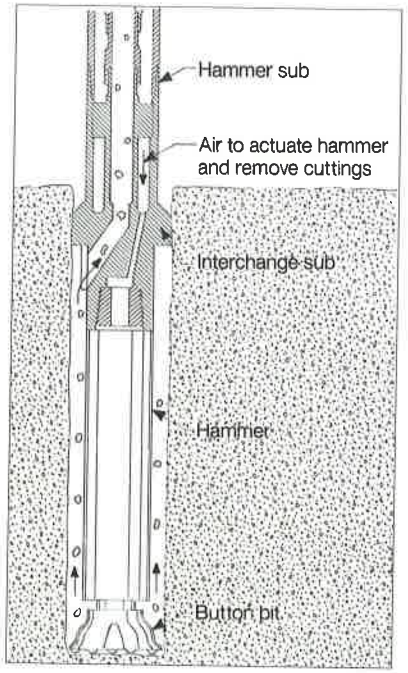

Figure 7.12. Diagram of typical downhole hammer configuration (Drilling Services Co.).

Casing Advancement Drilling Methods

Casing advancement drilling methods are used in unconsolidated or difficult conditions when it is desirable to advance the casing as the borehole is created, usually using downhole hammer drilling. Four methods commonly are used for this type of drilling.

Casing Driver

Some manufacturers provide casing drivers that can be fitted to tophead drive, direct air rotary rigs (Figure 7.13). The driver can be suspended in the mast—independent of the rotary drive unit—because of its rather short length. Using a casing driver allows the casing to be advanced during drilling but both drilling and driving can be adjusted independently, based upon the nature of the specific formation. Drivers usually are designed so that they also can drive upward, for example to remove casing or to expose a screen.

Three drilling procedures can be performed when using the casing driver: (1) advancing the drill bit and casing as a unit; (2) driving the casing first (in unconsolidated materials only) and then drilling out the plug in the casing; and (3) advancing the drill bit a few feet beyond the casing, then withdrawing it into the casing, and then driving the casing.

The casing is pulled back to set the screen. It is wise, however, to add a short piece of riser pipe to the top of the screen so that it won't be lost if the casing is pulled back too far.

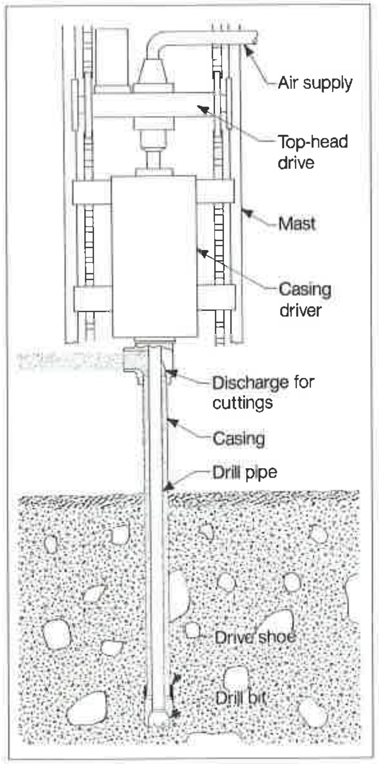

Figure 7.13. Casing drivers can be fitted to tophead drive rotary rigs to simultaneously drill and drive casing (Atlas Manufacturing).

Underreamer

Wings—underreamers—on the drill bit swing out under the casing during drilling allowing the casing to follow the bit into the borehole. When drilling is complete the underreamers are retracted and the entire drill string is removed through the casing (*see* Figure 7.14).

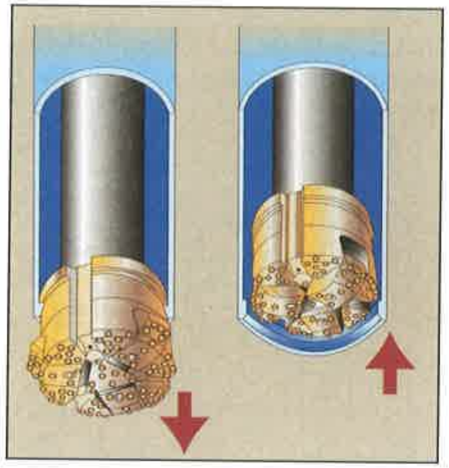

Figure 7.14. Underreaming system (NUMA).

Casing Rotator

The drilling rig is equipped with a device that clamps around the casing to rotate and advance it into the ground (see Figure 7.15). To facilitate drilling, a drive shoe with cutting teeth can be welded onto the end of the casing. The casing can be rotated clockwise or counter-clockwise as required, and the distance from bit face to casing end can be adjusted.

Figure 7.15. Casing rotator rig (Schramm, Inc.).

Casing Float Shoe Engaged by Downhole Hammer

A shoulder on the hammer hits against a mating drive shoe welded to the end of the casing, to drive the casing into the ground as drilling proceeds (*see* Figure 7.16). The casing remains in the borehole after the drillstring is removed.

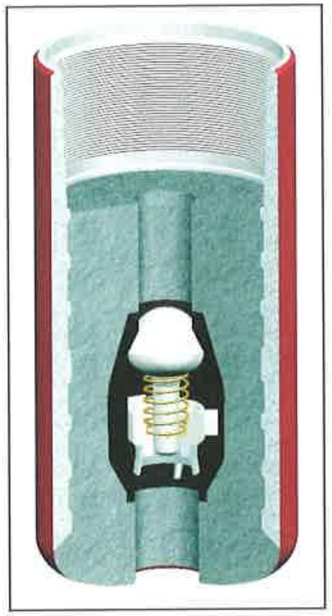

Figure 7.16. Casing float shoe (Weatherford Corp.).

REVERSE CIRCULATION METHODS

In reverse circulation rotary drilling, the flow of the drilling fluid is reversed and the drilling fluid (with cuttings) moves upward inside the drillpipe and discharges at the surface, typically into one or more settling pits. The pump suction is connected to the kelly and drillpipe through the swivel. Centrifugal pumps frequently are used because they handle cuttings without experiencing excessive wear. For large-diameter water-well drilling, uphole velocities of 150 ft/min (45 m/min) or greater are recommended.

Fluid returns to the borehole—via gravity—down the annulus to the bottom of the hole. It reenters the drillpipe, with more cuttings entrained, through ports in the drill bit (Figure 7.17, Figure 7.18). A native drilling mud develops when suspended clay and silt recirculate as drilling proceeds but, when needed, polymer additives are used to reduce friction and to control water loss or the swelling of water-sensitive clays. In deeper wells with deep static water levels, an engineered drilling fluid generally is used.

To prevent caving (from a loss of the hydrostatic pressure that supports the borehole) a positive fluid pressure must be maintained in the borehole at all times—even when drilling is suspended temporarily. Reverse circulation drilling is not commonly practiced where the static water level is less than 10 ft (3 m) below ground surface. A considerable quantity of make-up water must be immediately available at all times when drilling in permeable sand and gravel (at least three times the volume of the material removed during the drilling operation is recommended). The circulation rate during drilling commonly is 500 gpm (2,730 m^3/day) or greater.

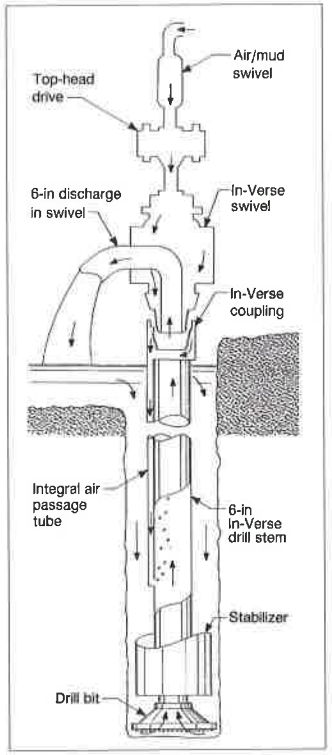

Figure 7.17. Air is injected into a special double-walled drill stem to increase the efficiency of cuttings removal.

Many reverse rigs are equipped with air compressors, and when drilling reaches sufficient depth for air-lift operation (generally 45 ft (13.7 m) to 60 ft (18.3 m)) the mud pump is bypassed and water and cuttings are air-lifted from the borehole. Compressed air is introduced through a 1¼-in (32-mm) to 1½-in (38-mm) air line made of plastic or metal. The air line is suspended inside the drillpipe or through external lines outside of the drillpipe. Most drillpipe used is threaded and coupled pipe that is up to 8 in (203 mm) in diameter, and is operated at depths of 2,000 ft (610 m) or deeper.

It is recommended that a reverse system use at least a 300-cfm (0.1 m^3/sec) compressor operating at 125 psi (862 kPa). The reverse-equipped rig operates most satisfactorily with a centrifugal pump or a piston pump.

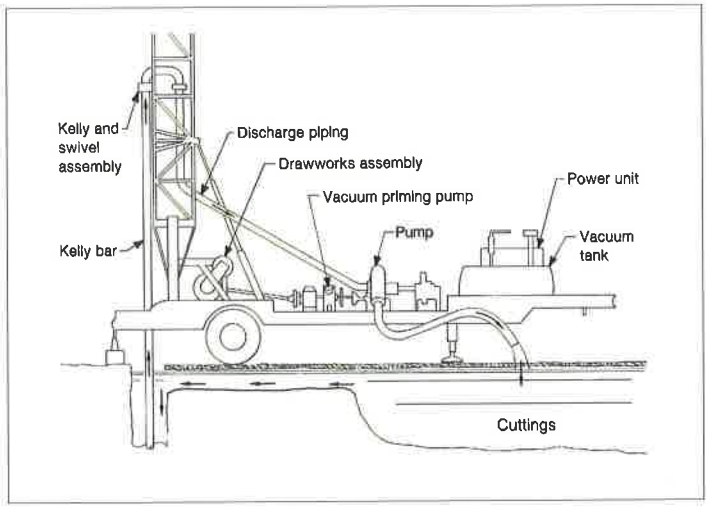

Figure 7.18. Reverse rotary circulation system. Drilling fluid flows from the mud pit down the borehole outside the drill rods, and passes upward through the bit into the drill rods after entraining the cuttings. Fluid flows through the swivel and mud pump and passes into the mud pit where the cuttings settle out.

Reverse circulation drilling is an economical method for drilling large-diameter holes in unconsolidated formations. Most water wells drilled using this method have a diameter of 20 in (508 mm) or larger. Filter packs typically are used in well completions because of the relatively large-diameter borehole.

DUAL-WALL AIR ROTARY DRILLING

Dual-wall drilling was developed in the mining industry to obtain accurate geologic samples from known depths. The method uses flush-jointed, double-wall pipe and the drilling fluid (air or liquid) moves via reverse circulation (Figure 7.19). Unlike in the conventional reverse circulation method, the drilling fluid does not flow downward outside the drillpipe, but rather is contained between the dual walls of the pipe and only contacts the borehole wall near the drill bit. The dual-wall drilling method is applied to water-well construction in all types of geologic formations, and larger rigs are being built for drilling large-diameter boreholes under difficult drilling conditions. Water wells can be drilled to depths of 1,000 ft (305 m) or more using this method.

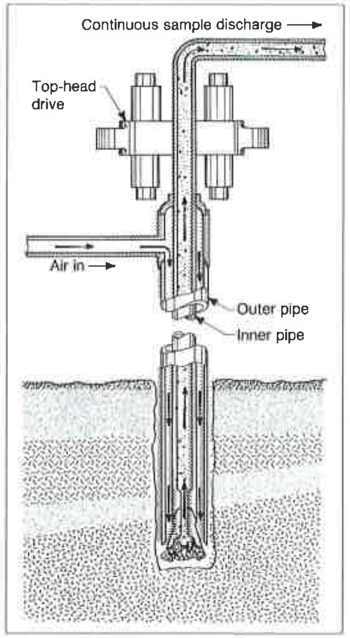

Figure 7.19. Drilling fluid is injected down the outer annulus of dual-walled pipe; cuttings are lifted to the surface through the inner pipe. The pipe is connected directly to either a downhole air hammer or a tricone bit.

A direct rotary, tophead drive machine can be converted into a reverse circulation rig. The equipment is modified by the addition of air assist, using a special 6-in (152-mm) inside diameter, side-discharge swivel assembly, and 5⅞-in (149-mm) drillpipe with built-in air channels. This equipment enables injection of compressed air through a stem into air channels mounted outside the drillpipe. The air then moves into the drilling fluid as it travels up the inside of the drillpipe (Figure 7.20). The drilling fluid and cuttings are assisted to the surface by an air-lift inside the 6-in diameter drillpipe.

Use of the reverse system can increase the capacity of a direct rotary rig to enable the drilling of large-diameter wells. Depending on the rig used, boreholes from 20 in (508 mm) to 30 in (762 mm) routinely can be drilled. If the capabilities of the rig are sufficient, then drilling boreholes of 30 in (762 mm) to 60 in (1,520 mm) is possible in unconsolidated formations.

NONCIRCULATION METHODS

Cable-Tool Drilling

Developed by the Chinese, the cable-tool percussion method has been in continuous use for about 4,000 years. Cable-tool drilling machines, also called percussion or "spudder" rigs, operate by repeatedly lifting and dropping a heavy drill string into the borehole. The reciprocating-tool action mixes the cuttings with water to form a slurry; water is added if little or no formation water present. Slurry accumulates as drilling proceeds, and it eventually reduces the impact of the tools to the point that the cuttings periodically must be extracted by a sand pump or bailer to facilitate optimum penetration rate. Effective action makes the cable-tool rig an ideal machine for well rehabilitation and work-over.

A full string of cable-tool drilling equipment consists of five components: drill bit, drill stem, drilling jars, swivel socket, and a cable (Figure 7.20). The cable-tool bit usually is massive and heavy so that it can crush and mix all types of earth materials. The drill stem gives additional weight to the bit, and its length helps to maintain a straight borehole when used for drilling into hard rock.

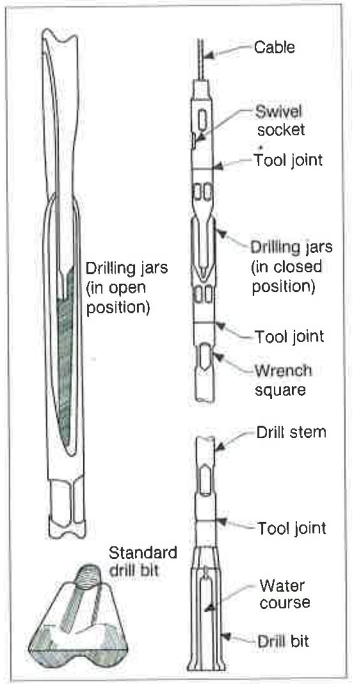

Figure 7.20. A full cable-tool drill string.

Drilling jars consist of a pair of linked, heat-treated steel bars, and their primary function is to free a stuck bit via upward blows of the free-sliding jars. The swivel socket connects the string of tools to the cable, and transmits the rotation of the cable to the tool string and bit so that new rock is cut on each downstroke, thus ensuring a round, straight hole. The cable drill line is a ⅝-in (16-mm) to 1-in (25-mm) left-hand lay cable that twists the tool joints on each upstroke to prevent the joints from unscrewing. A cable-tool rig is shown in Figure 7.21.

Relatively small-diameter holes can be drilled to greater depth, whereas the drilling of large-diameter holes is limited by the weight of the drill string and cable. The depth range for cable-tool rigs ranges from approximately 300 ft (90 m) to 1,500 ft (500 m).

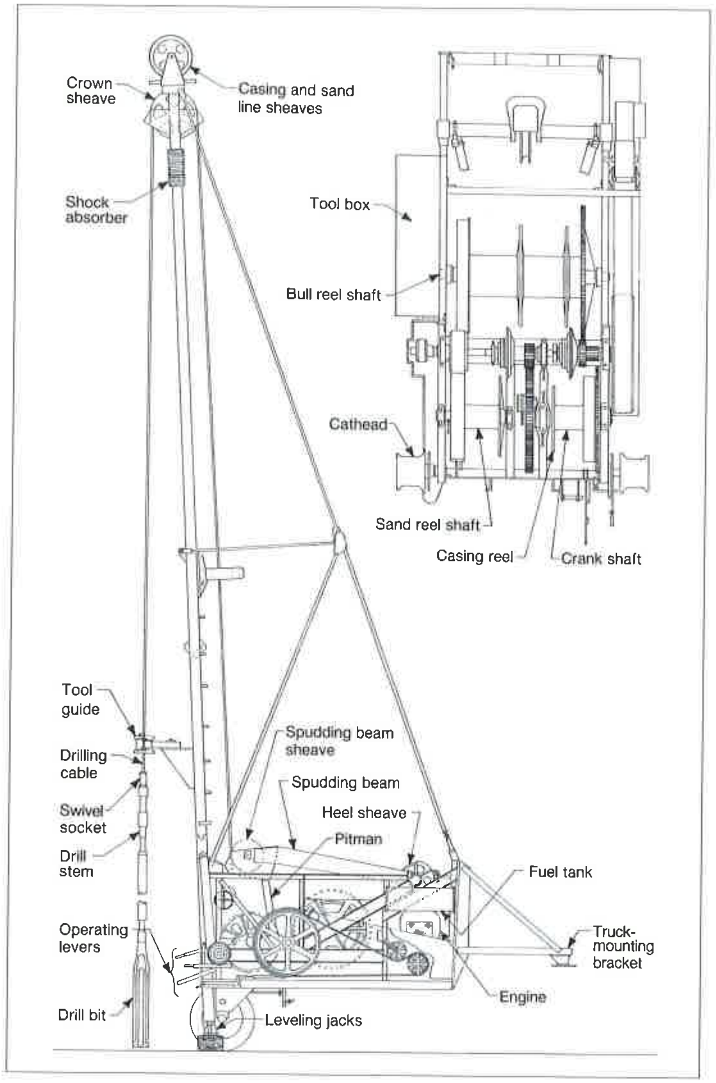

Figure 7.21. Bucyrus-Erie Model 22-W cable-tool rig. The percussion action is imparted to the drill line by the vertical motion of the spudding beam. The shock absorber mounted beneath the crown block helps control the impact of the bit (Bucyrus-Erie Co.).

Most boreholes that are completed in consolidated formations via the cable-tool method are drilled without using casing during part—and sometimes all—of the drilling operation. When drilling in unconsolidated formations, pipe or casing must follow the drill bit closely to prevent caving and to keep the borehole open. To prevent damage, a drive shoe (comprised of hardened and tempered steel) is attached to the bottom of the casing. When wall friction prevents further advancement, a smaller casing is inserted inside the first one and drilling continues. In some circumstances, two or three size reductions are required for the drill to reach the desired depth.

The casing sometimes is jacked (pushed into the ground by hydraulic jacks) as drilling and bailing proceeds. Drilling proceeds at a faster rate because it is not necessary to stop to drive pipe. Constant downward pressure on the casing during drilling minimizes caving and over-excavation. Casing also can be retrieved using jacks.

The cable-tool drilling method survives because it is reliable for use in a wide variety of geologic conditions. It remains a practical method in coarse glacial till; boulder deposits; basalts; or rock strata that are highly disturbed, broken, fissured, or cavernous. In thin and low-yielding aquifers, the cable-tool operation permits identification of zones that might be overlooked when using other drilling methods.

Bucket Auger Drilling

The bucket auger drilling method utilizes a large-diameter bucket auger to excavate materials (Figure 7.22) which then are collected in a cylindrical bucket that has auger-type cutting blades on the bottom. The bucket is attached to the lower end of a kelly bar that passes through—and is rotated by—a large ring gear that serves as a rotary table.

Wells more than 250 ft (76.2 m) deep have been drilled using this method, although attainment of depths of 50 ft (15.2 m) to 150 ft (45.7 m) is more common. Water wells drilled with bucket augers range in diameter from 18 in (457 mm) to 48 in (1,220 mm), but few wells are larger than 36 in (914 mm). Rotary bucket drilling primarily is used in clay formations that can stand without caving. Drilling in sand below the water table is difficult but it is not impossible if the borehole remains filled with water or drilling fluid.

Figure 7.22. Bucket auger drilling rig (Powers et al. 2007).

A major disadvantage of the bucket auger drilling method is that it is limited to use in relatively shallow depths (generally less than 100 ft (30 m)), and in unconsolidated sediments or poorly cemented sedimentary rocks. Table 7.2 summarizes the advantages and disadvantages of each drilling method.

Table 7.2. Advantages and Disadvantages of Drilling Methods

Direct Circulation Methods

Advantages	Disadvantages
Penetration rates are relatively high in all types of materials	Drilling rigs require a high level of maintenance
Minimal casing is required during the drilling operation	Mobility of the rigs can be limited
Rig mobilization and demobilization are rapid	Most rigs must be handled by a crew of at least two people
Well screens can be set easily as part of the casing installation	Collection of accurate samples requires special procedures
	Use of drilling fluids can cause plugging of certain formations
	The drilling method is difficult and less economical in extremely cold temperatures
	Drilling fluid management requires additional knowledge and experience

Air Rotary Drilling

Advantages	Disadvantages
Cuttings removal is extremely rapid	Restricted to use in semi-consolidated and well-consolidated materials
Aquifer is not plugged with drilling fluids	High initial cost and maintenance costs of large air compressors
Mud pumps are not used during air drilling, eliminating that maintenance cost	
Bit life is extended	
Drilling operations are not hampered by extremely cold weather	
Penetration rates are high (especially when using downhole hammers) in highly resistant rocks such as dolomite or basalt	
An estimate of the yield of a particular formation can be made during drilling	

Casing Advancement Methods

Advantages	Disadvantages
Wells can be drilled in unconsolidated geologic materials	Additional cost of equipment
A borehole is fully stabilized during the entire drilling operation	Noise of operation (casing hammers are noisy)
Penetration rate can be rapid even in difficult conditions	Clays or sticky shales can reduce depth capacity
Lost-circulation problems are eliminated.	
Accurate formation and water samples can be obtained	

Reverse Circulation Methods

Advantages	Disadvantages
Porosity and permeability of the formation near the borehole are relatively undisturbed (as compared to other methods)	Large water supply generally is needed during drilling
Large-diameter holes can be drilled quickly and economically	Reverse rotary rigs and components usually are larger and more expensive
Casing is not required during the drilling operation	Large mud pits are required
Well screens can be set easily as part of the casing installation	Some drill sites are inaccessible because of the rig size
Most geologic formations can be drilled (except igneous and metamorphic rocks)	For efficient operation, a larger crew generally is required as compared to that needed for other drilling methods
Little opportunity exists for washouts in the borehole because of the low velocity of the drilling fluid	Extra costs for drillpipe, special swivel, and air compressor (if the rig is not equipped with one)
Large-diameter boreholes can be drilled	Drillpipe handling time can increase for deep holes
Penetration rates are high in unconsolidated sediments	
Less drilling–fluid additive is required to lift the cuttings	
Reduced development time	

Dual-Wall Air Rotary Drilling

Advantages	Disadvantages
Continuous representative formation samples and water samples can be obtained	High initial cost of drilling rig and equipment
Estimates of aquifer yield can be made easily at many depths in the formation	Limited to rather small holes, less than 9 in (229 mm) to 10 in (254 mm)
Fast penetration rates are possible in coarse alluvial or broken fissured rock	Limited to depths of 1,200 ft (366 m) to 1,400 ft (427 m) in alluvial deposits (most effective at depth of 600 ft (183 m)) and at up to 1,900 ft (579 m) in hard rocks
Washout zones are reduced or eliminated	Well-trained drilling crew is needed
Screens and conventional casing can be installed	

Noncirculation Methods

Cable-Tool Drilling

Advantages	Disadvantages
Rigs are relatively inexpensive, have low energy requirements, and require little sophisticated maintenance	Slow penetration rates
Because of their size, machines can be operated in difficult terrain or areas where space is limited or road conditions do not allow heavy equipment	Casing costs usually are higher (because heavier-walled or larger-diameter casing can be required)
A borehole is stabilized during the entire drilling process, allowing drilling where lost circulation is a problem	Some geologic conditions make it difficult to retract long strings of casing without using special equipment
Wells can be drilled in areas where little make-up water exists	
Recovery of reliable samples is possible from every depth (unless heaving conditions occur)	
Wells can be bailed at any time to determine the approximate water yield at the current depth	

Bucket-Auger Drilling

Advantages	Disadvantages
Used for drilling large-diameter wells	Limited to depths of less than 100 ft (30 m)
	Can drill only in unconsolidated sediments (primarily clayey materials)

SUMMARY

Selection of the best, most efficient, and most effective drilling method requires an understanding of the geologic conditions of the formation and the physical limitations of the drilling rig and drilling method. Many drilling difficulties occur because the drilling professional either is unprepared to handle the wide range of subsurface conditions or has pushed the rig beyond its safe operating limits.

Table 7.3 provides relative performance ratings for the different drilling methods when used in various geologic formations. The relative performance differences between drilling methods, however, also depend on the experience level of the drilling professional, the presence of any geologic anomalies at the site, and the pressure conditions affecting the groundwater. Table 7.4 provides a comparison of drilling methods for various borehole sizes and conditions.

Table 7.3. Relative Performance of Different Drilling Methods in Various Types of Geologic Formations

Formation	Cable Tool	Fluid Rotary	Air Rotary	DTH Air Rotary	Casing Advancing Systems				Reverse Fluid	Dual-Wall Reverse	
					Hammer	Underreamer	Rotator	DTH Driven		DTH	Fluid Rotary
Sand & Gravel	4	5	NR	NR	6	2	5	2	4	6	6
Boulders In Drift	3 to 2	2 to 1	NR	NR	5	4	5	3	2 to 1	4	NR
Clay & Silt	4	5	NR	NR	5	3	5	2	5	5	4
Firm Shale	4	5	4	5	5	5	5	5	5	5	6
Sticky Shale	4	5	3	4	5	5	5	5	3	5	6
Brittle Shale	4	5	3	3	5	5	5	5	5	5	6
Sandstone, Poorly Cemented	4	4	NR	NR	4	5	5	5	4	5	6
Sandstone, Well Cemented	3	4	5	4	4	6	4	6	3	5	4
Chert Nodules	3	3	3	5	NR	5	NR	5	3	5	3
Limestone	3	5	5	6	NR	6	3	4	5	6	5
Limestone with Chert Nodules	3	3	5	6	NR	5	3	4	3	3	3
Limestone, Broken	3	3	5	6	NR	5	3	4	2	5	4
Limestone, Caverous	3	3 to 1	2	5	NR	4	3	4	1	5	5
Dolomite	3	4	4	6	NR	5	NR	3	5	5	4
Thin Basalt in Sedimentary	3	3	5	6	NR	5	NR	3	3	5	5
Basalts in Thick Layers	3	3	4	5	NR	4	NR	3	3	4	4
Basalt, Fractured	3	1	3	3	NR	3	NR	2	1	4	3
Metamorphic Rocks	3	3	4	5	NR	4	NR	3	3	4	4
Granite	3	3	4	5	NR	4	NR	3	3	4	3

NR - Not Recommended
* Assuming sufficient hydrostatic pressure is available to contain active sand (under high confining pressures)
Rate of Penetration
1 Impossible
2 Difficult
3 Slow
4 Medium
5 Rapid
6 Very Rapid

The following table provides a comparison of drilling methods for various borehole sizes and conditions (in U.S. customary units).

Table 7.4. Comparison of Drilling Methods for Various Borehole Sizes and Conditions

	Drilling Method	Relative Penetration Rate	Typical Borehole Diameter Range (in)	Depth Range (ft)	Borehole Damage	Cuttings Removal	Hole Stability Control
Direct Circulation	Mud Rotary	G	4 to 20	5,000+	H	G	G
	Air Rotary	E	4 to 12	5,000+	M	G	G
	Casing Rotator	E	12 to 30	500 to 1,200	I	E	E
	Casing Hammer	G	4 to 8	200 to 600	L	E	E
	Underreamer	E	6 to 48	300 to 1,000	L	E	E
	DTH Driven	G	4 to 48	200 to 800	L	E	E
Reverse Circulation	Mud Rotary	G	4 to 36	3,000	M	G	G
	Dual-Wall Air Rotary	E	5 to 12	2,500	L	G	F
Non-Circulation	Cable Tool	P to F	4 to 36	1,500	L	G	E
	Bucket Auger	F	24 to 48	150	M	F to G	F

Key: Excellent (E); Good (G); Fair (F); Poor (P); High (H); Moderate (M); Low (L).

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