CHAPTER 10

Well Drilling Methods

Various well drilling methods have developed because geologic conditions range from hard rock such as granite and dolomite to completely unconsolidated sediments such as alluvial sand and gravel. Particular drilling methods have become dominant in certain areas because they are most effective in penetrating the local aquifers and thus offer cost advantages. In many cases, however, the drilling contractor may vary the usual drilling procedure depending on the depth and diameter of the well, type of formation to be penetrated, sanitation requirements, and principal use of the well. It is obvious, then, that no single drilling method is best for all geologic conditions and well installations. In most cases, the drilling contractor is best qualified to select the particular drilling procedure for a given set of construction parameters. Successful drilling is both an art developed from long experience and the application of good engineering practices.

Well construction usually comprises four or five distinct operations: drilling, installing the casing, placing a well screen and filter pack, if required, grouting to provide sanitary protection, and developing the well to insure sand-free operation at maximum yield. Two or more of these operations may be carried out simultaneously, depending on the drilling method used. For example, when drilling into an unconsolidated formation by the cable tool or drill-through casing driver methods, the casing is installed as drilling proceeds. When a well point (screen) is driven, three operations are performed simultaneously: the borehole is opened, the casing installed, and the well screen set.

Well drilling and installation methods are so numerous that only the basic principles and some of their applications can be described in this chapter. The practical limits of major drilling methods are presented for various geologic conditions. Methods for installing well screens and procedures for well development are explained in Chapters 14 and 15, respectively.

CABLE TOOL METHOD

Developed by the Chinese, the cable tool percussion method was the earliest drilling method and has been in continuous use for about 4,000 years. Using tools constructed of bamboo, the early Chinese could drill wells to a depth of 3,000 ft (915 m), although construction sometimes took two to three generations. Cable tool drilling machines, also called percussion or "spudder" rigs, operate by repeatedly lifting and dropping a heavy string of drilling tools into the borehole (Figure 10.1). The drill bit breaks or crushes consolidated rock into small fragments, whereas the bit primarily loosens the material when drilling in unconsolidated formations. In both instances, the reciprocating action of the tools mixes the crushed or loosened particles with water to form

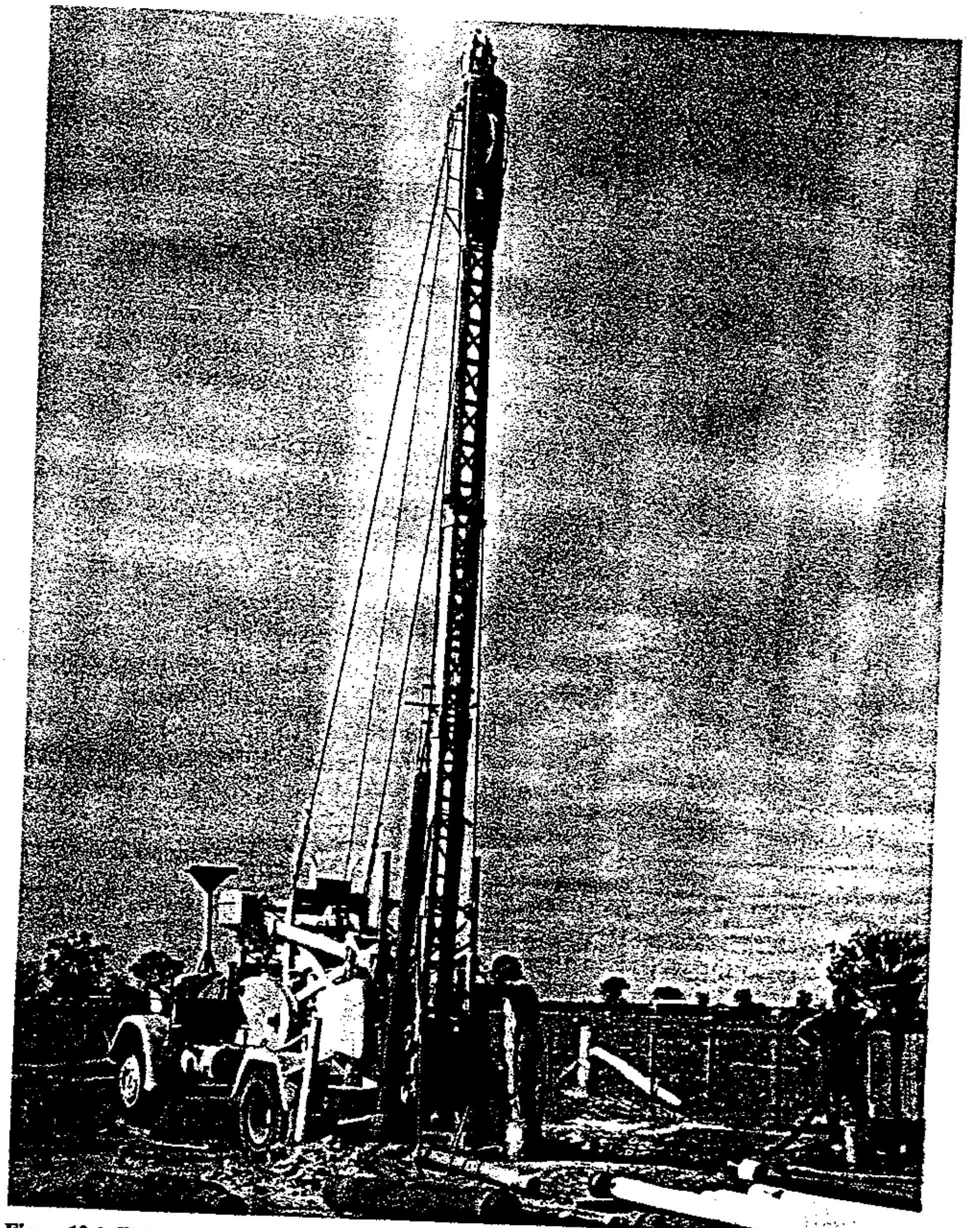


Figure 10.1. This small cable tool rig operating in Australia is equipped with a bailer to remove cuttings periodically from the borehole. Cable tool machines also are called percussion or "spudder" rigs.

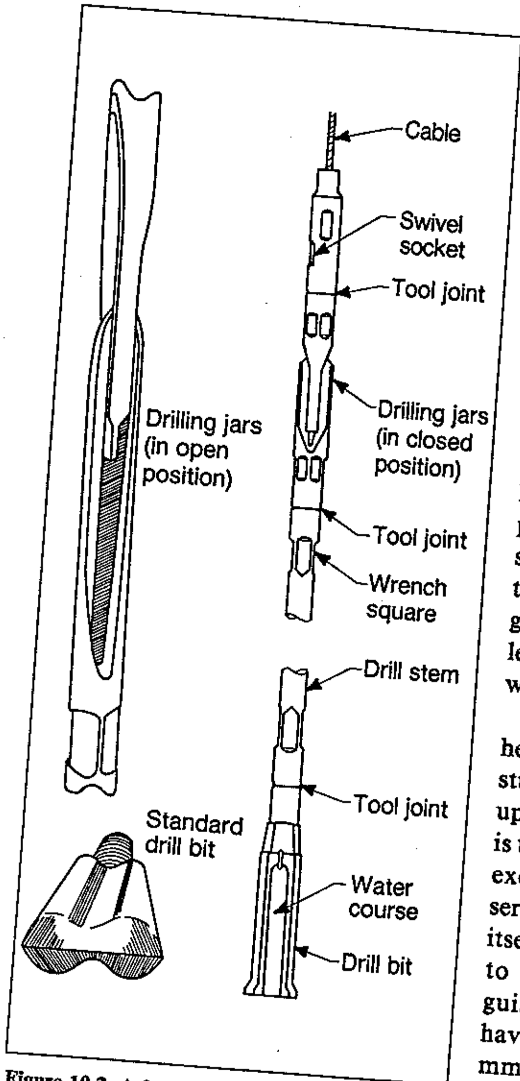


Figure 10.2. A full string of cable tools consists of five components that are necessary for drilling.

a slurry or sludge at the bottom of the borehole. If little or no water is present in the penetrated formation, water is added to form a slurry. Slurry accumulation increases as drilling proceeds and eventually it reduces the impact of the tools. When the penetration rate becomes unacceptable, slurry is removed at intervals from the borehole by a sand pump or bailer.

A full string of cable tool drilling equipment consists of five components: drill bit, drill stem, drilling jars, swivel socket, and cable (Figure 10.2). Each component has an important function in the drilling process. The cable tool bit is usually massive and heavy so as to 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 hole when drilling in hard rock.

Drilling jars consist of a pair of linked, heat-treated steel bars. When the bit is stuck, it can be freed most of the time by upward blows of the free-sliding jars. This is the primary function of the drilling jars; except in unusual circumstances, they serve no purpose in the drilling operation itself. The stroke of the drilling jars is 9 to 18 in (229 to 457 mm) and distinguishes them from fishing jars which have a stroke of 18 to 36 in (457 to 914 mm) or longer.

The swivel socket connects the string of tools to the cable; in addition, the weight of the socket supplies part of the upward energy to the jars when their use becomes necessary. The socket transmits the rotation of the cable to the tool string and bit so that new rock is cut on each downstroke, thereby assuring that a round, straight hole will be cut. The elements of the tool string are screwed together with right-hand threaded tool joints of standard API (American Petroleum Institute) design and dimension.

The wire cable that carries and rotates the drilling tool is called the drill line. It is a ⅝- to 1-in (16- to 25-mm) left-hand lay cable that twists the tool joint on each upstroke to prevent it from unscrewing. The drill line is reeved over a crown sheave at the top of the mast, down to the spudding sheave on the walking beam, to the heel sheave, and then to the working-line side of the bull reel (Figure 10.3). Bull reels are generally set up with a separator on the drum to provide a working-line side and a

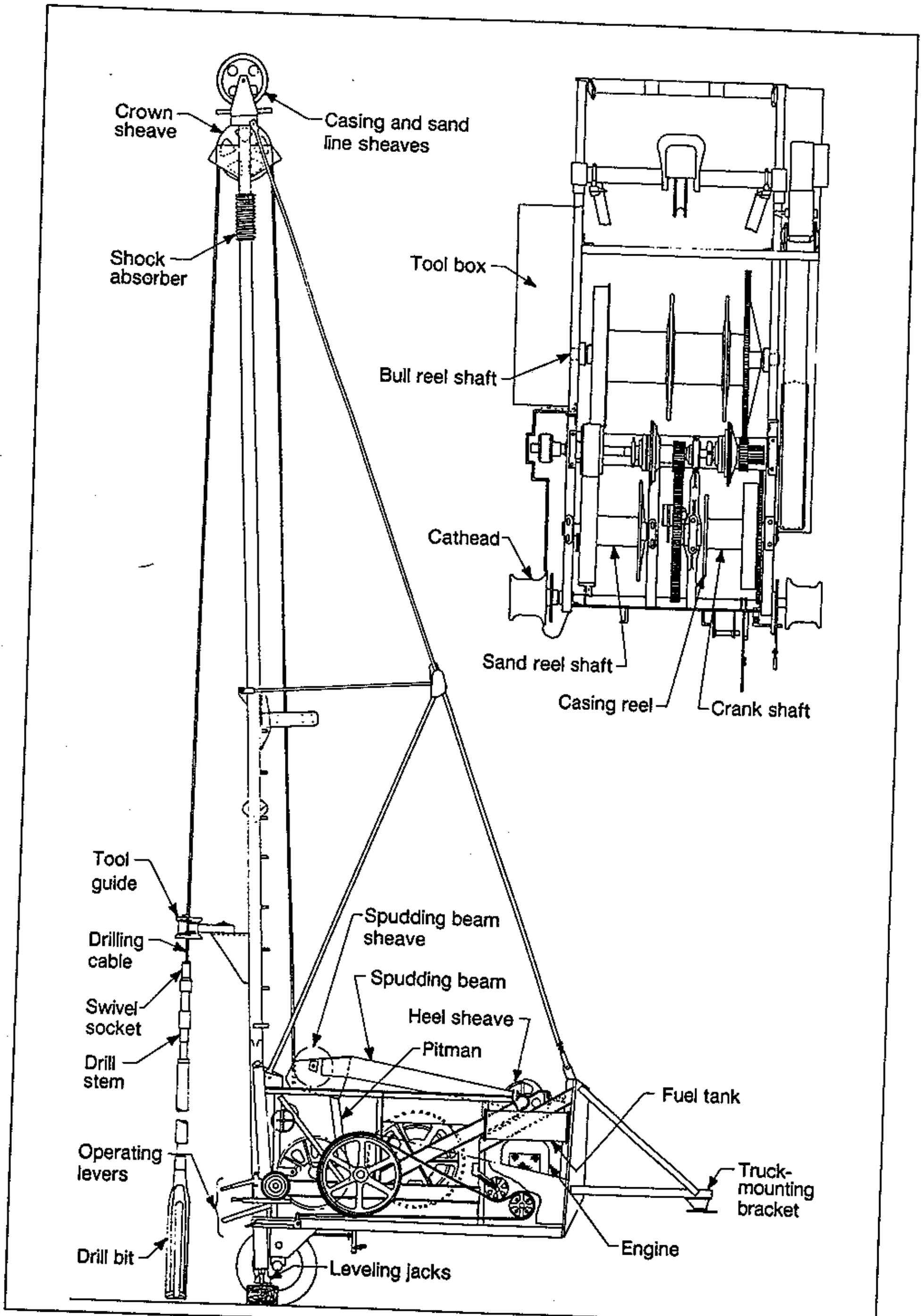


Figure 10.3. Engineering drawing of a Bucyrus-Erie Model 22-W shows how the drill line is reeved in a typical cable tool rig. The spudding action is imparted to the drill line by the vertical motion of the spudding beam. The shock absorber mounted beneath the crown block helps control the impact of the bit on the rock. *(Bucyrus-Erie Company)*

storage-line side.

Bailers used to remove the mud or rock slurry consist of a pipe with a check valve at the bottom. The valve may be either a flat pattern or a ball-and-tongue pattern called a dart valve (Figure 10.4). A bail handle at the top of this tool attaches to a cable called the sand line. The sand line is threaded over a separate sheave at the top of the mast and down to the sand-line reel. The diameter of the sand line can vary according to the anticipated loads.

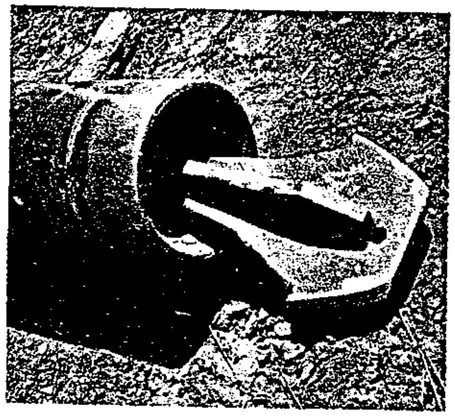


Figure 10.4. Dart valve bailers are used periodically to remove the slurry from the borehole. *(Bergerson-Caswell Company)*

Another type of bailer is called the sand pump or suction bailer. This bailer is fitted with a plunger so that an upward pull on the plunger tends to produce a vacuum that opens the valve and sucks sand or slurried cuttings into the tubing. The sand pump can have a bit bottom, but more often in water well drilling it has a flat bottom with a flap-type valve (Figure 10.5). Some sand pump bailers have a latch bottom for slurry release. Most sand pumps are either 10 or 20 ft (3 or 6.1 m) long.

The characteristic up and down drilling action of a cable-tool machine is imparted to the drill line and drilling tools by the walking beam. The walking beam pivots at one end while its outer end, which carries a sheave for the drill line, is moved up and down by a single or double pitman connected to a crank shaft. The vertical stroke of the walking beam, and thus the drill tools, can be varied by adjusting the position of the pitman pin on the bull gear and the pitman connection to the walking beam. The number of strokes per minute can be varied by changing the speed of the drive shaft. The bull gear is driven by a pinion mounted on a clutch. This clutch, the friction drive for the sand line (on smaller cable tool rigs only), and the drive pinion for the drill-line reel are all mounted on the same drive shaft assembly.

Figure 10.5. Sand pumps are another common type of bailer that are fitted with a flap-type bottom valve. As the sand pump is alternately lowered and raised, slurry is sucked into the pump barrel. Slurry is released at the surface into a chute that directs the slurry into a container if a sample is desired or onto the ground away from the rig. *(E. H. Renner & Sons, Inc.)*

Another drum, called a casing reel, is frequently added to the basic machine assembly. The casing reel is capable of exerting a powerful pull on a third cable, the casing line. This cable is used for handling pipe, tools, and pumps, or other heavy hoisting. It may be used to pull a string of casing when the cable is reeved with blocks to make two-, three-, or four-part lines. Reinforcement of the derrick by means of a "stiff leg" may be required to utilize the maximum pull that can be applied.

Another commonly used auxiliary hoisting device on a cable tool machine is called a cathead. Use of this drum requires that a heavy line of manila rope be carried on a separate sheave at the top of the derrick. This line may be used for handling light loads and alternately lifting and dropping tools such as a drive block or bumper which are used to drive or lift casing. Synthetic ropes made with nylon or dacron are considerably stronger than manila rope, but they are not resistant to abrasion or heat and therefore cannot be used with a cathead. Two or three loose turns of the free end of the rope are wrapped on the cathead. When the cathead is rotating, the driller pulls on the free end of the rope, causing the coils to tighten and grip the cathead. This raises the load at the other end of the rope. When the driller reduces the pulling pressure on the rope, friction between the rope and the revolving cathead is reduced and the load descends at a controlled rate. The cathead is a live drum; that is, there are no clutches to engage or disengage during use.

Every cable tool machine has certain interdependent limits on borehole depth and diameter. For example, if a hole is relatively small in diameter, it may be drilled to relatively great depth. In large-diameter holes, the weight of the drill string and cable may become so excessive that the machine cannot function, thereby limiting well depth at the initial diameter. Collapsing formations may further limit the effective depth for large-diameter casing, because considerable friction develops between the casing and borehole wall while the casing is being driven. In many cases, the casing size is progressively decreased as the hole is deepened, thereby reducing friction and also the weight of the drilling tools. Friction between the borehole wall and casing can be reduced by the addition of a drilling fluid slurry around the outside of the casing during driving. This small amount of slurry will also decrease the energy required for pulling back casing to expose screens set within the casing. In water well drilling, the depth capability for cable tool rigs ranges from 300 to 5,000 ft (91.5 to 1,520 m).

The drilling motion of the cable tool machine must be synchronized with the gravity fall of the tools for effective penetration. Several factors (thickness of the slurry in the borehole, whip in the cable, hole alignment, and rocks protruding in the borehole) may interfere with the free gravity fall, and the driller must adjust the motion and speed of the machine to the vertical movement of the tools. Effective drilling action is obtained when the engine speed is synchronized with the fall of the tools and the stretch of the cable, while paying out the correct amount of cable to maintain proper feed of the bit. The bit should strike the bottom of the hole at the extreme (elastic) limit of the cable and immediately snap upward so that a sharp blow is given to the earth material by the bit. This requires some resilience and elasticity in the cable and certain parts of the rig mechanism. An elastic snubber or shock absorber is usually installed in the mounting of the drill-line crown sheave to provide part of the resilience in the system. The shock absorber compresses as the walking beam completes its upstroke and starts its pull on the cable. Cable tension then reaches its maximum, because the tools are still moving downward. The shock absorber's rebound helps to lift the tools sharply after they strike bottom. The objective is to give the tools that peculiar whip at the end of the stroke which is essential to rapid drilling. At the surface, the cable will appear to be constantly in tension. When properly done, this technique conserves power and increases drilling speed. The shock absorber also dampens the vibration that occurs when the drill bit strikes the bottom of the hole; it protects the derrick and the rest of the machine from severe shock stresses.

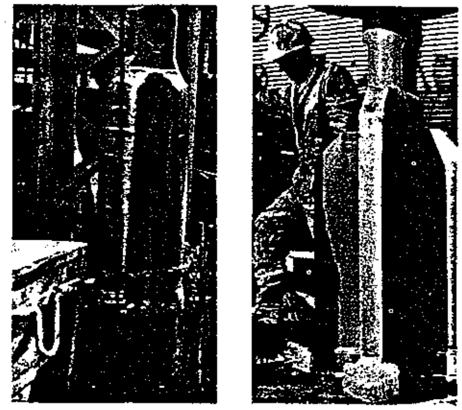


Figure 10.6. Several types of bits are used in cable tool drilling depending on the nature of the geologic materials. Standard and star types are the most common bit configurations. *(Keys Well Drilling; E. H. Renner & Sons, Inc.)*

Drilling Consolidated Formations

Most boreholes completed in consolidated formations by the cable tool method are drilled "open hole," that is, no casing is used during part or all of the drilling operation. When drilling in consolidated rock, the cable tool bit is essentially a crusher. Its performance depends on the energy it can deliver to the bottom of the hole when the proper drilling motion is maintained. Factors that affect drilling rate or efficiency are: resistance of the rock; dip of the rock structure; weight of drill tools; length of stroke; strokes per minute; diameter, sharpness, and shape of bit; clearance between the tool string and the hole; and density and depth of the accumulated slurry. Each driller relies on the drilling machine manufacturer for guidance on these factors, and adds to this basic knowledge from personal experience. Two common bits used in cable tool drilling are shown in Figure 10.6. A partial listing of bit types and dimensions is given in Appendix 10.A.

Drilling Unconsolidated Formations

Drilling in unconsolidated formations differs from hard-rock drilling in two ways. First, pipe or casing must follow the drill bit closely as the well is deepened to prevent caving and keep the borehole open. Usually the casing has to be driven by an operation similar to pile driving. Second, the drilling action of the bit is largely a loosening and mixing process. Actual crushing is of little importance except when a large stone or boulder is encountered.

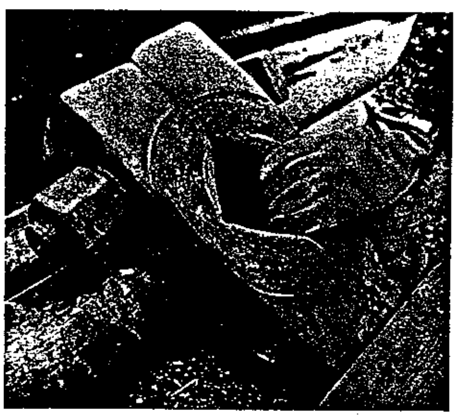


Figure 10.7. To drive casing, drive clamps are mounted on the upper wrench square of the drilling stem. The tools provide driving weight. *(NWWA)*

A drive shoe made of hardened and tempered steel is attached to the lower end of the casing string. This shoe prevents damage to the bottom of the casing when it is being driven. For the pipe-driving operation, a drive head is fitted to the top of the casing to serve as an anvil and protect the top of the casing. Drive clamps — constructed of heavy steel forgings made in halves — are attached to the square near the top of the drill stem. Drive clamps act as the hammer face, and the tools provide the weight for driving the pipe (Figure 10.7). The tools are lifted and dropped by the spudding action of the drilling machine.

The usual procedure is to drive the casing initially for 3 to 10 ft (0.9 to 3 m). Material in the casing is then mixed with water by the drill bit to form a slurry. Most of the slurry is bailed out and the pipe is driven again. Each time that the casing is cleaned out, more water must be added if none is encountered in the formation being drilled. In some cases, the hole is drilled 3 to 6 ft (0.9 to 1.8 m) below the casing; the casing is then driven down to the undisturbed material and drilling is resumed. Driving, drilling, and bailing operations are repeated until the casing is at the desired depth.

When friction on the outside of the casing increases to the point where the casing cannot be driven any deeper or further driving might damage it, a string of smaller casing is inserted inside the first one. Drilling is then continued inside the smaller casing. The diameter of the well is thus reduced; two or three reductions may be required in certain cases before reaching the desired depth. If friction problems are anticipated, casing in the upper part of the borehole should be one or two sizes larger than the diameter specified for completion of the well.

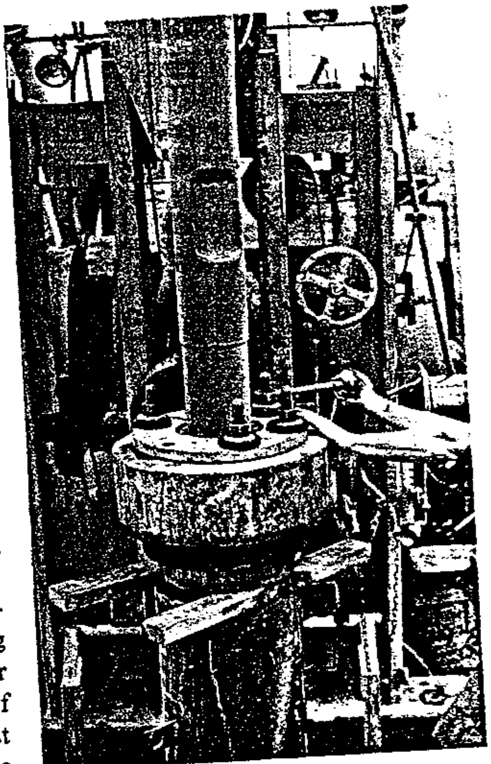


Figure 10.8. An alternative type of drive clamp (sometimes called a drive block) is shown being attached to the drill string.

When penetrating most unconsolidated formations, driving the casing occupies as much time as the actual drilling and bailing. The physical nature of clay, silt, sand, gravel, and marl profoundly affects the rate at which casing can be driven. The best driving weight and setting of the spudding motion is determined from experience in a given locality.

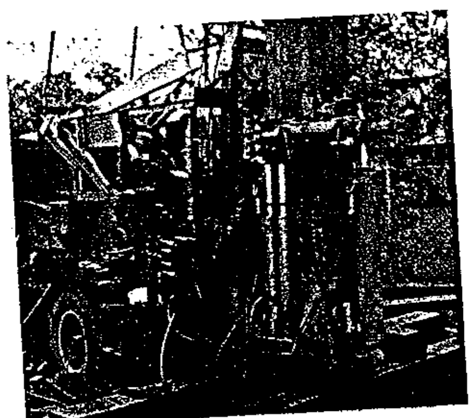


Figure 10.9. Hydraulic jacks can be used to pull the casing into the ground while drilling and bailing proceed. *(A. M. Bisley and Company)*

Sometimes a drive block is used in place of drive clamps on the drilling tools for driving casing. A drive block assembly, similar to that shown in Figure 10.8, is set on top of the casing each time the casing is driven. The block is lifted and dropped by using the cathead. The cathead and block can also be used to bump back the casing.

In some cable tool operations, the casing is not driven at all, but is pushed into the ground by hydraulic jacks as drilling and bailing proceeds (Figure 10.9). Casing can also be pulled back by using the jacks. Several advantages of this method are immediately apparent. Drilling proceeds rapidly because it is not necessary to stop the drilling and bailing to drive pipe. Because downward pressure is maintained constantly on the casing during drilling and bailing, caving and overexcavation are minimized. Perhaps most important, the jarring action of ordinary driving procedures, which compacts sand and gravel formations near the casing and causes excessive friction, is avoided. Sixteen-inch (406-mm) casing has been hydraulically jacked to depths of 1,000 ft (305 m) in unconsolidated formations, and subsequently pulled back 150 ft (45.7 m) to expose the screen. In this case, the jacks provided more than 500,000 lbs (227,000 kg) of lifting force.

When drilling in shallow sands, the casing may follow the bit down without being driven. In these areas, the casing may have to be held to prevent it from sinking too rapidly and to maintain plumbness. Also, these formations may be drilled more rapidly by using the sand pump bailer (suction bailer) to remove the sand without a bit. In Argentina, near Buenos Aires, temporary or surface casing has been installed to depths of 200 ft (61 m) using this method.

Another drilling technique, called the open-hole or reverse cable tool method, has been used for many years in Japan and has been used recently in the Western United States. With the borehole full of water or drilling fluid, heavy sand pumps or bailers are operated inside the casing to cut the borehole. Holes to 24 inches (610 mm) in diameter with cobbles to 12 in (305 mm) can be drilled in this manner. Large-diameter irrigation wells have been drilled to 100 ft (30.5 m) and screened within one day using this method. In isolated cases, the hole can be drilled open-hole even in completely unconsolidated formations, because the hydrostatic water pressure prevents caving of the borehole walls.

The cable tool method has survived for thousands of years because it is reliable for a wide variety of geologic conditions. It may be the best, and in some cases the only, method to use in coarse glacial till, boulder deposits, or rock strata that are highly disturbed, broken, fissured, or cavernous. In situations where the aquifers are thin and yields are low, the cable tool operation permits identification of zones that might be overlooked in other drilling methods. The cable tool method offers the following advantages:

1. Rigs are relatively inexpensive.
2. Rigs are simple in design and require little sophisticated maintenance.
3. Machines have low energy requirements.
4. Borehole is stablized during the entire drilling operation.
5. Recovery of reliable samples is possible from every depth unless heaving conditions occur.
6. Wells can be drilled in areas where little make-up water exists.
7. Wells can be constructed with little chance of contamination.
8. The driller maintains intimate contact with the drilling process and the materials encountered by keeping a hand on the drilling cable.
9. Generally, only one person is needed to operate the drilling rig, although a helper is usually available to assist.

10. Because of size, machines can be operated in more rugged, inaccessible terrain or in other areas where space is limited.
11. Rigs can be operated in all temperature regimes.
12. Wells can be drilled in formations where lost circulation is a problem.
13. Wells can be bailed at any time to determine the approximate yield at that depth.

Some disadvantages of the cable tool method include the following:

1. Penetration rates are relatively slow.
2. Casing costs are usually higher because heavier wall or larger diameter casing may be required.
3. It may be difficult to pull back long strings of casing in some geologic conditions, unless special equipment is available.

Other drilling techniques have been devised because of some inherent disadvantages of the cable tool method. Because the method is often slow, each cable tool driller can complete only a limited number of holes per year despite high operating efficiency. In times of high customer demand, the driller may not be able to take on much new business without adding new machines, an expense the long-term economics of the business may not allow. In addition, drillers experienced with cable tool rigs may not be available.

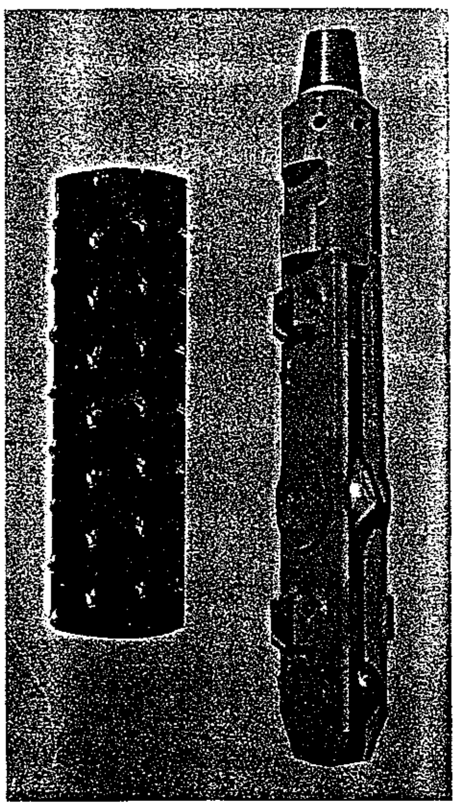


Figure 10.10. Casing perforators offer a crude method to gain access to the aquifer when well screens cannot be used. This perforator is activated by compressed air. *(Driltech, Inc.)*

CALIFORNIA STOVEPIPE METHOD

The California stovepipe method of drilling applies the same principles as the usual cable tool method, but differs in three ways: a heavy bailer called a mud scow is used as both drill bit and bailer, laminated steel casing in short lengths is used in place of standard steel pipe, and hydraulic jacks are used to force the casing downward as opposed to driving the casing by impact of the tools.

When the casing reaches the desired depth, a casing perforator is used to puncture holes in the pipe opposite the water-bearing formation (Figure 10.10). The size of the openings produced by the perforator is relatively uncontrolled and wells completed this way often pump large quantities of sand. The telescope method of installing well screens (described in Chapter 14) cannot be utilized because the spot-welded casing joints are too weak to withstand the pull-back forces required to expose the well screen. If line pipe is used for casing, however, well screens that will control sand may be installed by the pull-back method. The hydraulic jacks that pull down the casing in the stovepipe method can then be reversed to pull back the casing.

DIRECT ROTARY DRILLING

The direct rotary drilling method was developed to increase drilling speeds and to reach greater depths in most formations (Figure 10.11). The borehole is drilled by rotating a bit, and cuttings are removed by continuous circulation of a drilling fluid as the bit penetrates the formation. The bit is attached to the lower end of a string

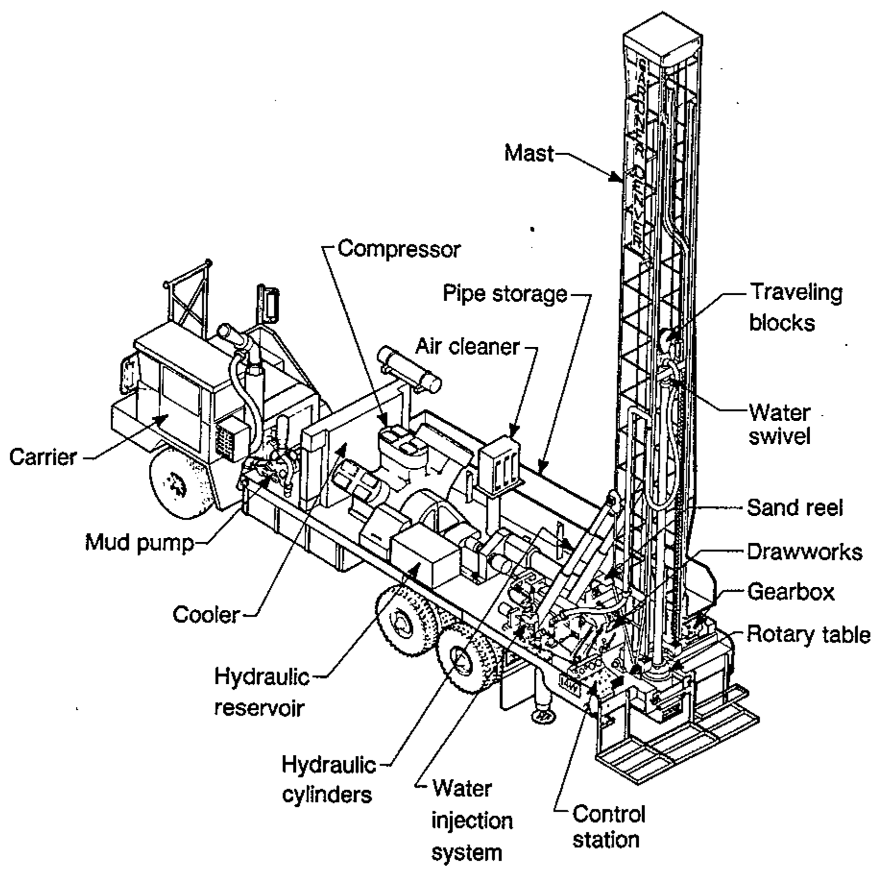


Figure 10.11. Schematic diagram of a direct rotary rig illustrates the important operational components of this truck-mounted drilling machine. This machine, operating with either an air-based or water-based drilling fluid, can drill more rapidly than a cable tool rig. *(Gardner-Denver Company)*

of drill pipe, which transmits the rotating action from the rig to the bit. In the direct rotary system, drilling fluid is pumped down through the drill pipe and out through the ports or jets in the bit; the fluid then flows upward in the annular space between the hole and drill pipe, carrying the cuttings in suspension to the surface. At the surface, the fluid is channeled into a settling pit or pits where most of the cuttings drop out. Clean fluid is then picked up by the pump at the far end of the pit or from the second pit and is recirculated down the hole (Figure 10.12). For relatively shallow wells, 150- to 500-gal (0.6- to 1.9-m^3) portable pits may be used; much larger portable pits, 10,000 to 12,000 gal (37.9 to 45.4 m^3), are used for deeper wells. Mud pits may also be excavated for temporary use during drilling and then backfilled after completion of the well (see Chapter 11 for various mud pit configurations).

Before 1920, the type of rotary drill used in water well drilling was commonly called a whirler. This equipment used the well casing itself as the drill pipe. The lower end of the pipe was fitted with a serrated cutting shoe with an outside diameter a little larger than the drill pipe couplings. The sawteeth of the shoe cut and loosened the materials as the pipe was rotated. Water was pumped under pressure through the pipe to lift the cuttings to the surface. Native clays and silt were depended upon to seal the borehole wall to maintain circulation; prepared drilling fluids were not used. The method was suitable for drilling only relatively small-diameter, shallow wells in unconsolidated formations that did not contain cobbles or boulders.

In the 1930's, shot-hole rotary drills, used for seismograph work in oil exploration, were successfully adapted for drilling small-diameter water wells. Shot-hole machines, however, could not drill the large-diameter holes necessary for water well work because the mud pump and drill pipe were generally too small to circulate enough drilling

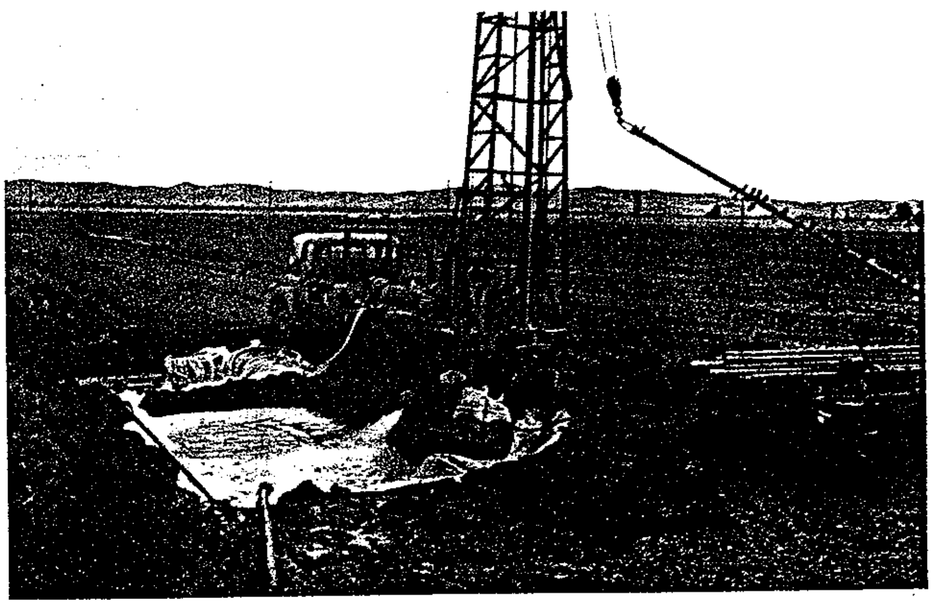


Figure 10.12. Drilling fluid from the borehole flows into the larger pit where the cuttings settle out. The fluid then flows into the second pit through a constricted opening. The mud pump on the rig withdraws drilling fluid from this pit to inject down the drill rods to the bit. This Italian driller has lined the drilling fluid pits with polyethylene film to reduce fluid loss into the ground. Note the homemade hole cleaner or scratcher the driller uses to keep the borehole open during drilling.

Figure 10.13. Drag bits are used in rotary drilling for fast penetration in unconsolidated or semiconsolidated sediments.

fluid to efficiently drill even an 8-in (203-mm) well. In time, truck-mounted portable rigs for drilling large-diameter water wells were developed from oil field exploration technology.

The components of the rotary drilling machine are designed to serve two functions simultaneously: operation of the bit and continuous circulation of the drilling fluid. Both are indispensable in cutting and maintaining the borehole. For economic and efficient operation, rotary drillers must acquire considerable knowledge concerning these factors and how they relate to various formation conditions.

In direct circulation rotary drilling for water wells, two general types of bits are used — the drag bit (fishtail and three- and six-way designs) and the roller cone bit, usually called a rock bit. Drag bits have short blades, each forged to a cutting edge and faced with durable metal (Figure 10.13). Short nozzles direct jets of drilling fluid down the faces of the blades to clean and cool them. Drag bits have a shearing action and cut rapidly in sands, clays, and some soft rock formations, but they do not work well in coarse gravel or hard-rock formations.

Roller (cone) bits exert a crushing and chipping action, making it possible to cut hard formations (Figure 10.14). The rollers, or cutters, are made with either hardened steel teeth or tungsten carbide inserts of varied shape, length, and spacing, designed so that each tooth applies pressure at a different point on the bottom of the hole as the cones rotate. The teeth of adjacent cones intermesh so that self-cleaning occurs. Long, widely spaced teeth are used in bits designed to cut soft clay formations, whereas shorter, closer spaced teeth are used for denser formations. Some roller bits are made with carbide buttons for particularly dense and abrasive formations such as dolomite, granite, chert, basalt, and quartzite.

The tricone bit, used as an all-purpose bit in every type of formation, has conically shaped rollers on spindles and bearings set at an angle to the axis of the bit. Another design has four rollers; two are set at an angle and two are normal to the vertical axis of the bit. The cutting surfaces of all roller bits are flushed by jets of drilling fluid directed from the inside (center) of the bit. The jets can be sized so as to maximize the cutting action of the bit. The jets are also effective in breaking up or washing away soft formation materials.

When hole enlargement becomes necessary, two other types of bits are used — reamers and underreamers (Figure 10.15). A reamer is used to straighten, clean, or enlarge a borehole. This tool sometimes consists of a 10- to 20-ft (3- to 6.1-m) section of drill pipe with specially hardened surfaces on vertical ribs. Other types of reamers are constructed of flanges welded on short sections of drill pipe and mounted between the bit and the stabilizer. In the underreaming process, the borehole diameter is enlarged beneath the permanent casing. Underreamers are particularly useful when a filter pack must be placed around a screen, but the cost of drilling the entire borehole at the larger diameter required for the filter pack would be prohibitive.

The bit is attached to the lower end of the drill pipe, which resembles a long tubular shaft. The drill string usually consists of four parts: the bit, one or more drill collars or stabilizers, one or more lengths of drill pipe, and, in table-drive machines, the kelly (Figure 10.16). Selection of the bottom-hole assembly will depend on the physical conditions of the geologic materials; these include dip of the formation, presence of faults or fractures, and drillability of the formation.

Each drill collar is a heavy-walled length of drill pipe; one or more drill collars are used to add weight to the lower part of the drill-stem assembly (Figure 10.17). The concentration of weight just above the bit helps to keep the hole straight, and provides sufficient weight for the bit to maintain the proper penetration rate. Drill collars fitted with stabilizer bars or rollers are even more effective in drilling straight boreholes. Table 10.1 presents representative data on recommended sizes of drill collars.

Stabilizers are an important component of the bottom-hole tools (Figure 10.18). To be effective in maintaining straight holes in soft formations, the stabilizer must have large wall contact. Increased contact can be achieved by using stabilizers with longer and wider blades, or by using longer stabilizers. The flow of drilling fluid upward around the stabilizer must not be restricted too much, however, because cuttings may pack around the stabilizer. This leads to sticking and a possible loss of circulation if back pressure builds up. Weakening of the formation structure can also result from the pressure increase. Accumulation of cuttings around the stabilizer may also cause local zones of erosion in the bore-

Figure 10.14. Roller or cone-type bits are preferred when drilling consolidated rock. The number of teeth on each roller cone depends on the drilling difficulty. As the rock becomes harder and more difficult to drill, the bit should have more teeth on each cone. For particularly dense or abrasive formations, carbide buttons are used instead of teeth on the roller cones. Roller cone bits are often constructed in configurations that will enlarge the borehole in stages as the bit penetrates the formation. For the bit shown, the primary bit is 17½ in (445 mm) and the reamer is 22 in (559 mm).

hole wall. In relatively hard formations, the stabilizer can perform satisfactorily with less wall contact.

Drill pipe is seamless tubing manufactured in joints that are usually 20 ft (6.1 m) long, although other lengths are available. Each joint is equipped with a tool-joint pin on one end and a tool-joint box on the other (Figure 10.19). Outside diameters of drill pipe used for direct rotary drilling generally range from 2⅜ to 6 in (60 to 152 mm). High circulation rates for drilling fluids in water well drilling require that the drill pipe diameter be adequate to hold friction loss in the pipe to an acceptable level so as to reduce the power required for the pump. For efficient operation, the outside diameter of the tool joint should be about two-thirds the borehole diameter; this ratio may be impractical, however, for holes larger than 10 in (254 mm).

In table-drive machines, the kelly constitutes the uppermost section of the drill string column. It passes through and engages in the opening in the rotary table, which is driven by hydraulic or mechanical means (Figure 10.20). The outer shape of the

Table 10.1. Ideal Size Range for Drill Collars

Hole size, in	Casing size to be run, in OD	Calculated ideal drill collar range, in		API drill collar sizes which fall in the ideal range, in
		Min.	Max.	
6⅛	4½	3.875	4.750	4⅛, 4¾
6¼	4½	3.750	4.875	4⅛, 4¾
6¾	4½	3.250	5.125	3½, 4⅛, 4¾, 5
7⅞	4½	2.125	6.125	3⅛, 3½, 4⅛, 4¾, 5, 6
	5½	4.225	6.125	4¾, 5, 6
8⅜	5½	3.725	6.500	4⅛, 4¾, 5, 6, 6¼, 6½
	6⅝	6.405	6.500	6½
8½	6⅝	6.280	6.750	6½, 6¾
	7	6.812*	6.750	6¾
8¾	6⅝	6.030	7.125	6¼, 6½, 6¾, 7
	7	6.562	7.125	6¾, 7
9½	7	6.812	7.625	6, 6¼, 6½, 7, 7¼
	7⅝	7.500	7.625	7⅝†
9⅞	7	5.437	8.000	6, 6¼, 6½, 6¾, 7, 7¼, 7¾, 8
	7⅝	7.125	8.000	7¼, 7¾, 8
10⅝	7⅝	6.375	8.500	6½, 6¾, 7, 7¼, 7¾, 8, 8¼
	8⅝	8.625*	8.500	8¼
11	8⅝	8.250	9.625	8¼, 9, 9½
12¼	9⅝	9.000	10.125	9, 9½, 9¾, 10
	10¾	11.250*	10.125	10
13¾	10¾	9.750	11.250	9¾, 10, 11
14¾	11¾	8.750	12.000	9, 9½, 9¾, 10, 11, 12†
17½	13⅜	11.250	13.375	12†
20	16	14.000	14.750	14†
24	18⅝	15.500	16.750	16†
26	20	16.000	19.500	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)

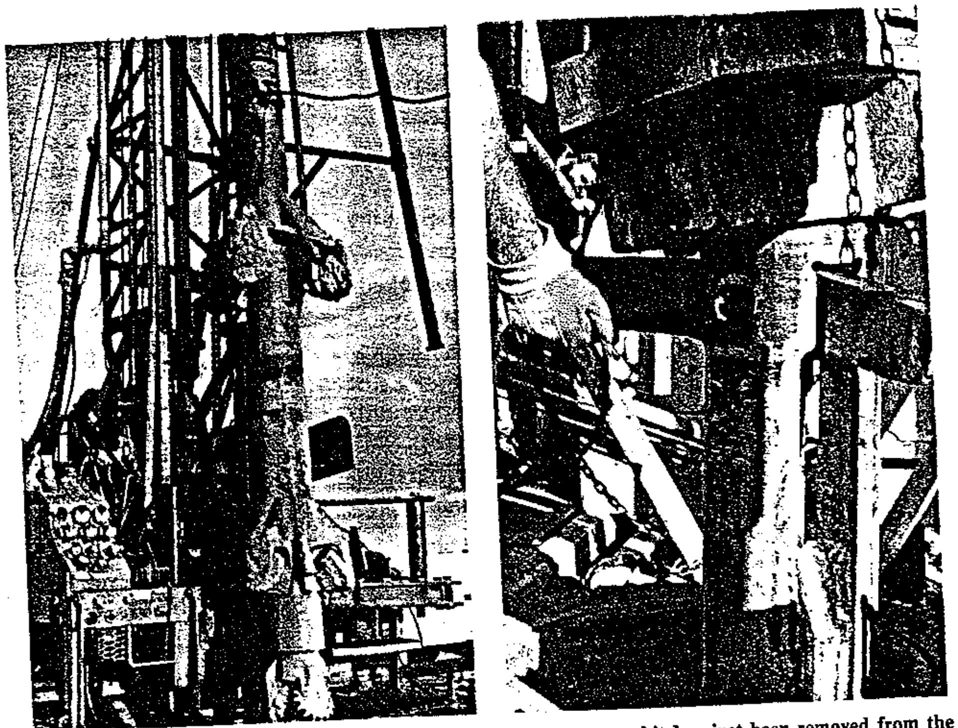


Figure 10.15. On the left, a three-tiered 48-in (1,220-mm) reamer bit has just been removed from the borehole. ***(Snider Drilling Ltd.)*** **For soft sediments, underreamers (right) are constructed of blades that extend outward from the bit.**

kelly may be square or hexagonal, or round with lengthwise grooves or flutes cut into the outside wall. Made about 3 ft (0.9 m) longer than one joint of drill pipe, the kelly has an inside bore that is usually smaller than that of the drill pipe because of the heavy wall thickness required. The square, hexagonal, or grooved circular section of the kelly works up and down through drive bushings in the rotary table. With the bushings properly in place around the kelly, the entire drill stem and bit are forced to turn with the rotary table. While rotating, the kelly slips down through the drive bushings to feed the bit downward as the hole is drilled. The lower end of the kelly is provided with a replaceable substitute joint (sub), called a "kelly saver," that connects to the drill pipe. The sub saves the tool joint on the kelly from excessive wear resulting from the screwing and unscrewing of innumerable sections of drill pipe. The upper end of the kelly connects to a swivel (by a left-hand threaded joint) that is suspended from a traveling block in the derrick (Figure 10.21). A heavy thrust bearing between the two parts of the swivel carries the entire weight of the drill string while allowing the drill pipe to rotate freely.

Some rotary drilling machines use a top-head drive to rotate the drill string (Figure 10.22). In this system, the rotational unit moves up and down the mast; energy is obtained from a hydraulic transmission unit powered by a motor-driven pump.

In both the rotary table and top-head drive mechanisms, the driller can determine the rotation speed depending on the resistance of the formation and the rate of penetration. For shallow boreholes of 200 to 400 ft (61 to 122 m), pull-down pressure may be applied to the bit. Down-hole pressures on the bit can be increased beyond

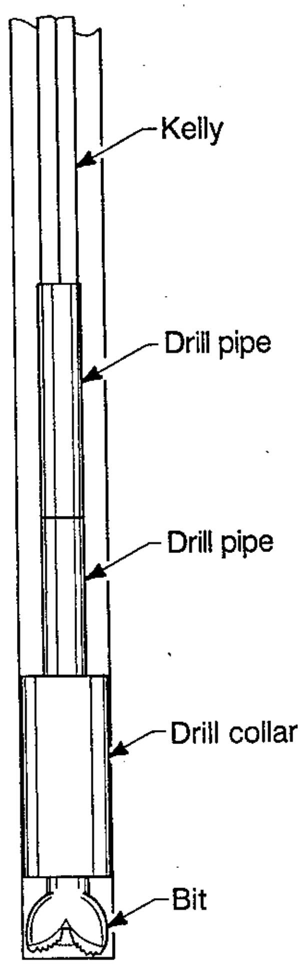


Figure 10.16. The drill string for a direct rotary rig consists of a bit, drill collar or stabilizer, drill pipe, and kelly for table drive units.

the weight of the drill string by exerting a pull-down force derived from the weight of the drilling rig. The chain assemblies (or cables) on the mast are used to transfer part of the weight of the drilling rig to the drill string. Caution should be used to avoid excessive pull-down pressure (weight) because hole deflection (crooked holes) may result. To avoid crooked holes, many drillers will use drill collars that concentrate additional weight on the bit rather than exert pull-down pressure. Rotation speed is adjusted to the pull-down or existing pressures on the bit. In general, the higher the pressure on the bit, the slower the rotation should be. In most deep direct rotary boreholes, the driller must hold back (suspend) part of the drill string weight from the swivel so that the weight on the bit does not become excessive. In general, the driller may start holding back when the weight of the drill string exceeds 10,000 lb (4,540 kg), although the exact figure depends on the bit being used. Bit manufacturers usually indicate the optimum pressure that an individual bit should exert against the formation for maximum cutting rates.

Adding drill rods (pipe) to the drill string or removing rods to change bits or take split-spoon or core samples is a major part of every rotary drilling operation. "Tripping in" and "tripping out" are the terms used to describe the process of running the bit into or pulling the bit from the hole. Most newer drilling rigs have been designed to make this process as fast and automated as possible. With some new machines, it is possible to pull back a 20-ft (6.1-m) rod and remove it from the drill string in approximately 30 seconds. In general, top-head drive machines, especially those equipped with carousels (drill rod storage racks mounted on the mast), offer an advantage in rod handling speed, although recent modifications in table-drive machines have enabled this type of rig to match the speed of the top-head drive rotaries.

When a rod is to be added, the swivel is just above the rotary table (in a table-drive machine). Usually the driller will circulate the drilling fluid for a few minutes to make sure that most of the cuttings are out of the hole to prevent the bit and drill string from sand-locking when the circulation is stopped to add a drill rod. The kelly is raised until the joint between the kelly sub and the uppermost drill rod is just above the drive table. Slips are placed in the table to hold the drill string (Figure 10.23). The kelly is then disconnected and placed out of the way momentarily. A sand line (cable) is joined to another rod section using a quick-release elevator (clamp). The rod is hoisted into place above the rod held in the table and the two are threaded together, usually with the aid of automatic pipe clamps. The slips are removed and the string is lowered by the sand line until the top (tool-joint box) of the just-added drill rod is just above the table. The slips are reinserted, the elevator is removed, and the kelly is rethreaded to the drill string. After lowering the kelly into the drive table, drilling can continue.

In top-head drive machines, no kelly is required and therefore the bottom sub of the hydraulic drive motor is connected directly to the drill rod. Additional rods can be taken directly from a carousel by the top-head drive unit. If the machine is equipped with side storage racks, a sand line must be used to raise the drill rod into position.

Internal pressure created by the drilling fluid can cause a momentary but forceful surge of drilling fluid out of the drill string at the point where the kelly is disconnected from the upper drill rod. Drillers usually break this joint slowly to allow the pressure to dissipate so that drilling fluid is not expelled violently. Occasionally during the addition of a drill rod, drilling fluid may continue to overflow from the top of the rods. Confining pressures within permeable material in the borehole may be causing this flow, but it is more likely that clay "collars" packed around the drill rods are falling deeper into the borehole, thereby pushing drilling fluid back up the center of the rods.

Direct rotary drilling, the most common method, offers the following advantages:

1. Penetration rates are relatively high in all types of materials.
2. Minimal casing is required during the drilling operation.

Figure 10.17. Heavy collars added to the drill string above the bit help keep the borehole straight.

3. Rig mobilization and demobilization are rapid.
4. Well screens can be set easily as part of the casing installation.

Major disadvantages include the following:

1. Drilling rigs are costly.
2. Drilling rigs require a high level of maintenance.
3. Mobility of the rigs may be limited depending on the slope and condition (wetness) of the land surface.
4. Most rigs must be handled by a crew of at least two persons.
5. Collection of accurate samples requires special procedures.
6. Use of drilling fluids may cause plugging of certain formations.
7. Rigs cannot be operated economically in extremely cold temperatures.
8. Drilling fluid management requires additional knowledge and experience.

Figure 10.18. Stabilizers mounted just above the bit in the drill string are important in maintaining a straight borehole. Flat-bar steel plates welded to the stabilizer help maintain borehole diameter and provide channels for the passage of drilling fluid. *(Hydro Drillers)*

DRILLING FLUIDS

Drilling fluid control is essential to efficient rotary drilling. There must be proper coordination of the hole size, drill pipe size, bit type, pump capabilities, and drilling fluid characteristics based on the geologic conditions at the site if drilling is to proceed efficiently. Drilling fluids include air, clean water, and scientifically prepared mixtures of special-purpose materials*. The essential functions of a drilling fluid are to:

1. Lift the cuttings from the bottom of the hole and carry them to a settling pit.
2. Support and stabilize the borehole wall to prevent caving.
3. Seal the borehole wall to reduce fluid loss.
4. Cool and clean the drill bit.
5. Allow cuttings to drop out in the settling pit.
6. Lubricate the bit, bearings, mud pump, and drill pipe.

The viscosity (the degree to which a fluid resists flow under an applied force) of the drilling fluid and the uphole velocity required to remove cuttings will depend on a number of factors that are discussed in Chapter 11. An uphole velocity

*Because the majority of rotary drilled holes are completed using a water-based drilling fluid, air will not be discussed here, but is thoroughly covered in Chapter 11.

of 100 to 150 ft/min (30.5 to 45.7 m/min) is used by many drillers (Table 10.2). The ability of the fluid to lift cuttings increases rapidly as viscosity and velocity are increased. After cuttings are brought to the surface, however, it is essential that they drop out as the fluid flows through the settling pit. The desired results are obtained by selecting the appropriate drilling fluid additive, properly designing the mud pits, controlling the viscosity and weight of the drilling fluid, and adjusting the pump speed.

When circulation of the drilling fluid is interrupted for some reason, to add drill pipe for example, the cuttings being carried by the mud column tend to drop back toward the bottom of the hole. Cuttings can bridge on tool joints and build up on top of the bit if they settle rapidly. Excessive pump pressures may then be required to move these cuttings and resume circulation; if the cuttings cannot be removed, the drill pipe and bit become stuck in the hole (sanded in). Many drilling fluids develop gel strength, that is, the ability to suspend cuttings when flow slows or stops. It may be advisable before adding drill pipe to circulate the fluid for a few minutes without applying bit pressure to clear the hole of most cuttings. This is particularly important for deep holes.

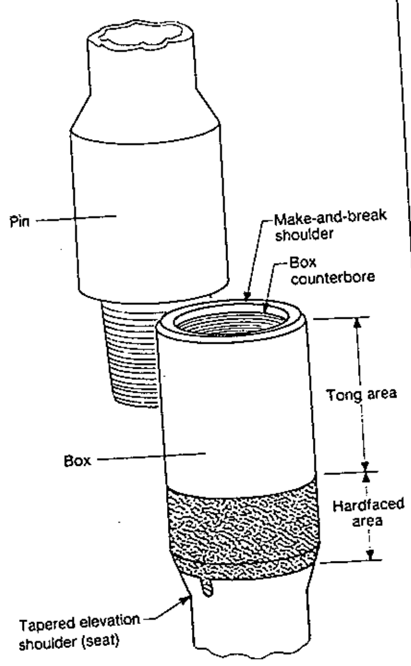


Figure 10.19. Drill pipe is heavy-walled seamless tubing with tool-joint pin and box-end fittings.

The drilling fluid prevents caving of the borehole because it exerts pressure against the wall. As long as the hydrostatic pressure of the fluid exceeds the earth pressures and any confining pressure in the aquifer, the hole will remain open. The pressure at any depth is equal to the weight of the drilling fluid column above that point.

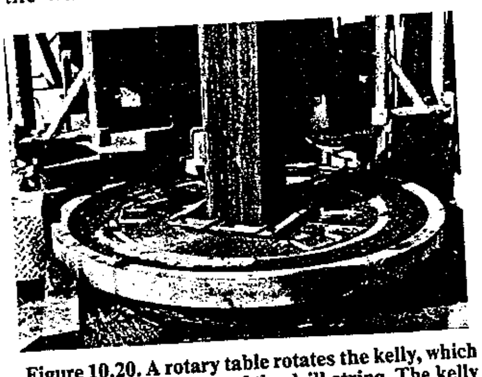


Figure 10.20. A rotary table rotates the kelly, which is connected to the top of the drill string. The kelly can be square, hexagonal, or round with flutes cut into the outer wall. *(Huron Drilling)*

The weight of the drilling fluid required for a given situation cannot be predicted precisely without test borings. Most water well drillers rely on past experience in making up drilling fluid. If caving occurs while drilling, weighting material may be added to increase the drilling fluid weight or special additives may be added to isolate any swelling clays. To prevent excessive intrusion of fine drilling fluid par-

Table 10.2. Pump Output and Annular Velocities for Different Sizes of Holes

Size of drilling bit		Pump output normally used		Annular velocity of drilling fluid*	
in	mm	gal/min	ℓ/min	ft/min	m/min
6	152	150 to 200	568 to 757	169 to 223	52 to 68
6¾	171	200 to 250	757 to 946	173 to 220	53 to 67
7⅞	200	300 to 400	1,140 to 1,510	169 to 226	52 to 69
8½	216	300 to 400	1,140 to 1,510	164 to 220	50 to 67
9⅞	251	400 to 500	1,510 to 1,890	130 to 170	40 to 52
12¼	311	600 to 700	2,270 to 2,650	115 to 130	35 to 40
15	381	750 to 900	2,840 to 3,410	92 to 115	28 to 35
17½	445	800 to 1,000	3,030 to 3,790	69 to 92	21 to 28

*Annular velocity of drilling fluid may be slightly different depending on the size of the drill pipe.
(Ingersoll-Rand)

ticles into the formation, the drilling fluid weight should be just heavy enough to maintain hole stability. Numerous additives are available for imparting specific properties to drilling fluids. Chapter 11 discusses the various kinds of drilling fluids, with particular reference to their advantages and disadvantages in certain geologic formations.

As drilling progresses, a film of small particles builds up on the wall of the borehole. This flexible lining, which may consist of clay, silt, or colloids, forms when the pressure of the drilling fluid forces small volumes of water into the formation, leaving the fine, suspended material on the borehole wall. In time, the lining completely covers the wall and holds loose particles or crumbly materials in place. It protects the wall from being eroded by the upward-flowing stream of drilling fluid, and acts to seal the wall and reduce the loss of fluids into surrounding permeable formations. Although the flexible lining effectively controls fluid losses in the borehole, it cannot prevent the hole from collapsing if the hydrostatic pressure created by the drilling fluid is not

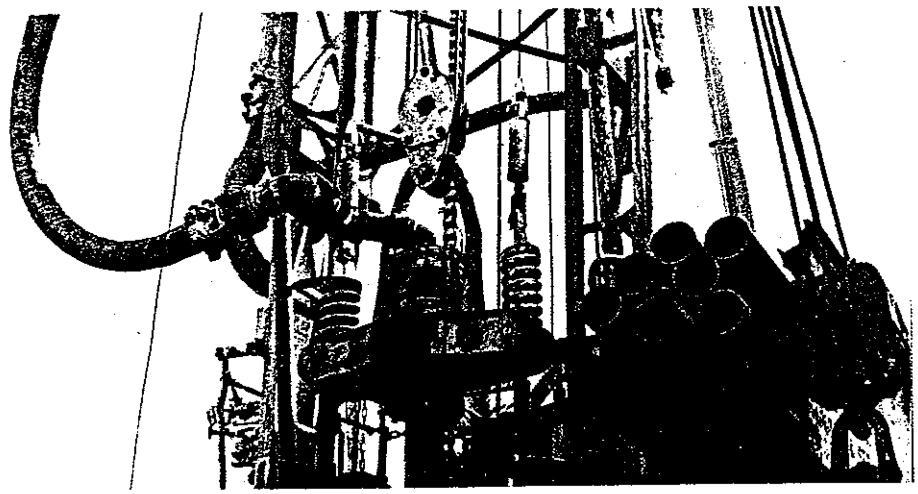


Figure 10.21. The upper end of the kelly connects to a swivel suspended from a traveling block in the mast. *(E. H. Renner & Sons, Inc.)*

greater than the pressure exerted by the water in the formation.

The drill bit is cooled and cleaned by the jets of fluid that are directed at relatively high velocity over the cutting faces and body section of the bit. A properly prepared drilling fluid is an excellent lubricant, but the viscosity must be controlled so that the concentration of cuttings does not become excessive.

In direct rotary drilling, water and special viscosity-building additives are usually mixed to produce a drilling fluid. Drilling fluids can be mixed in either a portable pit carried from site to site (Figure 10.24) or in a pit excavated next to the drilling rig. Cuttings collecting on the bottom of the pit must be removed periodically to maintain the efficiency of the pit (Figure 10.25). When enough drilling fluid has been mixed and sufficient time has elapsed to insure complete hydration, it is circulated into the hole using a mud pump. The size of the mud pump must be chosen carefully so that the correct uphole velocity can be maintained. Centrifugal and piston mud pumps are discussed in Chapter 17.

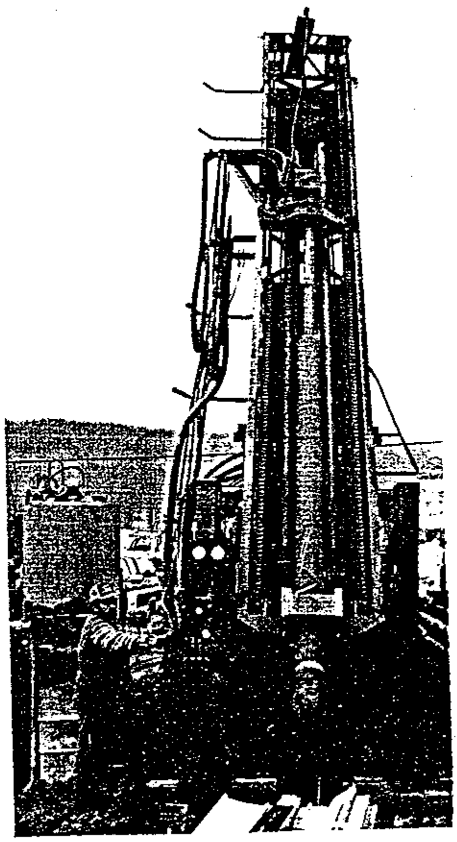


Figure 10.22. On some direct rotary rigs, a top-head drive is used to rotate the drill string. The amount of torque delivered to the bit by a top-head drive is usually somewhat less than that produced by a table drive, but the rod-handling speed is exceptionally good. *(Olson Brothers Well Drilling)*

In clay-rich formations, the driller may begin drilling with clean water which quickly mixes with the natural clays in the borehole to form a thin clay slurry. This drilling fluid is used in the upper portion of the borehole, commonly the first 100 to 300 ft (30.5 to 91.5 m). Thereafter, most drillers will mix fluids with additives of either high-quality clays or natural or synthetic polymers so that proper viscosity and hydrostatic pressure can be maintained in the borehole.

REVERSE CIRCULATION ROTARY DRILLING

In direct rotary drilling, the viscosity and uphole velocity of the drilling fluid are the controlling factors in removing cuttings effectively. Unless cuttings can be removed, drilling cannot continue. Because of limitations in pump capacity and therefore effective cuttings removal, most direct rotary machines used to drill water wells are limited to boreholes with a maximum diameter of 22 to 24 in (559 to 610 mm). This size may not be sufficient for high-capacity wells, especially those that are to be filter packed. Also, as hole diameters increase past 24 in, the rate of penetration by direct rotary machines becomes less satisfactory. To overcome the limitation on hole diameter and drilling rate, reverse circulation machines were designed; originally they were used only in unconsolidated formations. Recently, reverse circulation drilling has been used in soft consolidated rocks such as sandstone and even in hard rocks using both water and air as the drilling fluid.

The design of a reverse circulation rig is essentially the same as that of the direct rotary rig except most pieces of equipment are larger. For example, larger compressors and mud pumps are required because of the larger diameter boreholes. Only table drives are used in reverse circulation drilling because of the large borehole diameter and the torque required to turn the bit. The components of many reverse rotary rigs are mounted on long-bed trailers rather than being mounted on trucks.

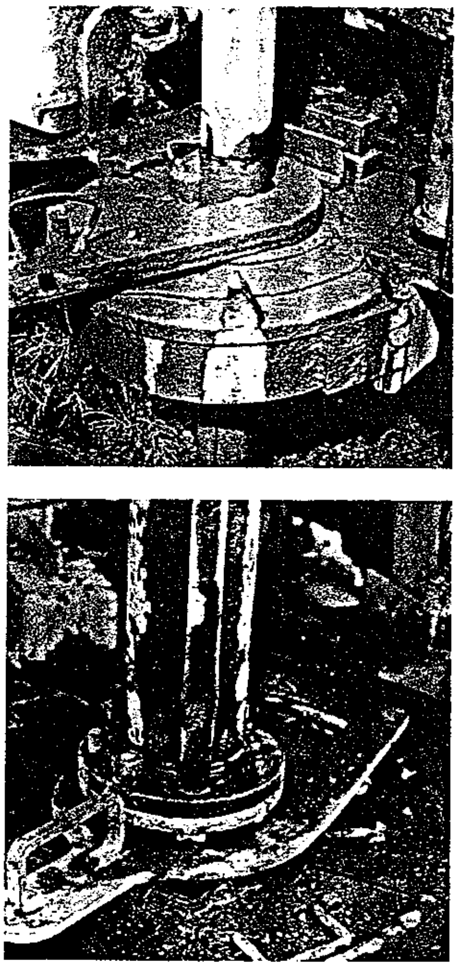


Figure 10.23. Various types of slips are inserted into the kelly just above the drive table to hold the drill string when adding or removing a drill pipe (joint). In the upper photo, the drill rod is being held by a plain-end wrench. The wrench is also used to set up or break the connections between rods when tripping in or out. The drill pipe in the lower photo has flanged connections and an external air line mounted on the outside of the drill pipe. This type of drill pipe is generally used in reverse rotary drilling. *(Huron Drilling)*

In reverse circulation rotary drilling, flow of the drilling fluid is reversed when compared with the direct rotary method. The suction end of the centrifugal pump, rather than the discharge end, is connected through the swivel to the kelly and drill pipe. The drilling fluid and its load of cuttings move upward inside the drill pipe and are discharged by the pump into the settling pit (Figure 10.26). Centrifugal pumps with large passageways are often used to pump the drilling fluid because they can handle cuttings without excessive wear on the pump. In operation, however, most of the cuttings do not actually enter the pump but bypass it by means of an eductor system. An uphole velocity of at least 150 ft/min (45.7 m/min) is recommended. The fluid returns to the borehole by gravity flow. It moves down the annular space between the drill pipe and borehole wall to the bottom of the hole, picks up the cuttings, and reenters the drill pipe through ports in the drill bit.

In the reverse circulation rotary method, the drilling fluid can best be described as muddy water rather than drilling fluid; drilling fluid additives are seldom mixed with the water to make a viscous fluid. Suspended clay and silt that recirculate with the fluid are mostly fine materials picked up from the formations as drilling proceeds. Occasionally, low concentrations of a polymeric drilling fluid additive are used to reduce friction, swelling of water-sensitive clays, and water loss.

To prevent caving of the hole, the fluid level must be kept at ground level at all times, even when drilling is suspended temporarily, to prevent a loss of hydrostatic pressure in the borehole. The hydrostatic pressure of the water column plus the velocity head (inertia of the water moving downward) outside the drill pipe support the borehole wall. Erosion of the wall is usually not a problem because velocity in the annular space is low.

Water infiltrates the permeable formations surrounding the borehole. Some of the fine particles suspended in the fluid are filtered out on the wall of the hole, resulting in a thin mud deposit that partially clogs the pores and reduces the water loss. A considerable quantity of make-up water is usually required and must be immediately available at all times when drilling in permeable sand and gravel. Under these conditions, water loss can increase suddenly, and if this causes the fluid level in the hole to drop significantly below the ground surface, caving usually results. Water loss can be reduced by mixing clay additives with the fluid, but this is usually avoided unless absolutely necessary. As little as 20 gpm (109 m^3/day) of make-up water is enough in some cases, whereas as much as 1,000 gpm (5,450 m^3/day) may be needed when drilling through a highly permeable aquifer such as coarse, dry gravel.

The settling pit and water supply pit should hold at least three times the volume of the material to be removed during the drilling operation (Figure 10.27). The circulation rate for the water used in drilling is commonly 500 gpm (2,730 m^3/day) or more.

Many reverse rotary drilling rigs are equipped with air compressors to aid in circulating the drilling fluid. When drilling has reached a depth sufficient for proper operation of an air lift within the drill pipe, the mud pump is bypassed. Compressed air is introduced through a 1¼- or 1½-in (32- or 38-mm) plastic or metal air line

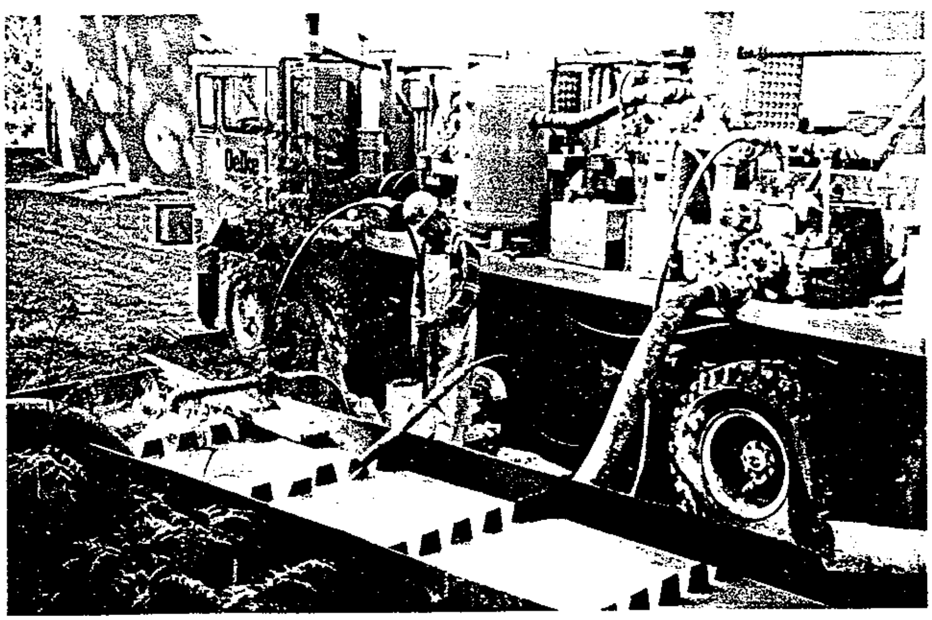


Figure 10.24. A portable mud pit can be transported from site to site. *(Oelke Drilling Company)*

suspended inside the drill pipe, or through an external air line attached to the outside of the drill pipe (Figure 10.28). The external air line system may consist of two pipes welded on opposite sides of the drill pipe. The air is injected by means of a manifold into the drill string at the proper depth. In these processes, water is lifted to the surface from the borehole. Air-lift pumping procedures are discussed in more detail in Chapter 15.

Figure 10.25. Cuttings that have settled to the bottom of a small portable pit are removed periodically to maintain the efficiency of the pit.

Any cobbles or boulders larger than the drill pipe or the openings in the drill bit cannot be brought out in the drilling operation, because most reverse rotary bits cannot break cobbles. Thus, further penetration is impossible when a few large cobbles or boulders collect in the bottom of the hole. One solution is to drive the boulders into the borehole wall as they are encountered by a Zublin-type bit (Figure 10.29). If the boulders are relatively stable

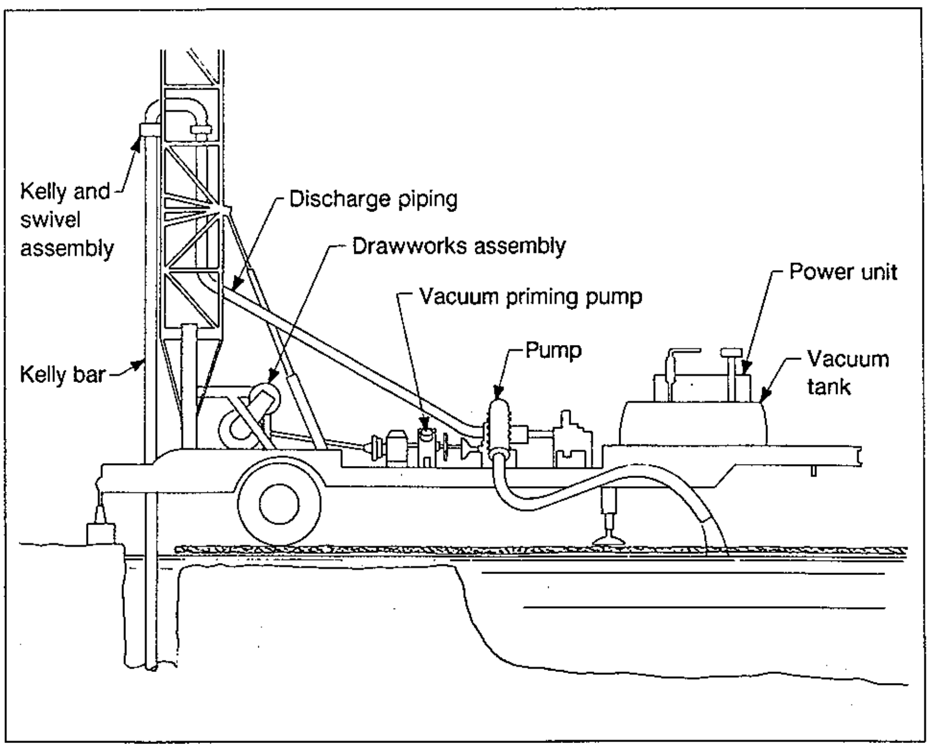


Figure 10.26. In a reverse rotary circulation system, the drilling fluid flows from the mud pit down the borehole outside the drill rods, then passes upward through the bit into the drill rods after entraining the cuttings. After flowing through the swivel and mud pump, it passes into the mud pit where the cuttings settle out.

in the hole, a roller cone bit can be used to grind them into small fragments; cement may be used to stabilize the boulders prior to grinding. Orange-peel buckets or boulder catchers are often used to fish out large boulders or cobbles (Figure 10.30). Common types of drag and roller bits for reverse drilling are shown in Figure 10.31. Note the coarse tooth structure on the roller reamer bit that is suitable for semiconsolidated formations.

Most new drill pipe used in reverse circulation rotary drilling is threaded and coupled pipe that can be as much as 8 inches (203 mm) in diameter and operated at depths of 2,000 ft (610 m) or more. Formerly, most drill pipe used for reverse circulation drilling had flanged joints that were joined by four to eight bolts per flange.

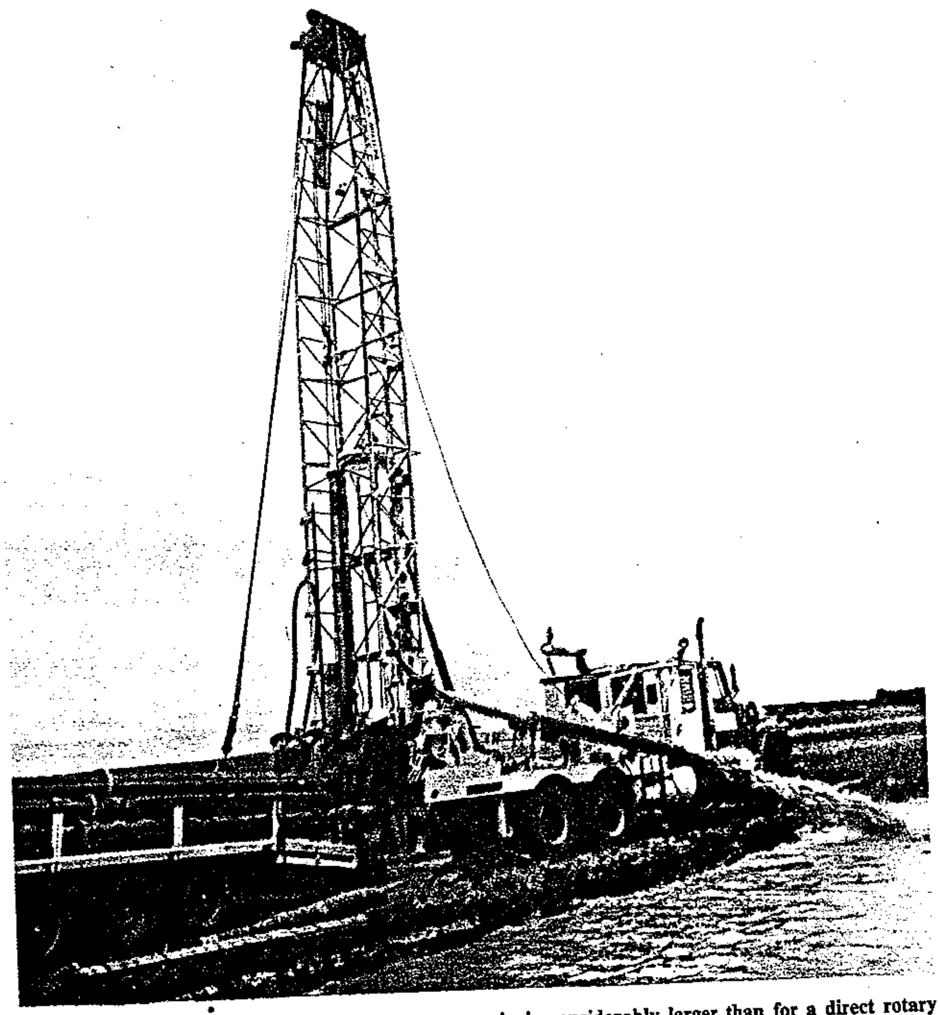


Figure 10.27. The settling pit for a reverse rotary rig is considerably larger than for a direct rotary machine because fluid losses in the borehole are always much higher. The pit should contain at least three times the volume of the material to be removed during drilling. *(Portadrill, Inc.)*

Flanged pipe is suitable for relatively shallow boreholes, but the labor of attaching sections for deep holes led to the adoption of threaded and coupled pipe.

When flanged pipe is used, the smallest practical borehole that can be drilled is about 18 in (457 mm) because the diameter of the flanges is about 11 in (279 mm). The diameter of the hole must be large in relation to the drill pipe so that the velocity of the descending water is about 1 ft/sec (0.3 m/sec) or less to prevent erosion of the borehole wall. If air-conductor pipes are attached to the flanges, they must be aligned properly to allow for air movement.

Reverse circulation drilling is the least expensive method for drilling large-diameter holes in unconsolidated formations. When geologic conditions are favorable, increasing the diameter of the borehole does not appreciably increase the cost of the well. Therefore, most water wells drilled by this method are 24 inches (610 mm) in diameter or larger [to 60 in (1,520 mm)]. Filter packs are installed almost universally in wells drilled by reverse circulation drilling because of the relatively large diameter of the borehole.

Reverse circulation drilling is most successful in soft sedimentary rocks and unconsolidated sand and gravel where the static water level is 10 ft (3 m) or more below ground level. In cases of high static water level, ramps are built above grade to support the drilling rig, or the weight of the drilling fluid is increased to obtain the necessary hydrostatic pressure. The reverse circulation drilling method may not be satisfactory when the static water level is too high and adequate water supplies are not available. Advantages of the reverse circulation method include the following:

1. The porosity and permeability of the formation near the borehole is relatively undisturbed compared to other methods.
2. Large-diameter holes can be drilled quickly and economically.
3. No casing is required during the drilling operation.
4. Well screens can be set easily as part of the casing installation.

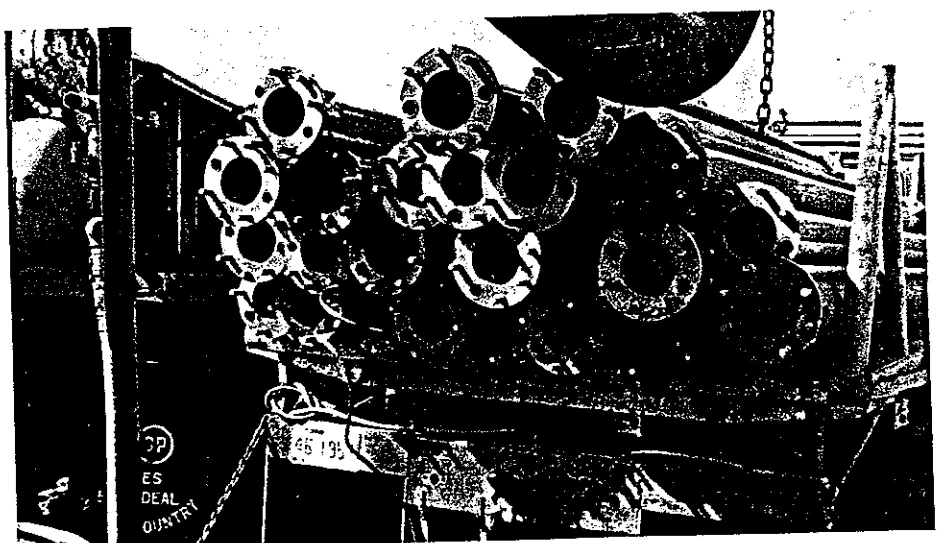


Figure 10.28. Compressed air can be added to the drill rods to enhance upward flow of the drilling fluid. The drill pipe shown on the truck has external air lines mounted on the outside of the drill rods to conduct the air down to the injection manifold.

5. Most geologic formations can be drilled, with the exception of igneous and metamorphic rocks.
6. Little opportunity exists for washouts in the borehole because of the low velocity of the drilling fluid.

Disadvantages include the following:

1. Large water supply is generally needed.
2. Reverse-rotary rigs and components are usually larger and thus more expensive.
3. Large mud pits are required.
4. Some drill sites are inaccessible because of the rig size.
5. For efficient operation, more personnel are generally required than for other drilling methods.

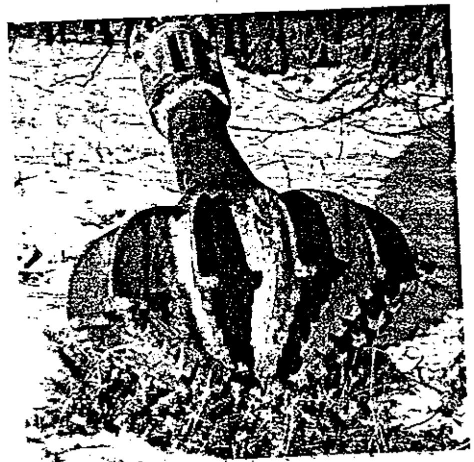


Figure 10.29. Boulders collecting at the bottom of the borehole present a significant problem in reverse rotary drilling. Some contractors use a Zublin-type bit to drive the boulders into the borehole wall when they are encountered.

AIR DRILLING SYSTEMS

Two different drilling methods use air as the primary drilling fluid — direct rotary air and down-the-hole air hammer. In conventional reverse circulation methods, air is used as an assist but not as the primary drilling fluid. In the air rotary method, air alone lifts the cuttings from the borehole. A large compressor provides air that is piped to the swivel hose connected to the top of the kelly or drill pipe. The air, forced down the drill pipe, escapes through small ports at the bottom of the drill bit, thereby lifting the cuttings and cooling the bit. The cuttings are blown out the top of the hole and collect at the surface around the borehole (Figure 10.32). Injecting a small volume of water or surfactant and water (foam) into the air system controls dust and lowers the temperature of the air so that the swivel is cooled.

Figure 10.30. Orange-peel buckets are used to remove boulders from the bottom of the borehole in reverse rotary drilling. Two sizes are shown in this photograph. *(Layne Northwest)*

Air drilling can be done only in semiconsolidated or consolidated materials. Therefore, to achieve the capability to operate in completely unconsolidated as well as consolidated formations, air rotary drilling machines are often equipped with a mud pump in addition to a high-capacity air compressor (Figure 10.33). Conventional water-based drilling fluids are then used when drilling through the overlying, caving formations above the bedrock (or more consolidated formations), whereas air is used once bedrock has been reached. Thus drillers are uti-

Figure 10.31. Large-diameter drag and roller cone bits provide satisfactory penetration rates for reverse drilling. Drag bits are used in unconsolidated formations only. Note the air-assist lines mounted in the drag bit and the coarse-tooth structure of the reamer bit. *(Moab Bit and Tool Company)*

lizing various options of drilling technology to adjust to the different physical characteristics of the formation. In many instances, casing may have to be installed through the overburden to avoid caving or excessive erosion of the borehole wall after changing to air circulation.

Cuttings are removed by grinding the material finely enough so that the uphole velocity of the air is sufficient to lift them to the surface. The lifting capacity of the air can be enhanced by adding a small amount of surfactant and water solution to the air. Larger cuttings can then be removed, thereby increasing the drilling rate.

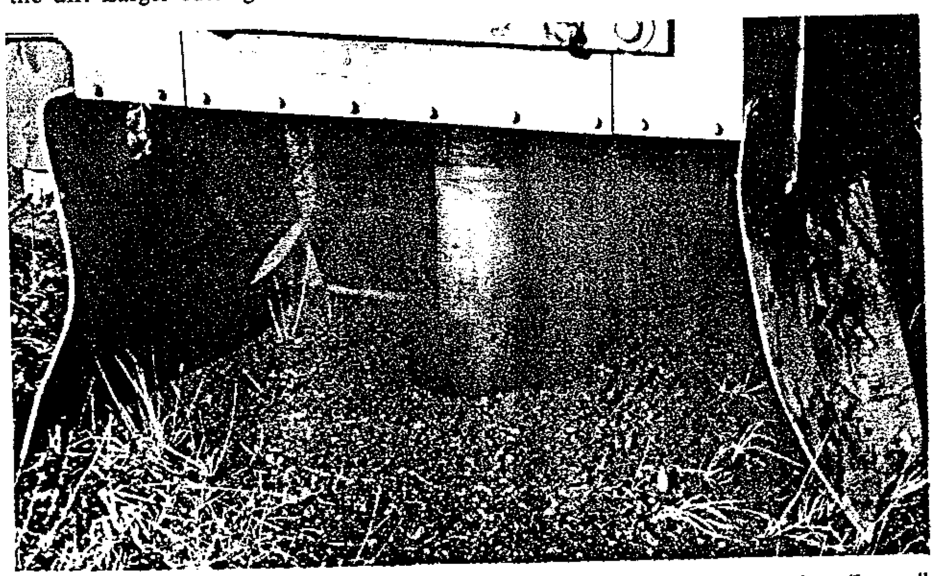


Figure 10.32. In dry-air drilling, cuttings are blown up the borehole and collect at the surface. *(Ingersoll-Rand)*

Foam also reduces loss of air to the formation. Suggestions for appropriate uphole velocities and the use of various drilling fluid additives are presented in Chapter 11.

Roller-type rock bits, similar to those designed for drilling with water-based fluids, can be used when drilling with air. Tricone rock bits up to about 12-in (305-mm) diameter are commonly used. Larger sizes are available. Button bits, made with sintered tungsten-carbide inserts set into the perimeters of steel rollers, are used successfully in many areas. Figure 10.34 lists the formations drilled effectively by carbide and steel-tooth bits in rotary air drilling.

Field tests with various sizes of bits have shown that the penetration rate is often faster and the bit life longer when using air as compared with water-based drilling fluids. Better bottom-hole cleaning is partly responsible for this difference in performance. If too much water comes into the hole during drilling, however, the penetration rate is no better than when drilling with water-based drilling fluids. Air also keeps the bit bearings cool and clean and causes some oxidation of the bearings; the oxidized material then becomes a lubricant. On the other hand, water-based drilling fluids are often abrasive and cause wear on the bearings.

A second direct rotary method using air is called the "down-the-hole" drilling system. A pneumatic drill operated at the end of the drill pipe rapidly strikes the rock while the drill pipe is slowly rotated (Figure 10.35). The percussion effect is similar to the blows delivered by a cable tool bit. The hammer is constructed from alloy steel with heavy tungsten-carbide inserts that provide the cutting or chipping surfaces. Tungsten-carbide is extremely resistant to abrasion, but drill bits do become dull with continued use. The inserts are sharpened by grinding when operating conditions indicate that the bit is not cutting properly. Alternatively, the bits can be provided with carbide buttons that can be periodically replaced when worn.

Rotation of the bit helps to assure even penetration and, therefore, straighter holes even in extremely abrasive or resistant rock types. The rates of penetration in several rock types are higher than those obtained by other drilling methods or other types of tools. Six-in (152 mm) and 6½-in (165 mm) hammer bits are most commonly used, although sizes range up to 17½ in (445 mm). Cuttings are removed continuously by the air used to drive the hammer. Unlike the conventional cable tool bit that is constantly striking previously broken rock fragments, the bit (or buttons) on the air hammer always strike a clean surface. Thus, the air hammer is highly efficient.

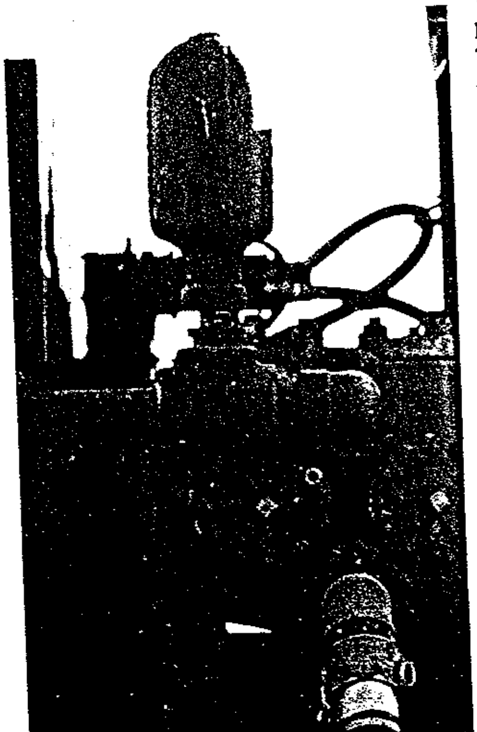


Figure 10.33. Many air rotary drilling rigs are equipped with conventional mud pumps so they can be used to drill in unconsolidated overburden. *(Schramm, Inc.)*

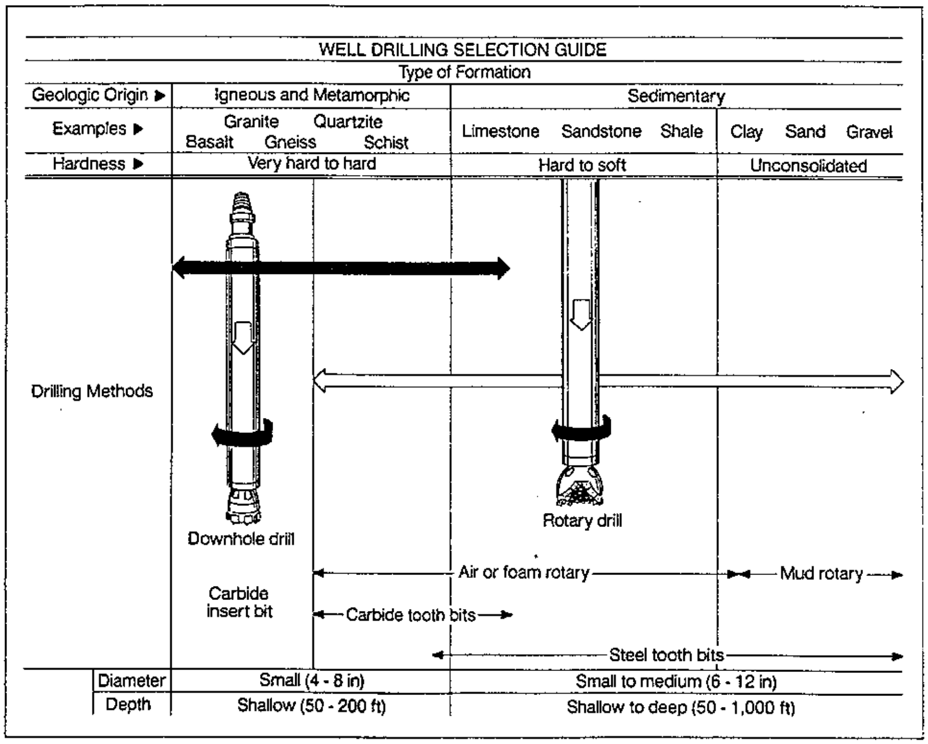


Figure 10.34. Guide for the use of bit types in air-drilling systems. *(Ingersoll-Rand)*

Compressed air must be supplied to the hammer at a pressure of 100 to 110 psi (690 to 758 kPa). Some tools require as much as 200 psi (1,380 kPa). To remove cuttings effectively, the upward velocity in the space outside the drill pipe should be about 3,000 ft/min (915 m/min) or more. For drilling 4-in (102-mm) holes, the air supply must be at least 100 cfm (0.047 m^3/sec) [assuming a 2⅞-in (73-mm) drill rod]; for 6-in (152-mm) holes, at least 330 cfm (0.156 m^3/sec) is needed*. Proper rotation

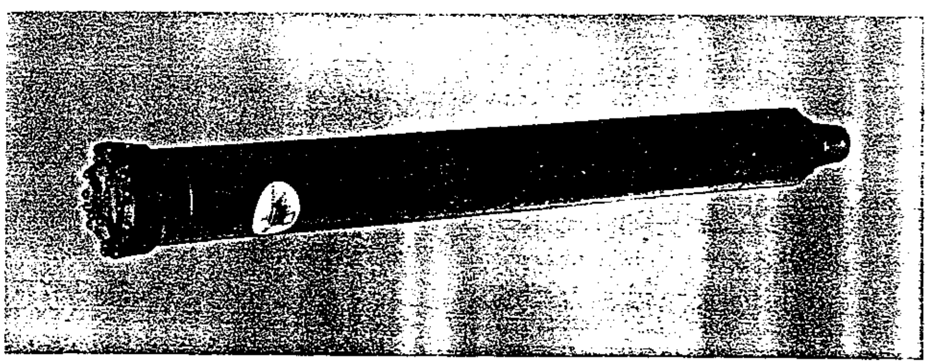


Figure 10.35. A down-the-hole hammer is extremely effective in penetrating dense, resistant formations such as basalt, quartzite, and granite. *(Ingersoll-Rand)*

*260 cfm (0.123 m^3/s) is needed when using a 4½-in drill rod. Other recommendations are presented in Chapter 11.

speed is from 10 to 30 rpm; reduced speed is best in harder and more abrasive rock. Advantages of using air drilling methods include the following:

1. Cuttings removal is extremely rapid.
2. Aquifer is not plugged with drilling fluids.
3. No maintenance costs for mud pumps (mud pumps are not used during air drilling).
4. Bit life is extended.
5. Drilling operations are not hampered by extremely cold weather.
6. Penetration rates are high, especially with down-the-hole hammers, in highly resistant rocks such as dolomite or basalt.
7. An estimate can be made during drilling of the yield from a particular formation.

Disadvantages include the following:

1. Restricted to semiconsolidated and well-consolidated materials.
2. Initial cost and maintenance costs of large air compressors are high.

IN-VERSE DRILLING

A recent innovation for the top-head drive, direct rotary machine involves the addition of an air assist by using a special 6-in (152-mm) inside diameter, side discharge swivel assembly and 5⅞-in (149-mm) drill pipe with built-in air channels. This equipment permits compressed air to be injected through an injection stem into air channels mounted outside the drill pipe and then into the drilling fluid as it moves up inside the drill pipe (Figure 10.36). Thus, the drilling fluid and cuttings are assisted to the surface by an airlift inside the 6-in diameter conductor (drill) pipe. This method is known as the In-Verse system and converts a direct rotary, top-head drive machine into a reverse circulation rig.

Use of the In-Verse system can increase the capacity of a direct rotary rig to drill large-diameter wells. Depending on the rig, boreholes from 20 to 30 in (508 to 762 mm) can be drilled routinely. If the pulling capabilities of the rig are suffi-

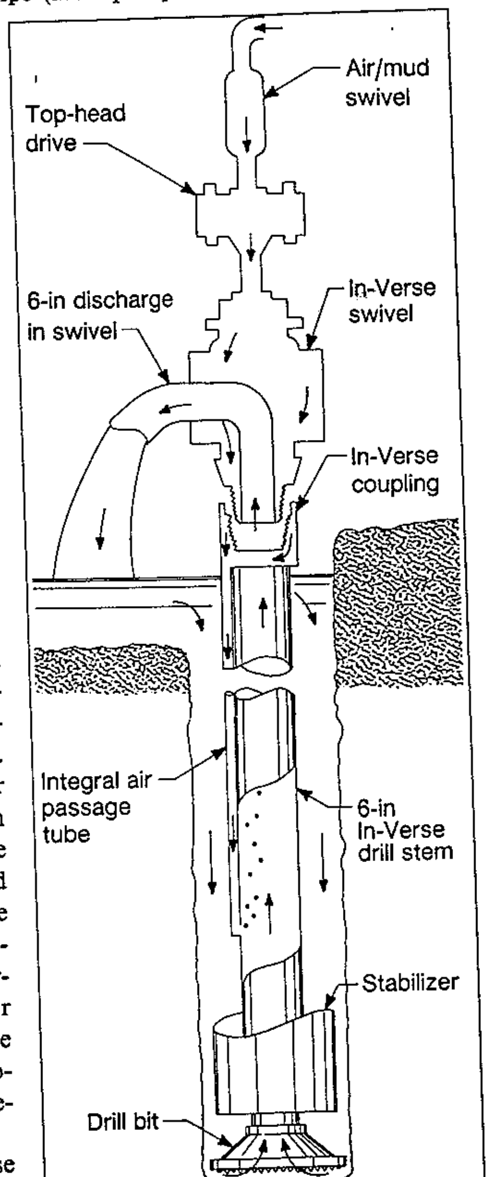


Figure 10.36. In In-Verse drilling, air is injected into a special double-walled drill stem to increase the efficiency of cuttings removal. Use of this system permits top-head drive, direct rotary rigs to drill large-diameter boreholes by reverse circulation methods. *(In-Verse Tool Corporation)*

cient, enough torque is available, and larger bits can be accommodated under the centralizer, boreholes of 30 to 60 in (762 to 1,520 mm) are possible in unconsolidated formations. Boreholes smaller than 12 in (305 mm) are not recommended because the drill pipe has an outside diameter of approximately 9 in (229 mm) at the tool joint and significant erosion of the borehole wall may occur depending on the degree of formation consolidation.

It is recommended that at least a 300 cfm (0.1 m^3/sec) compressor operating at 125 psi (862 kPa) be used for the In-Verse system. At this pressure, the maximum stem submergence is approximately 250 ft (76.2 m). If the borehole must extend past 250 ft (76.2 m), 50 to 60 ft (15.2 to 18.3 m) of drill pipe are pulled and another injector stem is installed in the drill string. Thus, if the drilling rig is equipped with only 250 ft of air channel pipe and the hole will be 500 ft (152 m) deep, the drill pipe with the air channels must be mounted above the conventional drill pipe for any depth over 250 ft. This requirement increases drill pipe handling time somewhat.

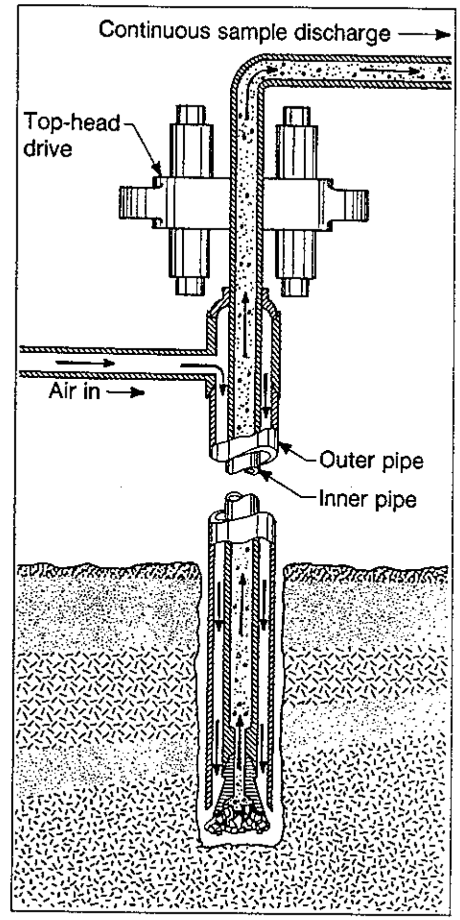


Figure 10.37. Water wells can be drilled to depths of 1,000 ft (305 m) or more using the dual-wall reverse circulation method. The drilling fluid (air or water) is injected down the outer annulus of dual-walled pipe; cuttings are lifted to the surface through the inner pipe. The pipe is connected directly to either a down-the-hole air hammer or a tricone bit. Main use is in test drilling.

The In-Verse equipped rig operates most satisfactorily with a centrifugal pump or a 3 x 4 or 5 x 6 piston pump.* The latter pump will operate at approximately 300 psi (2,070 kPa). This size pump would be required to drill test holes or wells smaller than 12 inches (305 mm) in diameter using direct rotary drilling.

Advantages of the In-Verse system include the following:

1. Large-diameter boreholes can be drilled.
2. Penetration rates are high in unconsolidated sediments.
3. Less drilling fluid additives are required to lift the cuttings.
4. Development time is reduced.

Disadvantages include the following:

1. Extra costs for drill pipe, special swivel, and air compressor (if the rig is not equipped with one).
2. Drill pipe handling time may increase for deep holes.

*Piston pumps are designated by two dimensions — the diameter of the piston and stroke length.

DUAL-WALL REVERSE CIRCULATION ROTARY METHOD

In mining exploration, a drilling system called the dual-wall method has been used for many years to obtain accurate geologic samples from known depths. The dual-wall method uses flush-jointed, double-wall pipe in which the drilling fluid (air or liquid) moves by reverse circulation (Figure 10.37). Unlike conventional reverse circulation, however, the drilling fluid does not run down the outside of the drill pipe. Instead, the flow is contained between the two walls of the dual-wall pipe and only contacts the walls of the borehole near the bit. Recently this method has been applied to water well exploration and construction in all types of geologic formations, although its principal use is still test drilling.

Available drill pipe diameters for the dual-wall method are:

3½-in OD x 1¾-in ID (89 mm x 44 mm)
4½-in OD x 2½-in ID (114 mm x 64 mm)
5½-in OD x 3¼-in ID (140 mm x 83 mm)
6⅝-in OD x 4¼-in ID (168 mm x 108 mm)
9⅝-in OD x 6¼-in ID (244 mm x 159 mm)

The 4½-in OD size is the most common. Male and female tool joints are used to connect the outer pipes; a connector sleeve with an "O" ring seals the joint between the inner pipes.

Dual-wall pipe can be driven into place in loosely consolidated materials by a steam-, gasoline-, or diesel-operated pile hammer as the formation is being cut by a drive bit. Air or water is forced down the annulus to lift the cuttings to the surface through the inner pipe. If bedrock is reached, drilling may be continued by direct rotary methods using the dual-wall pipe as temporary casing. The pile-driving method is generally not used in the water well industry because the hammering compacts unconsolidated formation materials. In addition, the method may not penetrate deeply enough for most water well applications.

More frequently, dual-wall pipe is set by standard reverse circulation methods using a top-head drive unit. The top-head drive should deliver about 4,500 to 5,000 ft-lb (6,100 to 6,780 J) of torque to be

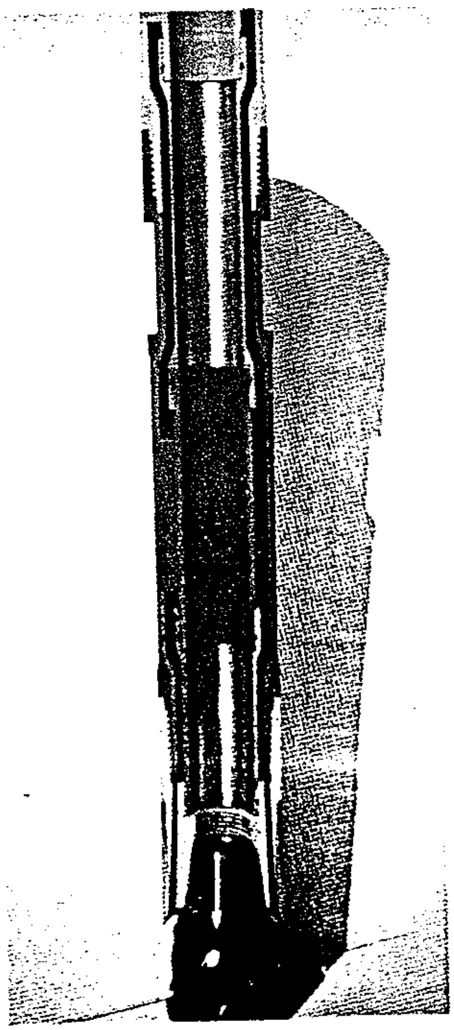


Figure 10.38. When a tricone bit is used in the dual-wall method, the cuttings enter the pipe just above the bit. Thus, samples taken at the surface come from a small vertical section of the formation and are unadulterated by overlying material. The dual-wall system is a popular method for geologic exploration because the samples are highly representative of the formations. *(Drilling Services Company)*

effective. Down-the-hole air hammers and tricone bits can be used to cut the formation. As in the pile-driving method, air or water lifts the cuttings. Surface casing is not needed when the dual-wall system is used.

The outer pipe of the dual-wall system must be able to operate within the normal tensile, column, and collapse pressures associated with rotary drilling. The inner pipe is under little physical stress, but the abrasion caused by earth materials moving up the pipe from the bit causes wear. In practice this abrasion will generally cause the inner pipe to wear out more rapidly than the outer pipe. The inner pipe can be replaced if necessary.

If dual-wall casing is being set by a top-head drive, several different types of bits can be used, but the bit size is normally one nominal size larger than the drill pipe. Thus, the space between the outer pipe and the borehole wall is small and the pipe partially (or totally) supports the wall like a conventional stabilizer. The bit is mounted into a permanent sub that has ports for passage of the drilling fluid. If a tricone bit (either a chisel-tooth or button-tip type) is used, the drilling fluid passes upward through the inner part of the bit. A bit-wear sleeve is attached as close as possible to the cutting face and serves as a wear ring. The drilling fluid passes from the annular space between the two pipes, through a predrilled bit sub, and is discharged toward the cutting surface along the periphery of the bit sleeve; after entraining the cuttings, the fluid passes upward through the inner pipe.

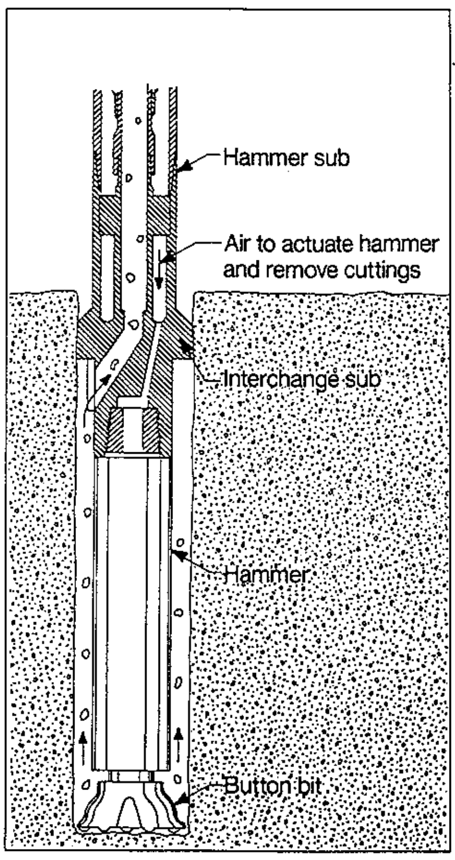


Figure 10.39. The cross-over channel in the interchange sub mounted on top of the hammer permits the cuttings to enter the inner casing. *(Drilling Services Company)*

When a tricone bit is used, the formation sample passing upward through the inner casing originates from a small vertical section of the formation (Figure 10.38). In the use of a down-the-hole hammer, however, the bit extends 4 to 5 ft (1.2 to 1.5 m) out from the bottom of the dual-wall pipe. Air is forced down inside the hammer, out the ports, and then passes up around the outside of the hammer shaft and into a special type of cross-over channel (interchange) sub and then into the inner casing (Figure 10.39). Thus, the formation sample or water sample passing up the pipe can originate over a longer vertical section (3 to 4 ft) of the formation. It must be remembered, however, that this distance is still small when compared with intervals sampled by other types of rotary air drilling.

At the surface, drilling fluid enters the annular space between the inner and outer pipes by a special side inlet swivel.

Drilling fluids can consist of dry air, air and water, air and water with surfactants, or water with clay or polymers. When air is used, velocities in the dual-wall system average 4,500 to 6,000 ft/min (1,370 to 1,830 m/min). After passing down the annular space and up inside the inner pipe, air passes with the formation sample into a cyclone that can be equipped with an automatic splitter (a three-tier sampler is often used) (Figure 10.40). A minicyclone can also be used. The minicyclone is approximately 1:10 scale and is mounted at 180 degrees away from the entrance of the 4-in (102-mm) hose conveying the cuttings from the hole. The sample is collected in a sausage-skin type of sample bag. Under ordinary drilling conditions, 5 ft (1.5 m) of sample bag will be filled for every 20 ft (6.1 m) of hole drilled.

In the past, most boreholes drilled using the dual-wall method rarely exceeded 500 ft (152 m). Recently, however, depths of 800 to 1,400 ft (244 to 427 m) have been reached by using booster compressors.

Screens and conventional casing can be installed when using the dual-wall drilling method. Screen and casing can be washed in over the dual pipes; small-diameter screens [1 to 2 in (25 to 51 mm)] can be installed through the bit; or the dual pipe can be pulled from the hole before a screen and casing are set.

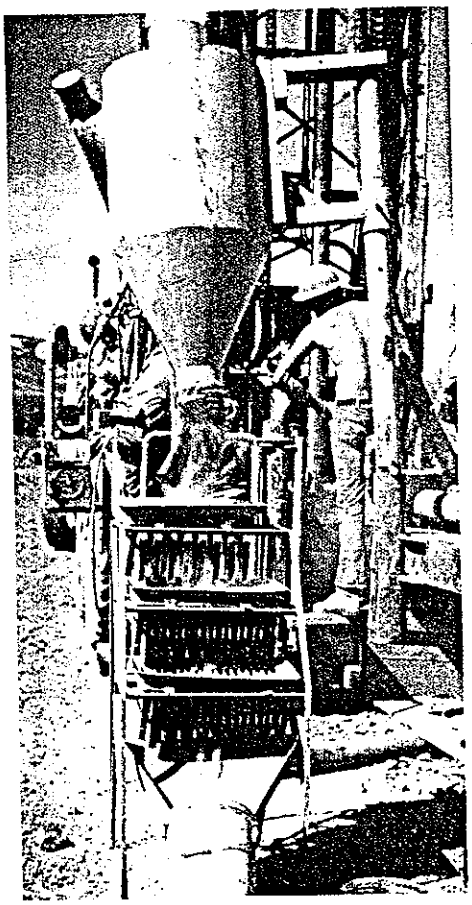


Figure 10.40. A cyclone segregates the cuttings from the drilling fluid (air or water) and deposits them into a sample splitter. A three-tier sampler is shown here. *(Drilling Services Company)*

Advantages of the dual-wall system include the following:

1. Continuous representative formation and water samples can be obtained.
2. Estimates of aquifer yield can be made easily at many depths in the formation.
3. Fast penetration rates are possible in coarse alluvial deposits or broken or fissured rock.
4. Problems of lost circulation are either eliminated or reduced drastically.
5. Washout zones are reduced or eliminated.

Disadvantages of the dual-wall system include the following:

1. Initial cost of drilling rig and equipment is high.
2. System is limited to rather slim holes [less than 9 to 10 in (229 to 254 mm)].
3. System is limited to depths of approximately 1,200 to 1,400 ft (366 to 427 m) in alluvial deposits [works best to 600 ft (183 m)] and generally up to 2,000 ft (610 m) in hard rocks.

4. Well-trained drilling crews are needed.

DRILL-THROUGH CASING DRIVER

Drilling rig manufacturers have long sought to build drilling machines that could combine the hole stability of the cable tool rig and the speed of an air rotary rig. Some manufacturers are now providing casing drivers that can be fitted to top-head drive, direct air rotary rigs (Figure 10.41). The driver can be suspended in the mast independent of the rotary drive unit because of its rather short length. Use of a casing driver permits the casing to be advanced during drilling, but both drilling and driving can be adjusted independently depending on the nature of the formation. Drivers are usually equipped so that they can be used to drive upward to remove casing or expose a screen.

In the casing driver system, the drill pipe and casing are usually preassembled as a unit [must be the same length, usually 20 ft (6.1 m)] and raised into position on the mast. The bottom of the casing is fitted with a forged or cast alloy steel drive shoe as in cable tool operations. A bit that fits inside the casing is attached to the bottom of the drill pipe (Figure 10.42). The top of the casing fits in the bottom of the casing driver by means of an anvil. The casing is driven by a piston that is activated by air pressure (Figure 10.43). Table 10.3 shows the relationship between air pressure, air consumption, and blows per minute for two sizes of drivers.

Three drilling procedures can be followed when using the casing driver: (1) the drill bit and casing advance as a unit, (2) the casing is driven first (in unconsolidated materials only) and then the plug in the casing is drilled out, and (3) the drill bit advances beyond the casing a few feet, is withdrawn into the casing, and then the casing is driven.

As drilling commences using the first procedure, the cone-type bit protrudes out the bottom of the casing, but rarely more than 12 in (305 mm). Cuttings are blown up the short open hole into the casing, and pass out the top through a horizontal tube. During drilling, the casing is simultaneously driven into the ground; that is, the casing advances at the same rate as the drill bit (Figure 10.44). The driller adjusts the pull-down and distance

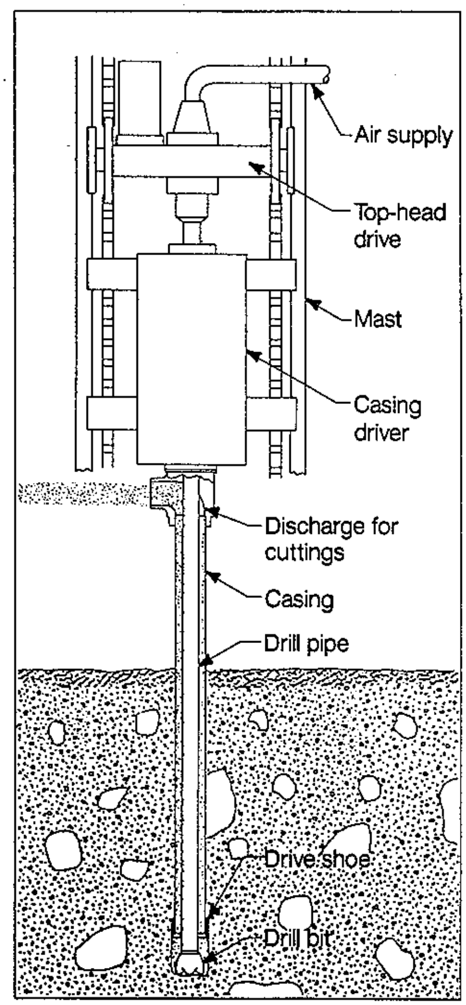


Figure 10.41. Casing drivers can be fitted to top-head drive rotary rigs to simultaneously drill and drive casing. *(Wellen Drill Tools, Inc.)*

the bit is outside the casing according to the rate of advance and speed of cuttings removal. Occasionally the bit may be pulled up within the casing for a few moments to allow the air pressure to blow out the cuttings. Cuttings removal is facilitated by periodically adding small volumes of water if the borehole has not encountered water. This method is particularly suitable for drilling in stratified deposits that have large differences in particle size, for example, sand and silt to boulders.

Figure 10.42. Either a down-the-hole hammer equipped with a button bit (shown here) or a roller bit is used in the casing-driver method. *(Wellen Drill Tools, Inc.)*

In the second procedure, the casing is driven into the ground approximately 0.5 to 1.5 ft (0.2 to 0.5 m) and the plug in the casing is then drilled out. The casing is usually driven only short distances so that each formation can be identified and sampled. During the casing-driving procedure, the drill bit is withdrawn inside the casing and rotation is continued. Air is constantly circulated down the drill pipe to prevent clogging of the casing.

In the third procedure, the drill bit advances out the end of the casing a few feet. When the hole begins to become unstable, the bit is retracted into the casing and the casing is driven with the air pressure still applied to the borehole. This method is particularly successful in semiconsolidated sands, but also functions well in loose alluvium.

The drill-through casing driver arrangement achieves high drilling rates in most unconsolidated formations, even in bouldery till (Figure 10.45). In fact, welding two joints of casing together often requires more time than drilling and driving a 20-ft (6.1-m) section of casing. When welding casing, some drillers weld straps across the welded joint for added strength. If rock underlies an unconsolidated formation, a down-the-hole hammer can be substituted for the cone bit once the casing is seated in the rock.

Table 10.3. Relationship Between Air Pressure, Air Consumption, and Blows per Minute for Two Sizes of Casing Drivers

Banger Model		Slammer Model	
Air pressure at:		Air pressure at:	
50 blows per minute	40 psi	50- 60 blows per minute	60 psi
120 blows per minute	80 psi	90-100 blows per minute	90 psi
Air consumption	245 cfm	Air consumption	450 cfm
Driving energy	2,100 ft/lb	Driving energy	6,300 ft/lb

(Tigre Tierra, Inc.)

If a screen is to be set, the casing can be pulled back by the top-head drive line, casing line, or, if some simple adjustments are made, by the casing driver (the driver can be adjusted to drive upward). It is wise to add a short piece of riser pipe to the top of the screen to prevent its loss if the casing is pulled back too far.

For some borehole diameters, it is possible to eliminate the casing driver but still drill and install casing at the same time. In loose overburden, an eccentric (off-centered) bit unit can be attached to a down-the-hole hammer (Figure 10.46). In this arrangement, the bit can cut a borehole slightly larger than the casing, allowing the casing to drop into place under its own weight. It may be necessary to drive the casing occasionally if it does not fall into place. This can be done in shallow holes by bringing the down-the-hole hammer out of the hole and driving on a driving cap placed on top of the casing. When consolidated rock is reached and the casing is seated, the rotation of the drill string is reversed for one revolution, causing the eccentric bit to center itself in the casing. It can then be withdrawn from the borehole and a conventional bit attached to the drill pipe. The new bit will cut a hole slightly smaller than the casing diameter.

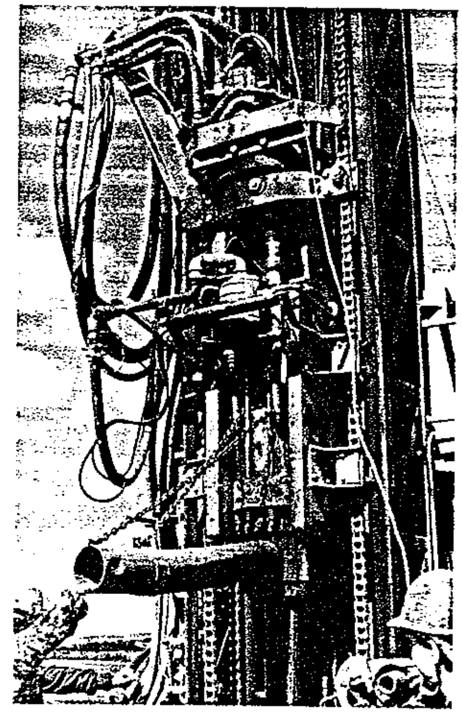


Figure 10.43. A casing driver is mounted in the mast of this top-head drive rotary rig. As the top-head drive turns the drill string, the casing driver, activated by air pressure, simultaneously drives the casing. *(Kramer Well Drilling)*

Figure 10.44. During drilling, the bit advances just ahead of the casing. If cuttings begin to collect in the casing, the bit can be withdrawn into the casing for a few moments to clear it. Small volumes of water can be added periodically to increase the rate of cuttings removal.

The ability to drill and drive casing simultaneously is a major technological advance. It reduces costs and minimizes operational difficulties for the drilling contractor, especially during extremely cold weather. The drill-through casing method is particularly successful in bouldery tills or coarse, highly stratified alluvial deposits where rotary methods are ineffective or cable tool methods too time consuming.

Advantages of using the drill-through casing driver include the following:

1. Wells can be drilled in unconsoli-

dated geologic materials that may be difficult to drill with cable tool or direct rotary methods.
2. Unlike other rotary methods, the borehole is fully stabilized during the entire drilling operation.
3. Penentration rates are rapid even under difficult drilling conditions.
4. Lost-circulation problems are eliminated.
5. Accurate formation and water samples can be obtained.
6. Casing drivers can be used in all weather conditions.
7. No water-based drilling fluid is required in unconsolidated materials.

Disadvantages include the following:

1. Additional cost of the casing driver.
2. Noise of operation (driving casing).

When air drilling techniques are used, the driller can easily see how much water is being blown out with the cuttings as the hole is deepened. From this observation, the driller can estimate when the borehole is deep enough to produce the desired yield. When static water levels are low, however, the air pressure in the hole may prevent water from entering the borehole.

The cost per foot of drilling with the air rotary system in consolidated formations is sensitive to the life and cost of the bits as well as to penetration rates. Experience in a given locality for specific types of consolidated rock must be depended upon for choosing the bit type that produces the best results economically.

JET DRILLING

There are two methods for installing wells in which a high-velocity stream of water is used in the drilling procedure. One of these, the jet-percussion system, is generally limited to drilling 3- to 4-in (76- to 102-mm) diameter wells to depths of about 200 ft (61 m). Large-diameter wells more than 1,000 ft (305 m) deep have been sunk by

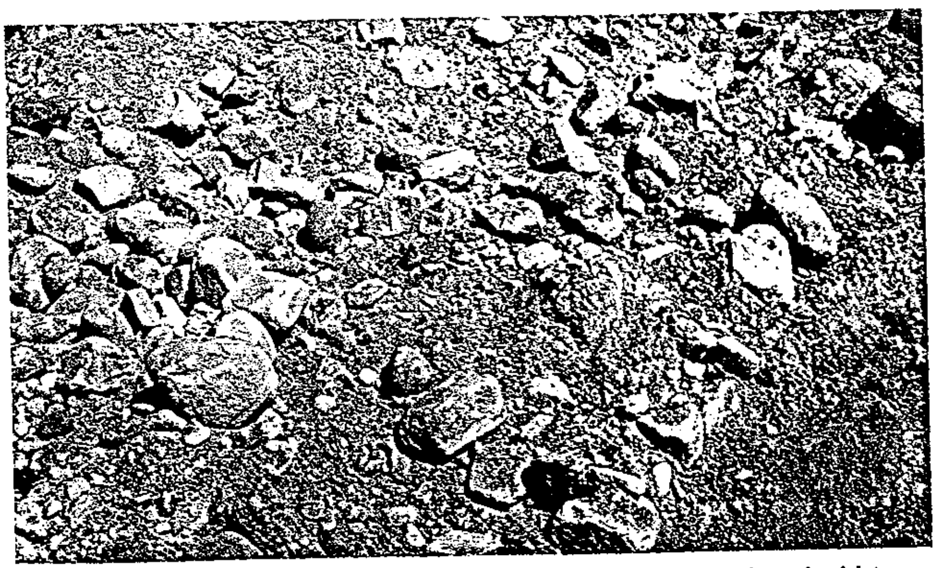


Figure 10.45. When drilling in bouldery till deposits, the time required to weld the casing joints may exceed the time required to drive each 20-ft (6.1-m) length of casing.

jet drilling, but other drilling procedures have displaced this method for deep, large-diameter holes.

Drilling tools for the jet-percussion method consist of a chisel-shaped bit attached to the lower end of a pipe string. Holes on each side of the bit serve as nozzles for water jets that keep the bit clean and help loosen the material being drilled. Water is pumped under moderate to high pressure through the drill pipe and out the drill bit. The drilling water then flows upward in the annular space around the drill pipe, carrying the cuttings in suspension. It overflows at the ground surface and is led into one or more pits where the cuttings settle to the bottom. The water is then picked up by the suction of the pump and recirculated through the drill pipe.

The discharge from the pump is delivered through a pressure hose and water swivel attached to the top of the drill pipe. The fluid-circulation system is similar to that of direct rotary drilling. With water circulation maintained, the drill rods and bit are lifted and dropped in a manner similar to cable tool drilling but with shorter strokes. The chopping action of the bit in combination with the washing action of the water jets opens the borehole. The drill rods are rotated by hand so that the bit cuts a round hole. Casing, fitted with a drive shoe, is normally sunk as drilling proceeds. The pipe is driven by using a drive-block assembly that can be attached to the upper end of the casing string.

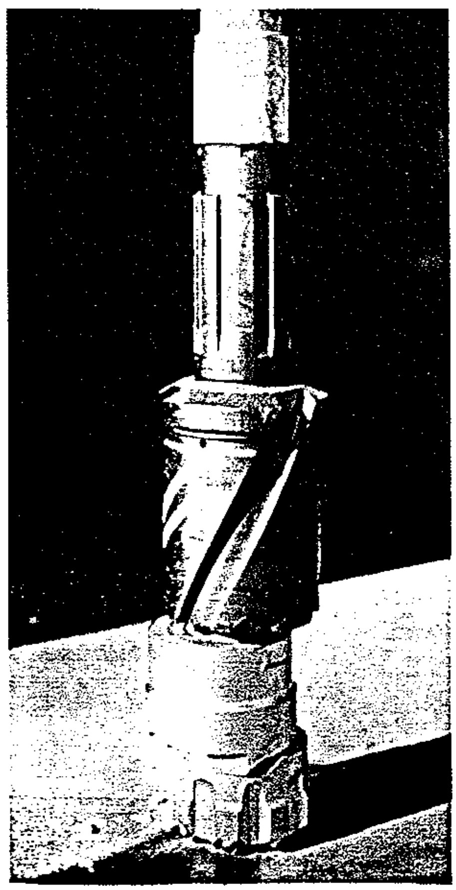


Figure 10.46. For some casing diameters, the use of an eccentric (off-centered) bit, attached to a hammer, can eliminate the continuous need for the casing driver. As the bit underreams the borehole, the casing will ordinarily drop by gravity, although some driving may be necessary. *(Stang Hydronics, Inc.; Atlas-Copco Bit)*

Open holes can be drilled to limited depths in unconsolidated materials by the jet method if drilling fluid additives are mixed with the water to form a low-viscosity drilling fluid. The viscosity is useful in lifting cuttings, but cannot be so great that it impedes the force of the jetting action at the bit. Casing must be installed, however, and must follow the bit rather closely whenever the uncased hole tends to cave or is in zones of high fluid loss. Jet-percussion drilling is commonly used for drilling small-diameter wells in water-bearing sand, but can also be used to penetrate some semiconsolidated and consolidated formations that are not too hard.

A second drilling procedure uses small-diameter pipe and well points with open bottoms that can be sunk in sandy formations by the washing action of a water jet without any type of drilling tools. This procedure is described in Chapter 14.

HYDRAULIC-PERCUSSION METHOD

This drilling procedure, often called the hollow-rod method, utilizes a string of drill pipe or drill rod similar to that used in the jet-percussion method. The bit is also similar, except that a ball check valve is provided between the bit and the lower end of the drill pipe. Water is introduced at the surface into the annular space between the drill rods and well casing to keep the hole full of water.

Drilling is done by lifting and dropping the drill rods and bit with quick, short strokes. As the bit drops and strikes bottom, water with cuttings in suspension enters

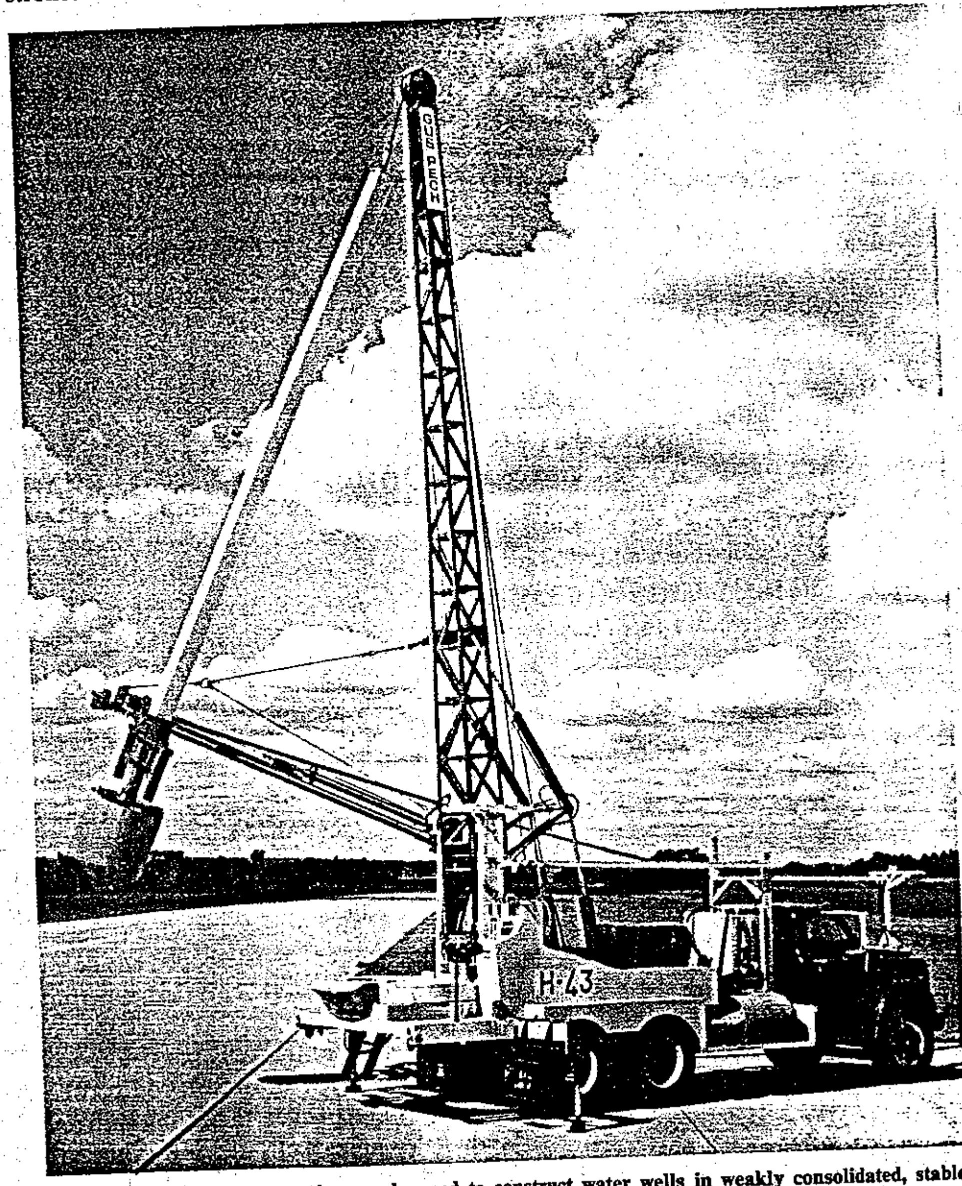


Figure 10.47. Bucket auger rigs can be used to construct water wells in weakly consolidated, stable formations. *(Gus Pech Manufacturing Co., Inc.)*

the ports of the bit. When the bit is lifted, the check valve closes and traps the fluid inside the drill pipe. Continuous reciprocating motion produces a pumping action to lift the fluid to the top of the string of drill pipe where it discharges into a settling tank. Water is returned to the hole from the settling tank. Casing is driven as drilling proceeds. A driving weight is usually clamped to the drill rods; with this weight attached, the drill rods are lifted and dropped so the weight strikes the top of the casing. The cable tool machine is well adapted to this system because no pressure pump is required.

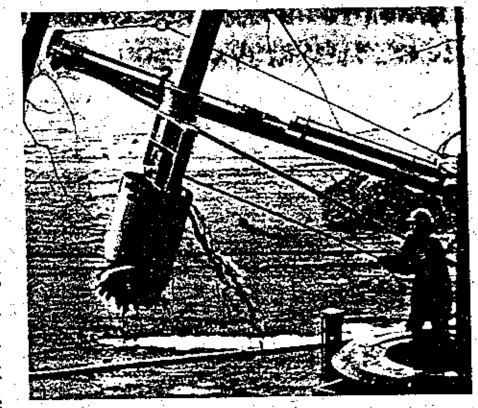


Figure 10.48. As drilling proceeds, material is excavated by a cylindrical bucket fitted with auger-type cutting blades on the bottom. When the bucket is full, it is raised above the drive table and swung off to the side by the dumping arm.

Advantages of this method include minimum equipment requirements and the ability to obtain accurate samples. Its use is limited, however, to drilling only small-diameter wells through clay and sand formations that are relatively free of cobbles and boulders.

BORING WITH EARTH AUGERS

Earth augers of various sizes and designs are used in certain areas for drilling water wells. Three principal types are used commonly: (1) large-diameter bucket auger, (2) solid-stem auger, and (3) hollow-stem auger.

Bucket Auger

The first method utilizes a large-diameter bucket auger to excavate earth materials. This method is referred to as rotary bucket drilling (Figure 10.47). The excavated material is collected in a cylindrical bucket that has auger-type cutting blades on the bottom (Figure 10.48). 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.

Figure 10.49. The massive kelly consists of two or more lengths of square tubing, each length telescoped inside the next larger size.

The kelly is square in cross section and consists of two or more lengths of square tubing, one length telescoped inside the other (Figure 10.49). This design permits boring to a depth several times the collapsed length of the kelly bar before having to add a length of drill rod between the kelly and bucket. In drilling with only the telescoping kelly serving as the drill stem, the bucket is lifted from the hole and dumped without disconnecting. If one or more drill rods are used for deeper boring, the drill rods must be removed each time the bucket is brought to the surface.

Wells more than 250 ft (76.2 m) deep have been drilled by this method, although depths of 50 to 150 ft (15.2 to 45.7 m) are more common. Water wells drilled with the bucket auger are from 18 to 48 inches (457 to 1,220 mm) in diameter, but few wells are larger than 36 in (914 mm). Special hardened teeth or tungsten carbide inserts are fixed to the cutting blades on the bottom of the bucket when augering in dense formations.

Figure 10.50. Large-diameter solid-stem augers are used to drill holes in stable formations. *(Getty Refining and Marketing Company)*

Rotary bucket drilling of water wells has found primary application in areas of clay formations that stand without caving while the borehole is drilled and pipe is installed to serve as well casing. Drilling in sand below the water table is difficult, but not impossible if the hole is kept full of water or drilling fluid. A considerable supply of water may be needed if the sand formation is quite permeable. Thus, many drillers will use drilling fluid additives such as bentonite or polymers to control fluid loss. The maximum demand for water may last for only a few hours, however, because drilling will proceed rapidly under favorable conditions.

Cobbles and boulders can cause much difficulty in the bucket-auger procedure because they must be picked out of the bottom of the hole individually by using an orange-peel bucket, stone tongs, or ram's-horn tool. The hole diameter must be large enough to permit the use of these tools when necessary.

In operation, an auger bit will remove a cylinder of material 24 to 48 in (610 to 1,220 mm) deep in a contiguous mass. Therefore, samples obtained by the bucket-auger method are representative of the formation being drilled, unless sloughing or caving of the borehole walls has occurred.

Solid-Stem Auger

A second boring method uses a solid-stem auger with either a single flight (one section) or continuous flighting (multiple sections)*. Augers having a single section of flighting are commonly called earth augers, construction augers, or large-diameter augers (Figure 10.50). Earth augers with diameters as large as 54 in (1,370 mm) have been used in shallow holes, but 14- to 24-in (356- to 610-mm) single-flight augers are more common. Borehole depths of 60 ft (18.3 m) are not unusual in stable ground using the smaller diameter augers.

Drilling rigs equipped with large-diameter earth augers are similar in most respects to bucket auger rigs. They usually employ a kelly bar drive system. As with bucket

*In a strict sense, flighting is the spiral flanges welded to pipe. However, each auger section is commonly referred to as a flight. A single flight consists of one length of auger with flighting; continuous flighting refers to multiple auger sections with continuous spiral flanges.

augers, special hardened teeth or cutters are used when augering through hard ground, cobbles, or soft rock. This method is ineffective in loose ground or when drilling below the water table. It is sometimes used to bore a large-diameter hole to the water table; thereafter, casing is set and other drilling methods are used to complete the well. Shallow water wells are often constructed by augering to the top of a sand aquifer, lowering small-diameter pipe to that depth, and then advancing the pipe into the saturated formation by a bail-down or jetting operation.

Solid-stem augers with continuous flighting are used to advance holes in stable formations. Solid-stem augers are not truly solid, because the continuous flight design is welded onto small-diameter pipe; but the hexagonal pin placed at both ends of the flight (section) makes this type of auger nonhollow. Drill rigs turn the auger sections using a rotary drive head mounted on a hydraulic-feed mechanism that pushes the auger section down or pulls it back. Single auger lengths are generally 5 ft (1.5 m); diameters range from 4 to 24 in (102 to 610 mm), with diameters of 6 to 14 in (152 to 356 mm) used in well drilling. Although depths of 400 ft (122 m) have been recorded with the 6-in auger, auger depths of 40 to 120 ft (12.2 to 36.6 m) are more usual for the common diameters.

For drilling, a special auger bit or cutter head is attached to the leading auger flight section and cuts a hole for the flights to follow. The cutter head is usually 2 in (51 mm) larger in diameter than the flights, providing about 1 in (25 mm) clearance. The cuttings are brought to the top of the hole by the flights which act as a screw conveyor. As the auger drills into the earth, more auger sections are added until the desired depth is reached or penetration is halted by obstructions, hard ground, or caving conditions.

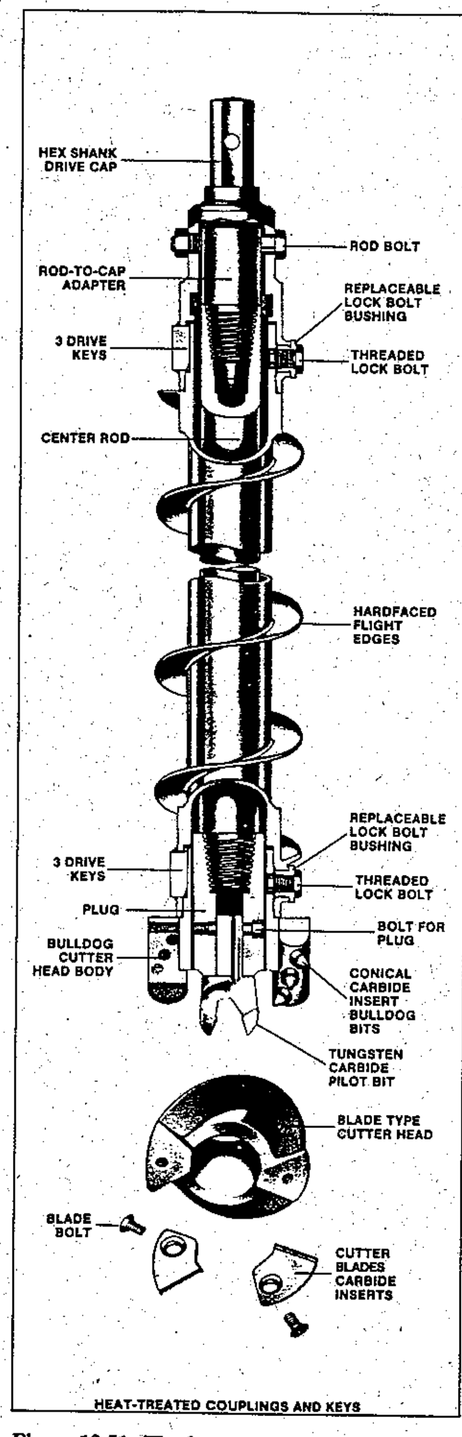


Figure 10.51. The lowest flight in a hollow-stem auger drill string is equipped with a cutter head and a pilot bit. *(Mobile Drilling Company, Inc.)*

Hollow-Stem Auger

The third augering method is the hollow-stem continuous-flight augering method. Although geotechnical and exploration drillers have been using the hollow-stem auger since the early 1950's, its use by the water well drilling industry has been quite limited until recently. The flights for the hollow-stem auger are welded onto larger diameter pipe with a cutter head mounted at the bottom (Figure 10.51). Unlike the solid-stem method, drill rods (drill stems) can pass through the center of the auger sections. A plug is inserted into the hollow center of the cutter head to prevent soil from coming up inside the auger. This center plug has an attached bit that helps advance the auger. The drill rod and plug connect through the auger flights to the top-head drive unit by small-diameter drill rods to insure that the drill rods and plug rotate with the flights. The center plug is omitted in stiff or dense formations because only 2 to 4 in (51 to 102 mm) of earth will rise up inside the hollow stem.

Hollow-stem augers with outside diameters ranging from 6¼ to 22 in (159 to 559 mm) [2½ to 13 in ID (64 to 330 mm ID)] have been used to drill water wells, although the common outside diameters are 6¼ to 13 in (159 to 330 mm) [2½ to 6 in ID (164 to 152 mm ID)]. Auger lengths are usually 5 ft (1.5 m), but on larger hollow-stem rigs, especially those equipped with carousel racks, the auger flights are 10 ft (3 m) long and are stored in 20-ft (6.1-m) sections. Holes as deep as 300 ft (91.5 m) have been drilled with 6¼-in diameter hollow-stem augers; more common depths in stable formations are 120 ft (36.6 m) with 6¼-in diameter hollow-stem augers and 40 ft (12.2 m) with 12-in (305-mm) diameter hollow-stem augers.

Hollow-stem augers are more effective than solid-stem augers because they can be used as temporary casing to prevent caving and sloughing of the borehole wall. The hollow-stem method is a fast and efficient means of drilling and completing small-diameter wells to moderate depths. Screens can be installed and filter packed without using casing or drilling fluids. Use of the hollow-stem auger method is also particularly advantageous in obtaining accurate samples (see Chapter 8). A major disadvantage of this method is the relatively high cost of hollow-stem flight augers.

DRIVEN WELLS

Driven wells can be installed only in unconsolidated formations that are relatively free of cobbles or boulders. Well points can be driven by hand methods to depths of about 30 ft (9.1 m), depending upon the tightness of the soil. Well points driven by hammers weighing 250 to 1,000 lb (113 to 454 kg) reach depths of 50 ft (15.2 m) and even more in favorable situations. In some cases, points are driven out the bottom of larger diameter casing when the aquifer has been reached. Points may be set to greater depths if the screen is protected by casing during driving. At a predetermined depth, the casing is pulled back to expose the screen (Figure 10.52).

Whether driving is to be done by hand or machine, the first step is to bore a hole that is slightly larger than the well point with a hand auger or post-hole digger. The bored hole must be vertical and should be as deep as possible. The drive point and one or more 5-ft (1.5-m) lengths of riser pipe are assembled. Drive couplings should have recessed ends and tapered threads to provide stronger connections than ordinary plumbing couplings. Pipe-thread compound is applied to the threads to make the joint airtight. When ready, the well-point and riser-pipe assembly is set in the bored hole and the hole backfilled. Before driving begins, a malleable iron drive cap is usually screwed to the top of the pipe. Occasionally, a drive coupling may be used when the driving hammer has a centering guide.

Hand driving is best done with a weighted pipe, similar to the type used for driving steel fence posts. It may be operated by one or two persons, depending on its weight. Driving can also be done with a heavy maul, but this is not recommended because it is difficult to deliver square, solid blows with the maul, and glancing blows may break or bend the pipe.

Driving tools can be suspended from a tripod or derrick. The driver must be hung directly over the center of the well so that it will strike square blows. The weight of these tools varies from 75 to 100 lbs (34 to 45 kg) or more. The heavier driving weights are more efficient and are usually operated with a light-duty drilling machine. For example, the spudding action of a cable tool machine is ideally suited for rapid driving with these tools. Other mobile, power-driven drivers are available and are ideal if a large number of points are to be set (Figure 10.53).

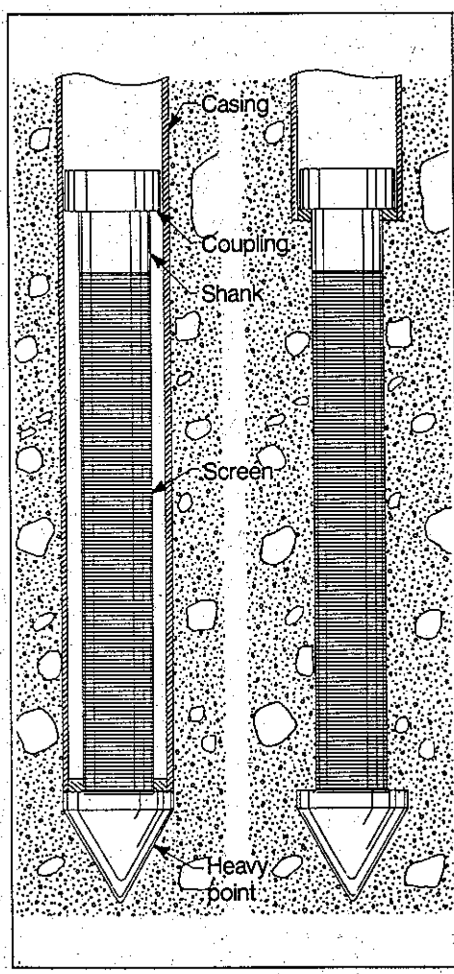


Figure 10.52. In rocky terrains, a drive point can be set at greater depths if it is protected by casing. For this procedure, the driller builds up or purchases a special heavy point that rests just beneath the bottom of the casing. During driving, the casing pushes the point downward, while the body of the casing protects the screened portion of the point.

To insure that the threaded joints remain tight, the riser pipe is turned slightly with a wrench periodically. Rotation of the riser pipe, however, does not make the well point drive more easily, and in fact the screen can be damaged by excessive twisting. The wrench should only be used to take up slack in the threaded joints (two wrenches are usually used to tighten joints to keep the point from turning).

Driven wells are usually pumped by suction lift; therefore, the static water level must be within about 15 ft (4.6 m) of the surface. If 2-in (51-mm) or larger pipe is used, certain jet or cylinder pumps can be installed to lift water from greater depths.

DRILLING PROCEDURES WHEN BOULDERS ARE ENCOUNTERED

In many formations, boulders or large cobbles can slow or even stop drilling progress regardless of the drilling method being used. If the casing or borehole is being deflected, the driller must do something about the boulders before drilling can be continued. Boulders occur commonly in glacial tills, extremely coarse outwash deposits, former beach zones now buried, conglomerate deposits that formed near the base of steep slopes, alluvial fans, and alluvial deposits in mountainous regions. Drilling costs can rise significantly when boulders are encountered in the hole.

In general, do not drill below a protruding boulder because it may fall partly into the hole causing the bit to become lodged. Whether boulders are removed or destroyed will depend on the drilling method being used. Alternative procedures include the following:

Cable Tool:

1. Change the bit.
2. Increase drill-string weight to break the rocks.
3. Bail out material below the boulder so that it drops into the hole. Fluid levels may have to be increased to keep the borehole open.
4. Blast the boulder.

Direct Rotary:

1. Increase the weight on the bit to grind through or crush the rock or force it to the side of the borehole.
2. Install a new or different bit.
3. Fish out the boulder if it is completely within the borehole.
4. Switch to air and use an air hammer.
5. Cement the boulder if it is sufficiently far above the aquifer, then continue drilling.
6. Blast the boulder.

Reverse Rotary:

1. Install a new bit to either push the boulder into the borehole or grind up the rock; cement can be used to stabilize the rock (if boulders are not near the aquifer).
2. Increase the weight on the bit.
3. Fish out the boulder.

Air Rotary with Casing Driver:

1. Keep the bit close to the bottom of the casing so boulders cannot become lodged between the bit and casing.
2. Drill and drive only short distances.
3. Increase the weight on the bit.
4. Pull back slightly to allow the boulder to fall into the borehole or be pushed into the borehole wall.
5. Change the bit, preferably to a down-the-hole hammer.
6. If boulders are sufficiently far above the aquifer, cement them into position so they can be drilled.

Figure 10.53. A mechanical driving device facilitates placing a large number of well points. *(Crystal Water Products)*

Several general points can be made concerning drilling through boulders:

1. The driller should proceed cautiously to prevent damaging the drive shoe or deflecting the casing.
2. It may be best to case through boulders.
3. Drill at least 5 to 10 ft (1.5 to 3 m) into the rock to make sure that bedrock has been reached.
4. If the casing has been dented by a boulder during driving, the casing diameter should be restored by using a casing swedge (the swedge is also useful in lining up broken casing so it can be lined with a sleeve).

Although blasting is recommended as a method for destroying boulders, it is the least acceptable solution because of possible casing and borehole damage. Therefore, any blasting procedure should be used with caution and only as a last resort. State, municipal, federal, and insurance requirements or codes relating to blasting should be thoroughly understood by the drilling contractor before using explosives. For drillers working in areas with relatively shallow boulder concentrations, conversion to air rotary rigs and the use of drill-through casing drivers are recommended.

If blasting is seen as the only solution, several important aspects should be considered. First, accurate measurements are vitally important in successful blasting procedures. The driller must know the precise depth of the hole, the length of casing in the hole, and the depth at which the charge is placed. Negligence in determining these depths can cause serious economic and safety problems.

Second, it is difficult to set specific rules for the size of the explosive charge. The amount required depends on several factors: general characteristics of the formation, size of the boulders, composition of boulders, depth of the hole, and diameter of the well to be drilled. Many drillers use an experimental approach. A charge of moderate size is used initially; if it proves to be too small, the operation is repeated with a larger one. Drillers with experience in a given local area can often judge the proper amount to use. It is nearly impossible to get into serious trouble when using a charge that is too small, although ineffective charges will slow down the overall drilling operation. Use of too much explosive in the beginning, however, may damage the casing and shatter the formation more than necessary. Never blast closer than 50 to 60 ft (15.2 to 18.3 m) from the surface.

Third, the explosive should always be set as far below the casing (if used) as possible. If necessary, the casing should be pulled back. Maintaining a high fluid level in a cable tool hole will keep the unconsolidated material from heaving into the hole when the casing is pulled back. Rupturing or bending of the casing caused by the explosion may necessitate abandonment of the borehole.

FISHING TOOLS

In most drilling methods, tools can be broken off or dropped into the borehole. The object or tool that is lost in the hole is called the "fish," which the driller retrieves by "fishing." Fishing jars are used in the cable tool method to retrieve tools from the hole. They are placed between the fishing stem [usually 10 ft (3 m) long] and a fishing tool such as a horn socket or center spear. In this position, the stem increases the impact of the jars on the fishing tool during the upstroke. The greater stroke of the fishing jars prevents accidental downstroke hitting during retrieval of the lost tool. Hitting both up and down will usually free the "fish" to be removed from the hole.

In the rotary drilling method, the shear stresses placed on the drill string are often excessive, unlike the cable tool method where only the force of gravity is utilized for drilling. These shearing stresses are magnified because the weight of the entire drill column is augmented by the hydraulic-driven pull-down weight that may be applied by the driller. These pull-down weights may reach 30,000 lb (13,600 kg) or more. Because the torque applied to the drill string can occasionally exceed the breaking strength of the equipment, special fishing tools have been developed to extract pieces of the sheared drill string from the hole.

Six fishing tools are used most commonly in rotary drilling operations: tapered tap, die collar, releasing spear, junk mill, circulating overshot, and magnet (Figure 10.54). Many drillers construct fishing tools that may be particularly suitable for their own equipment. After determining the depth at which the string or tool has been lost, the driller attempts to enter (tapered tap) or overshoot (die collar) the top of the lost drill rod and then rotate the fishing tool until it is firmly attached. Releasing spears can be used in place of a taper tap. They offer the advantage of quick release from the fish and provide easy re-engagement if necessary. If greater force is required to pull the fish, another type of tool called a releasing and circulating overshot is used. It consists of three main components — a top sub, a bowl that houses the engaging and packing-off element, and a guide to center the tool over the fish. A junk mill is used to grind up smaller objects lost in the borehole. Powerful magnets are useful in removing relatively small tools or other parts from the hole. To be successful, circulation must be established or maintained during most fishing operations.

One particularly common fishing operation in large-diameter holes involves retrieval of roller cones that have become detached from the bit. Failure of the bearings on which the cones rotate is the principal cause of cones falling to the bottom of the borehole. Bearing failure is usually attributable to excess weight on the bit, high operating temperatures, or excessive use. The most common techniques for retrieval of lost cones includes the use of a junk basket, a strong magnet, or a button or diamond bit to grind up the cone. Lost cones can sometimes cause abandonment of the well. To avoid this problem, the driller should immediately replace any bit on which a cone has become damaged or locked in place.

GROUTING AND SEALING WELL CASING

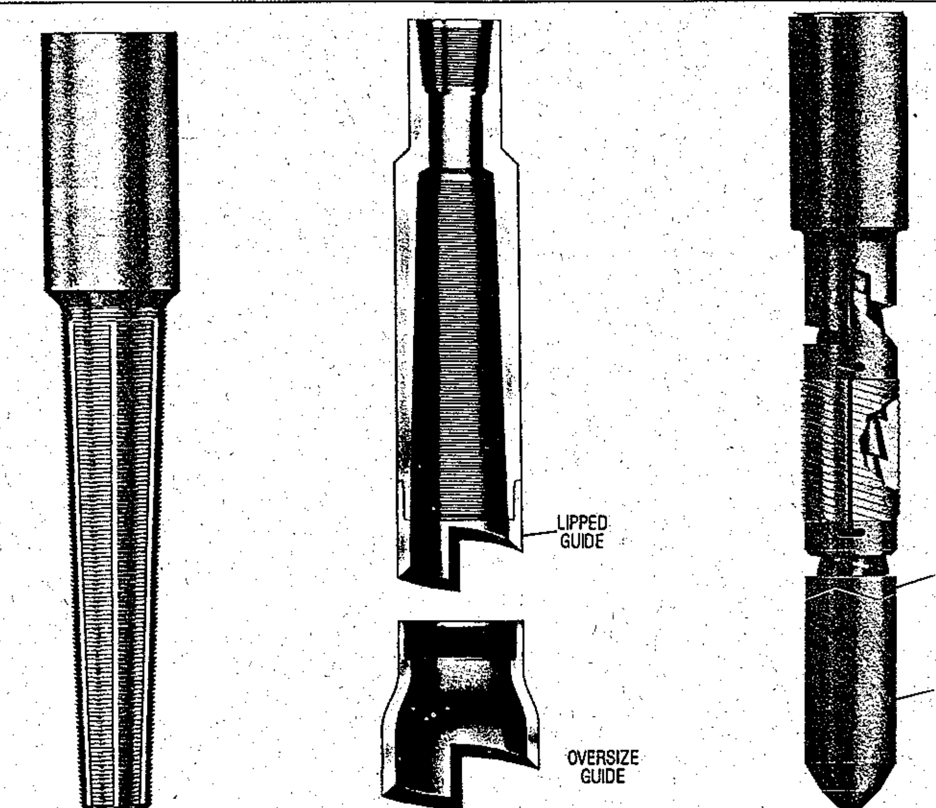
In engineering practice, grouting is the act of injecting certain substances into the void space of earth materials to reduce or eliminate their permeability, consolidate them, or increase their strength (Bowen, 1981). Thus, grouting is widely used in constructing tunnels, dams, bridges, and foundations for buildings. Low-viscosity grouting materials are used in soils having low hydraulic conductivity, whereas high-viscosity grouts are used in coarse-grained, highly permeable soils. Although several basic types of grouting materials exist, multiphase (suspension) systems are common in the water well industry.

Grouting (cementing) well casing involves filling the annular space between the casing and the drilled hole with a suitable slurry of cement or clay*. The term "grouting" is used by drillers to describe the process of mixing and placing grout. The length

*The terms "grouting" and "cementing" are often used interchangeably, but grouting is the preferred term because it refers to the filling of void spaces. Cement is the most common grouting material and thus cementing has become synonymous with grouting.

of the borehole section to be grouted will vary according to water well codes, aquifer structure, and water quality. Typically, all public water supply wells must be grouted from the surface to a depth of at least 50 ft (15.2 m) to prevent leakage of contaminants from the surface. Water wells constructed in rock that is overlain by relatively thin, loosely consolidated sediment will usually be grouted from the surface to the rock. In some formations where poor-quality aquifers are interspersed with high-quality water zones, the poor-quality aquifers are cemented off. Grouting is also standard practice in monitoring well construction.

The grouting methods described below focus primarily on the use of cement and water (neat cement), although the slurry may contain sand, bentonite, or hydrated lime in certain situations. A clay slurry made with a high-grade bentonite can also serve for grouting, provided it is used at a depth where drying and shrinking of the grout will not occur, and where water movement will not wash away the clay particles. Synthetic materials, especially polymers, are also used as grouting materials, but their extremely low solids content and great shrinkage if dried make them less suitable for sealing wells.

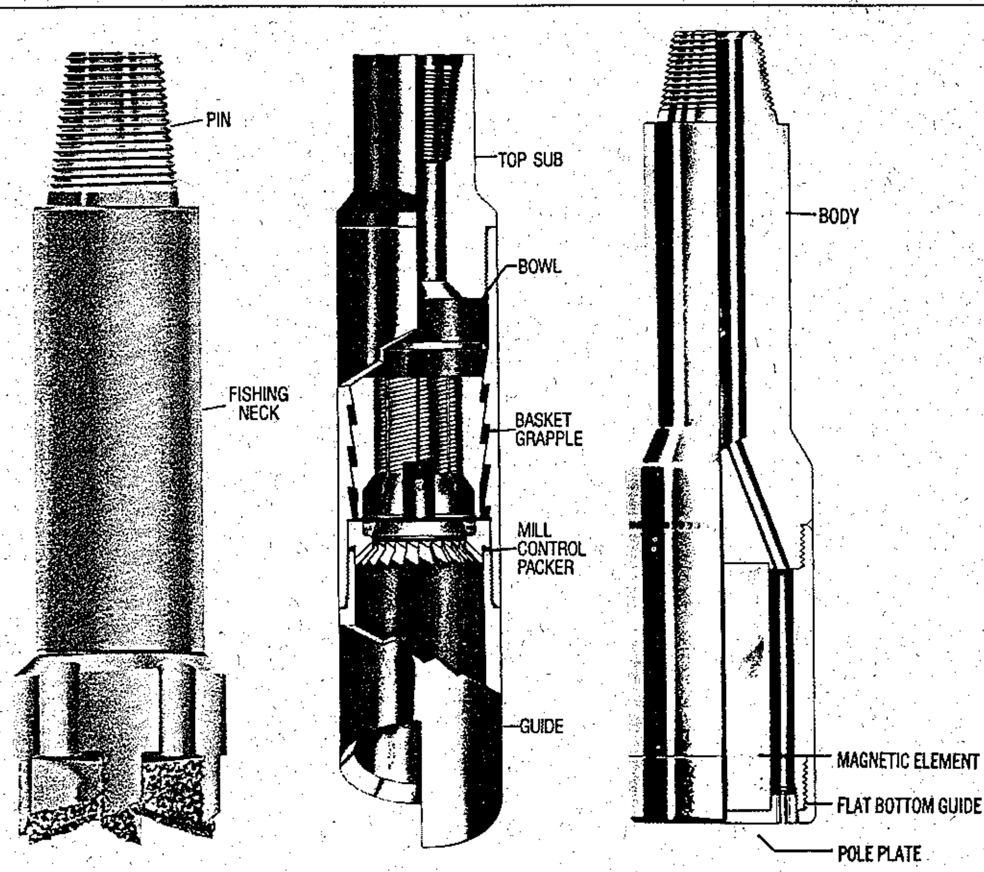


(a) Taper tap **(b) Die collar** **(c) Releasing spear w bull nose nut (shoul mandrel in enga position)**

Figure 10.54. In rotary drilling, six common types of fishing tools are used to recover drilling tools or casing lost in the borehole. *(Bowen Tools, Inc.)*

Various types of cement are manufactured to accommodate different chemical and physical conditions found in the subsurface environment. Five types are given in ASTM specifications and are used generally at the ground surface. The high pressures and temperatures encountered in deep wells, especially oil wells, has led to the development of eight classes of cement under API specifications. Table 10.4 lists five API cement classes used in water well construction, although Classes A, B, and C are more commonly used. Cement classifications used outside the United States are given in Appendix 10.B. The constituents of these cements are given in API Standard 10A.

The compressive strengths of portland (types A and B) and high-early cements (type C) are shown in Table 10.5 for setting times of 24 and 72 hours at various temperatures. Various compositions of cement have different compressive and tensile strengths after curing; compressive strengths are usually about 10 times greater than tensile strengths. Compressive strengths are determined by crushing small cubes of cement under laboratory conditions. For most drilling operations, the cement should reach a compressive strength of 500 psi (3,450 kPa) before drilling is resumed. The temperature in the borehole, chemistry of the formation water, dilution of the cement,



(d) Junk mill with fishing neck **(e) Releasing and circulating overshot with basket grapple** **(f) Magnet**

Table 10.4. Classifications of Cements Used in Water Wells

API Classification	Special Properties	Recommended Range for Well Depth ft.	m
A (similar to ASTM C150, Type I)	None	0-6,000	0-1,830
B (similar to ASTM C150, Type II)	Moderate to high sulfate resistance	0-6,000	0-1,830
C (similar to ASTM C150, Type III)	High early strength	0-6,000	0-1,830
G	Can be used with accelerators and retarders	0-8,000	0-2,440
H	Can be used with accelerators and retarders	0-8,000	0-2,440

and downhole pressure affect the rate at which the cement cures. Generally, the 500-psi compressive strength is reached between 12 and 24 hours after placement.

Equipment for mixing and placing cement grout need not be elaborate for most water-well work. However, the chemical reaction that causes grout to set and harden begins as soon as cement and water are mixed, and the equipment used to mix and place the grout must be adequate to complete the installation while the grout is still fluid (Figure 10.55).

The size of the annular space required for grouting depends on the method of grouting. Thus, planning the size of the borehole is important. The annular space to be grouted should have a diameter that is 4 to 8 in (102 to 203 mm) larger than the casing. The ideal result is a uniform sheath of cement around the casing for the entire vertical distance to be grouted. Tight places and "dead spots" result where casing not properly centered touches the wall of the hole, causing channeling of the slurry. Some

Table 10.5. Compressive Strengths of Portland and High Early Cement

Temperature		Borehole Pressure		Typical Compressive Strength							
				24 Hours*				72 Hours*			
				Portland		High Early		Portland		High Early	
°F	°C	psi	kPa	psi	kPa	psi	kPa	psi	kPa	psi	kPa
60	15.6	0	0	615	4,240	780	5,380	2,870	19,790	2,535	17,480
80	26.7	0	0	1,470	10,140	1,870	12,890	4,130	28,480	3,935	27,130
95	35.0	800	5,520	2,085	14,380	2,015	13,890	4,670	32,200	4,105	28,300
110	43.3	1,600	11,030	2,925	20,170	2,705	18,650	5,840	40,270	4,780	32,960

*Strengths based on the following criteria:

	Portland		High Early	
Water	5.19 gal/sack	19.6 ℓ/sack	6.32 gal/sack	23.9 ℓ/sack
Slurry weight	15.6 lb/gal	1,870 kg/m³	14.8 lb/gal	1,770 kg/m³
Slurry volume	1.18 ft³/sac	0.03 m³/sack	1.33 ft³/sack	0.04 m³/sack

(Halliburton, 1968; Courtesy of SPE Monograph, Cementing, 1976)

of the design criteria applying to grouting of well casing for sanitary protection are given in Chapter 18.

State or federal laws may dictate the minimum length of grout required for various casing diameters for certain types of wells. The drilling contractor should become familiar with specific regulations for the type of wells drilled.

It is important to recognize that cement grouts exert greater collapse pressure on casing than do either water or drilling fluid. Water alone exerts 0.433 psi (3 kPa) for every 1 ft (0.3 m) of depth in the borehole. Because some solids are added to water making up a drilling fluid, the weight is greater; a typical drilling fluid made with clay additives weighs approximately 9.5 lb/gal (1,140 kg/m^3), versus 8.33 lb/gal (998 kg/m^3) for water. Thus, the required collapse pressures for water well casing are usually calculated on the basis of 0.5 psi per ft (3.4 kPa per 0.3 m) of depth. The specific gravity of cement grouts is about twice that of water; the cement and water slurry will weigh approximately 123 lb/ft^3 or 16.4 lb/gal (1,970 kg/m^3). To calculate the potential pressure at the bottom of the casing (where it is greatest), the pressure increase with depth is assumed to be 0.8 psi per ft (5.5 kPa per 0.3 m) at a minimum. For example, the maximum pressure that could be exerted by the cement grout at the bottom of a 500-ft (152-m) casing is 0.8 times 500, which equals 400 psi (2,760 kPa). A safety factor of two is recommended when selecting the wall thickness for the casing. Any fluid inside the casing will reduce or balance the pressure exerted by the cement column, depending on the relative heights of the fluid and cement columns. But if the inside of the casing contains no water or drilling fluid, the casing must be

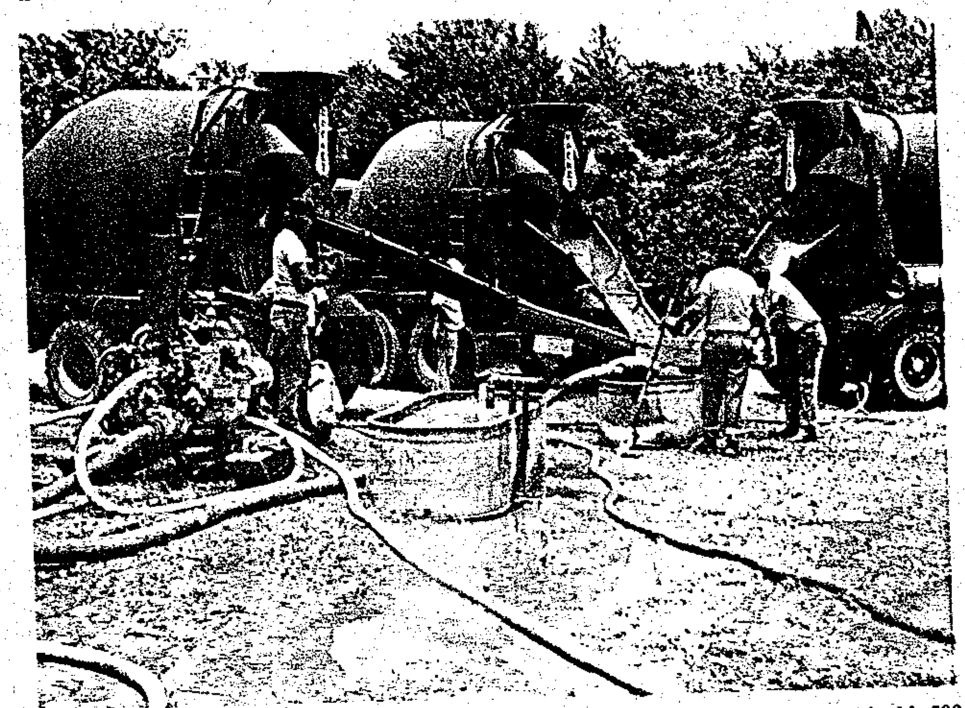


Figure 10.55. Three cement trucks are required to provide enough cement to grout the casing in this 500 ft (152 m) borehole. The cement is pumped from the stock tank into the borehole by a positive displacement duplex pump, shown on the left. *(Test Drilling Services)*

strong enough to support the entire grout column.

Proportioning Cement Grout

Laboratory tests indicate that 5.2 gal (19.7 ℓ) of water are needed to hydrolyze one 94-lb (42.6-kg) sack of portland cement. This mixture produces a slurry weight of 15.6 lb/gal (1,870 kg/m^3). An advantage of using the proper water-cement ratio is more effective bridging of cement particles in the pores of permeable formations, which prevents excessive penetration of the grout into these formations. Although thinner mixtures with more than 6 gal (23 ℓ) per sack are used for grouting foundation materials, this ratio is less suitable for water-well work. Shrinkage increases with greater water content, because water is squeezed out of the thinner mixtures by pressure against fine sand or other permeable formation materials. Cement will settle out of the slurry if the ratio is greater than 10 gal (38 ℓ) per sack of cement. Water used for grout should be free of oil and other organic material. Dissolved minerals should be less than 2,000 mg/ℓ; high sulfate content is particularly undesirable.

Bentonite clay can be added to the cement to hold cement particles in suspension,

Table 10.6. Effects of Additives on the Physical Properties of Cement

		Bentonite	Diatomaceous Earth	Pozzolan	Sand	Heavy Minerals	Accelerator	Sodium Chloride	Retarder
Density	Decrease	⊗	⊗	⊗					
	Increase				⊗	⊗		x	
Water Required	Less								
	More	⊗	⊗	x	x				
Viscosity	Decreased						x	x	⊗
	Increased	x	x	x	x	x			
Thickening Time	Accelerated						⊗	⊗	
	Retarded	x	x						⊗
Early Strength	Decreased	x	x	x					⊗
	Increased						⊗	⊗	
Final Strength	Decreased	⊗	⊗	x		x			
	Increased								x
Durabilty	Decreased	x	x						
	Increased			⊗					
Water Loss	Decreased	⊗							x
	Increased		x						

x Denotes minor effects.
⊗ Denotes major effects and/or principal purpose for which used.
(API, 1959; Smith, 1976)

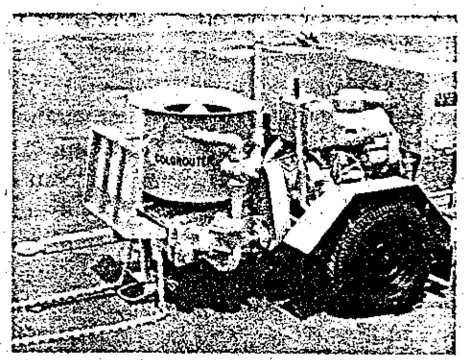


Figure 10.56. Portable grouting machines are capable of performing both the mixing and pumping operations. *(Acker Drill Company, Inc.)*

reduce shrinkage, and improve fluidity of the mixture. Approximately 3 to 5 lb (1.4 to 2.3 kg) of bentonite should be mixed with 6.5 gal (25 ℓ) of water per sack of cement. If the amount of bentonite exceeds 6 percent, excessive shrinkage of the cement will occur. It is best to mix the bentonite and water first, then add cement to the clay-water suspension.

Potential fluid-loss conditions may call for the addition of sand or other bulky material to permit the grout to bridge larger openings without excessive fluid loss. These coarse materials add to the difficulty of handling and placing grout, but they may be necessary to reduce cost of material where large openings are to be filled. The physical effect of additives commonly added to cement are given in Table 10.6.

Mixing the Grout

It is important that grout be mixed thoroughly and be free of lumps. If the mixture is purchased from a ready-mix concrete plant, the correct proportions must be assured. To avoid stones and lumps of concrete, the driller should insist that the delivery trucks be thoroughly cleaned before the grout is transported. It is best to provide a protective strainer on the tank from which the grout is pumped into the well.

Some drillers use small portable grouting machines that combine both the mixing and pumping operations (Figure 10.56). Many of these machines are equipped with a positive displacement pump because this type of pump can work efficiently against much greater head pressures with little loss in emplacement volume. The effective operation of a centrifugal pump is much more limited under high head conditions. Most drillers avoid using the mud pump on their rotary rigs because of the abrasive qualities of the cement and the difficulty in removing all traces of the cement from the pump after completing the cementing operation.

The volume of grout required cannot always be determined accurately. Irregularities in the size of the borehole and losses into fractured rock occur in many wells. Therefore, the driller must be prepared to augment initial estimates on short notice. Table 13.13 (page 445), which gives the volume of filter pack required, can also be used to estimate the minimum amount of grout required between different casing diameters or be-

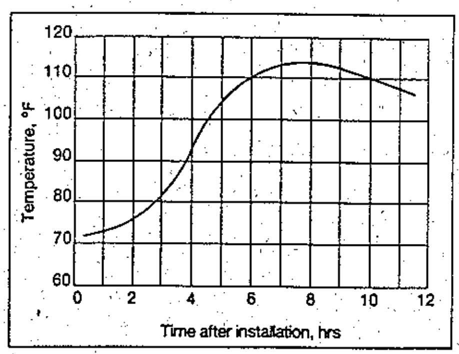


Figure 10.57. Heat is produced when cement is hydrated. The amount of heat released depends on the volume of cement used to grout the casing, the ambient temperature of the formation, and the pressure in the borehole. This graph shows the temperature change over time at a depth of 550 ft (168 m) where the formation temperature was 65° F (18.3°C), the mixing water temperature was 74° F (23.3°C), and the slurry weighed 15.4 lb/gal (1,850 kg/m³). *(Canadian Institute of Mining and Metallurgy, 1965)*

tween the casing and borehole wall.

When water is mixed with cement and hydration occurs, heat is released (Figure 10.57). The amount of heat released is a function of the volume of cement — the more cement, the more heat. If the formation temperature is high, the hydration process is accelerated and heat is released more quickly. If cement fills a 2-in (51-mm) annulus, the heat produced during hydration creates a maximum temperature rise of 35° to 45°F (19.5° to 25°C) (Smith, 1976).

Slurry Placement Methods

Successful placement of the cement will depend on the temperature and pressure in the borehole, how well the casing is centered in the hole, and the emplacement method. Temperature has a significant effect on how fast the cement slurry hydrates and thus how fast the cement develops strength. Pressures caused by the weight of the drilling fluid can reduce the rate at which the cement can be pumped. At high pressures (only a problem in deep water wells), the hardening time for the cement can be substantially reduced. The use of centralizers is important to assure a uniform thickness of cement around the casing. Centralizers should be placed every 40 ft (12.2 m) on the casing. Several placement methods are described below. Each method is satisfactory but care should be taken to assure that channeling does not occur, thus avoiding gaps in the cement.

Figure 10.58. A cement basket is mounted on the casing to support the column of cement grout to be placed above it. Use of a basket prevents grout from entering weak underlying formations or infiltrating the filter pack. *(Corner S. A.)*

To assure that grout will provide a satisfactory seal, it is necessary to place it in one continuous operation, before setting begins. Regardless of the grouting method used, the grout should be introduced first at the bottom of the space to be grouted. This procedure minimizes both contamination or dilution of the slurry and bridging of the mixture. Suitable pumps with sufficient air or water pressure should be used to force grout into the space to be filled. If the cement is pumped under turbulent flow conditions, drilling fluid removal is enhanced and voids are filled more completely.

Moyno™, diaphragm, and piston pumps are most often used to pump cement grout. The Moyno pump is a positive displacement pump with an effective output pressure of 225 to 250 psi (1,550 to 1,720 kPa); it cannot be permitted to pump sand, however. Diaphragm pumps, although having lower output pressures of 100 to 110 psi (690 to 758 kPa), can handle particles up to ¼ to ⅜ inches (6.4 to

9.5 mm) in diameter. They are not as efficient as the Moyno pump because of higher friction losses. Both types are used for batch mixing.

For larger grouting jobs, either piston pumps or, less frequently, centrifugal pumps are favored. Piston pumps of various sizes (2 x 3, 3 x 4, or 5 x 6) can build pressures to 120 psi (827 kPa), and have been used successfully to place grout to 3,000 ft (915 m) or more with a 2-in (51-mm) tremie pipe. Because they develop less pressure, centrifugal pumps can be arranged so that a hopper feeds the pump under pressure, thereby increasing pump output. The grout is usually placed in one continuous operation because so much water would be required to clean the pumps and pipe after batch mixing.

In cases where an open borehole has been drilled below the depth to which the casing is to be grouted, the lower part of the hole must be backfilled, or a bridge (cementing basket or formation packer shoe) must be set in the hole, to retain the slurry at the desired depth. Backfilling the hole to the proper level with sand is a common procedure. The sand must be fine enough so that cement will not penetrate downward more than a few inches. Controlled experiments indicate that there is no significant penetration by cement into uniform sand with grain size finer than 0.025 in (0.6 mm), or into nonuniform sand with hydraulic conductivity less than 3,000 gpd/ft² (122 m/day). Material sold ordinarily as plaster sand or mortar sand is usually satisfactory.

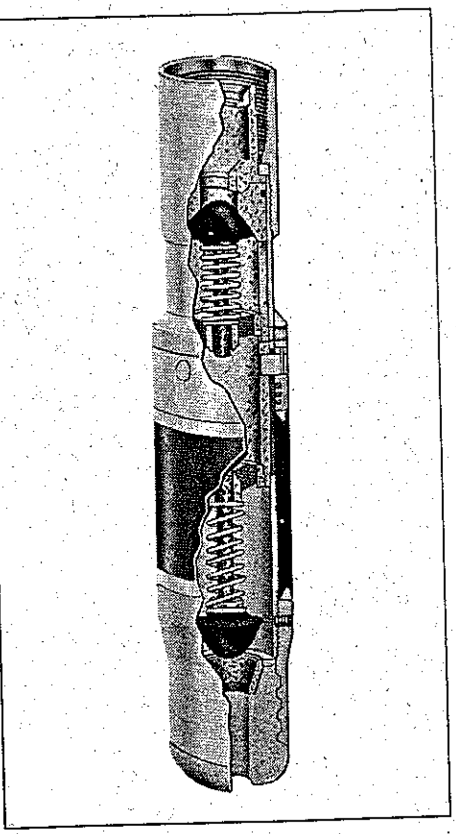


Figure 10.59. An external packer equipped with a float shoe can be installed in the casing string to facilitate placing cement grout. *(Halliburton)*

When the borehole cannot be backfilled, external packers combined with a float shoe or cement baskets are used to support the cement column. Cement baskets are installed on the outside of the casing by clamps (Figure 10.58). External packers must be installed in the casing string as the casing is run into the borehole (Figure 10.59); the packers are expanded before cementing begins.

Cement should be allowed to harden for 24 hours before drilling resumes, although some types of cement may require longer curing times. It is false economy to risk damaging a good grouting job by drilling the plug out too soon. If an attempt is made to drill out the plug prematurely, the drilling contractor ordinarily can determine if the cement is still soft.

Tremie Pipe Outside Casing

Grout can be placed through a string of small-diameter pipe (tremie or grout pipe) placed outside the casing. The casing is lowered into the hole with centering guides attached. Care must be taken to align the centering guides along the entire length of casing to be grouted so that the tremie pipe can pass by them. The lower end of the casing should be closed with a drillable plug or driven into clay so the grout cannot enter. To overcome the buoyant effect of the slurry, the casing may be filled with water or be held down by the weight of the drill rig. This may be dangerous if the drill rig is used and excessive pressures are built up in the borehole.

Grout can be placed by gravity through a tremie pipe, but pumping is preferred because the required volume of grout can be introduced rapidly and with little chance of leaving voids in the grout. Pump pressure must equal the hydrostatic pressure of the grout plus the fluid friction in the grout pipe and annular space.

For shallow holes where the grout is placed by a positive displacement pump, the cementing operation may be completed in a single step; that is, the position of the tremie pipe is not changed as the annulus is filled. If a centrifugal pump is used or if the hole is deep, the tremie must be raised periodically so the hydraulic head created by the cement does not exceed the working pressure of the pump. Usually the tremie is withdrawn one or more joints at a time, but the bottom of the tremie should always remain beneath the surface of the cement. The rate of tremie withdrawal will depend on the pumping rate and the volume of the annulus. The depth to the top of the grout can be detected by using a weighted line or a weight indicator. The volume (and therefore the height) of the grout can also be estimated by knowing the volume of material in the hopper before grouting begins.

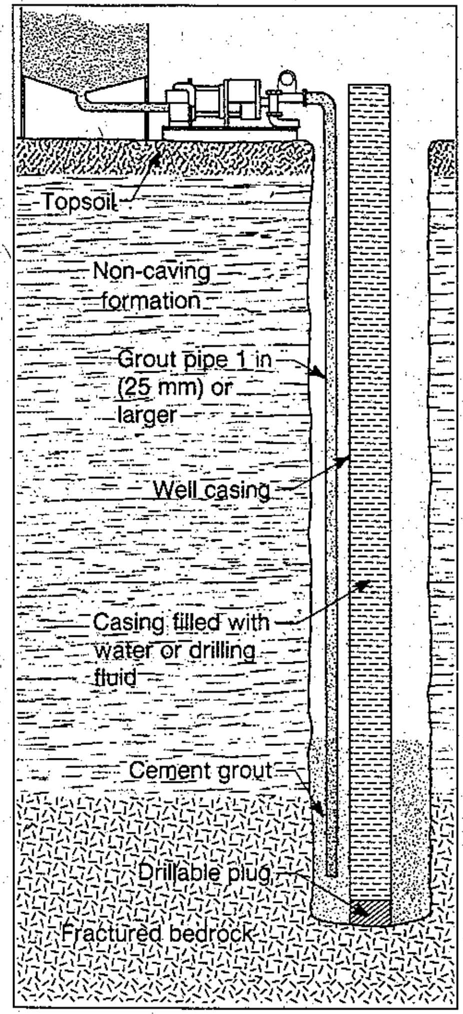


Figure 10.60. Grouting can be accomplished by means of a tremie pipe suspended in the annulus outside the casing. During grouting, the bottom of the tremie should always be submerged a few feet beneath the grout level. As the grout level rises, the tremie should be withdrawn at approximately the same rate.

The grout pipe must be large enough so that all the grout can be placed before hardening begins. A ¾- or 1-in (19- or 25-mm) grout pipe may be used, although 2-in (51-mm) pipe is used for deeper holes. The borehole should be 4 to 8 in (102 to 203 mm) larger than the casing to accommodate the grout pipe. Initially, the pipe should extend to the bottom of the annular space and should remain submerged in the slurry while the grout is being placed (Figure 10.60). Should the tremie become plugged, the output pressure can be increased, the tremie can be raised to reduce the pressure at the bottom of the line, or it can be vibrated or struck to dislodge the stuck material. If operations are interrupted for any reason, the pipe should be raised above the grout level and not be lowered into the slurry again until all air and water in the pipe have been displaced by grout.

When multiple filter-pack screens are separated by grouted casing sections, a larger diameter hole is drilled and placement of the slurry is usually done with a tremie outside the casing. The top of the filter pack is at least several feet above the top of the screen. A low-permeability sand is placed on top of the filter pack to contain the grout until it hardens (Figure 10.61). The grout is run up slightly higher than the formation to be isolated. Once the lower grout has set, filter pack material is again introduced for the next screen, followed by another layer of low-permeability sand, and then another grouted section if necessary.

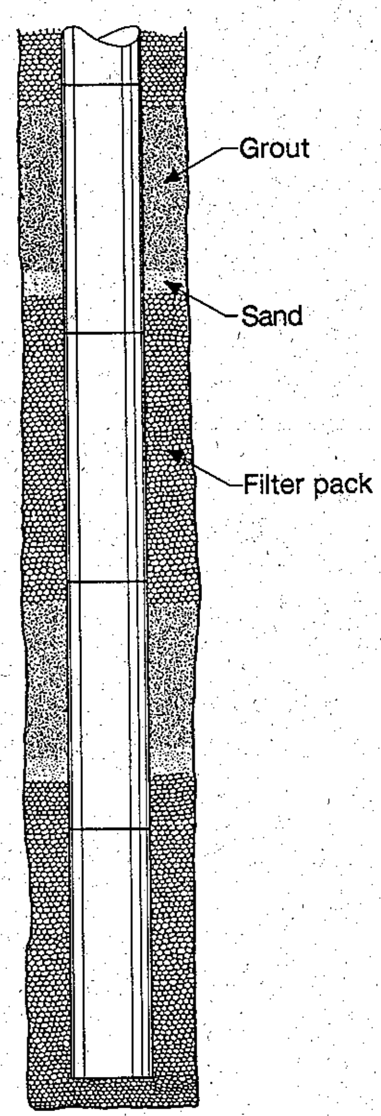


Figure 10.61. Sand is sometimes placed on top of the filter pack to prevent grout from penetrating into the pack.

Tremie Pipe Inside Casing (Inner String Method)

When the use of a grout pipe outside the casing is impractical, grouting may be done by using a grout pipe installed temporarily within the casing (Figure 10.62). In the oil-well industry, this is referred to as the inner-string method of cementing. A cementing plug (float shoe) is attached to the bottom of the casing, which permits the grout to pass into the annular space but prevents it from leaking back into the casing while grouting or after removing the grout pipe. Figure 10.63 shows a cementing plug with a ball-type check valve that prevents reverse flow of the grout. All the internal parts can be drilled out easily upon completion of the cementing.

In the grouting process, the casing is filled with water and suspended just above the bottom of the borehole. Grout is pumped through the grout pipe and float shoe and forced upward around the casing. When cement appears at the surface, displacing all other fluid in the annular space, the grout pipe is disconnected from the float shoe. Cement is washed out of the pipe by pumping water through it before removing it from the well. Because calcium residues may have a deleterious effect on the viscosity-building characteristics of some drilling fluid additives, the casing should be completely flushed with clean water after completing the cementing operation.

Casing Method of Grouting

The casing method of grouting, in which the slurry is forced down the casing and into the annular space (originally called the Halliburton method), has been adopted from the oil-well industry. In one method, two spacer plugs are used. One plug, introduced first, separates the cement slurry above from the drilling fluid in the casing; the other separates the slurry from water pumped in above it to wash the slurry from the casing (Figure 10.64).

After pumping water or drilling fluid through the casing to circulate fluid in the annular space and clear any obstructions from the hole, the first plug is inserted and the casing capped. A measured volume of grout is then pumped in, the casing is opened, a second plug is inserted, and the casing recapped. A measured volume of water is then added and pushed to the bottom of the casing, forcing most of the cement slurry from the casing and into the annular space. The water in the casing is held under pressure to prevent backflow of the slurry until it has set and hardened. When the cement has hardened sufficiently, the second plug and any cement remaining in the casing are drilled out; drilling is continued below the grouted section, through the first plug and into the formation. To protect the physical characteristics of some drilling fluids, it may be necessary to remove residual cement scale from casing walls with brushes or other descaling devices.

A modification of the double-plug procedure is favored by many drillers. After pumping a predetermined quantity of grout into the casing, a plug is installed on top of the grout and enough water is added to force most of the grout from the casing. The usual practice is to leave 10 to 15 ft (3 to 4.6 m) of grout in the casing. If only a single plug is used, that part of the slurry diluted by the drilling fluid

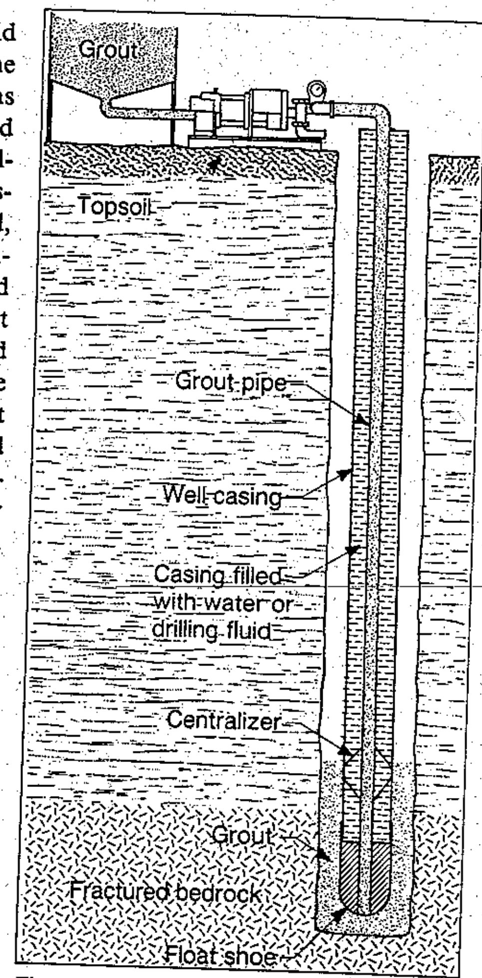


Figure 10.62. In the inner-string method of placing grout, the tremie is suspended in the casing. A cementing (float) shoe is attached to the bottom of the casing before the casing is placed in the borehole. A tremie pipe is lowered until it engages the shoe.

must be expelled to waste at the surface so that a sound, uncontaminated grout seal is achieved at the upper end of the casing. The use of a plug insures slurry and water separation, resulting in a proper grout seal at the lower end of the casing. To eliminate over or under displacement of the cement, a landing collar is set 10 to 20 ft (3 to 6.1 m) above the bottom of the casing to stop the drillable plug at the appropriate depth.

Spacer plugs should be made of materials that can be drilled easily (wood and cement are often used). When a plug settles on sand or clay, the cushioning effect of the soft formation permits the plug to sink into the formation before it is drilled out. Wood and some rubber-fiber combinations have been known to push down through 5 to 20 ft (1.5 to 6.1 m) of clay before being destroyed by the drill bit. Shredded fibers of wood are quite voluminous and can obstruct flow into the well if they are simply pushed aside while the water-bearing formation is drilled. To avoid damaging the bottom of the casing by exerting excessive pump pressure after the plugs have come together, a wire line is sometimes attached to the upper plug so that plug depths can be measured accurately.

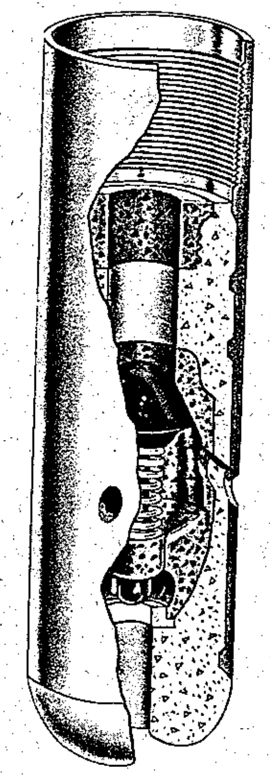


Figure 10.63. Cement can pass from the tremie through the bottom or sides of the shoe into the annulus. The cementing shoe has a ball-type check valve that prevents the grout from reentering the casing when the tremie pipe is withdrawn. The internal parts can be drilled out easily once the grout has hardened. *(Halliburton)*

In some cases it may be necessary to grout the borehole after the entire hole has been drilled. For example, if a screen has been installed in the lower portion of the casing string, and the annular space above the screen must be grouted, a cement basket (or baskets) is used to isolate the screen from the annulus to be filled with cement. Before the casing and screen string is installed, at least one, but preferably two, cement baskets are attached above the screen and a drillable bridge plug is placed in the casing above the screen. Holes are cut into the casing above this plug with a cutting torch, mills knife, or other type of perforator. A cement slurry is introduced into the casing and forced into the annular space above the cement basket (Figure 10.65). Grout is usually extended 5 ft (1.5 m) above and below the formation to be sealed. The bridge plug is drilled out after the cement has hardened. This method of placing grout should not be used in formations where low-quality water must be sealed off in multiple-screen installations or where screens are filter packed. The presence of the baskets interferes with the grouting and filter packing procedures.

Grouting Failures

Several factors may contribute to grouting failures. Some common problems are premature setting, partial setting, insufficient grout column length, voids or gaps in the grout, excessive shrinkage, and casing collapse. Premature setting of the cement can be a serious problem and is usually caused by incorrect assumptions concerning borehole temperature, or by hot mixing water, improper water-to-cement ratios, contaminants in the mixing water, mechanical failures, and interruptions of the pumping operation. Voids within the grouted annulus, another major grouting problem, are usually caused by contact of the casing with the borehole wall or by the presence of washouts.

Testing the Grout Seal

Before drilling out the grout plug, the effectiveness of the grout seal can be checked by three methods: measuring water-level change in the casing over time, pressure testing, and analysis of an acoustic (sonic) cement-bond log. In wells with a low static water level, the casing can be filled with water or drilling fluid and later checked for any water loss. If the static water level is high, the casing can be nearly emptied and any influx of water into the casing can be measured. This procedure should not be used with thin-walled casing. When pressure testing, the grout must be able to contain pressures of 7 to 10 psi (48.3 to 69 kPa) after curing for at least one hour. If the acoustic log is used, it must show that no voids or gaps exist in the grouted annular space (see Chapter 8).

Two other methods of checking the continuity of the grout are available, but they are not used often in the water well industry. The first consists of a temperature

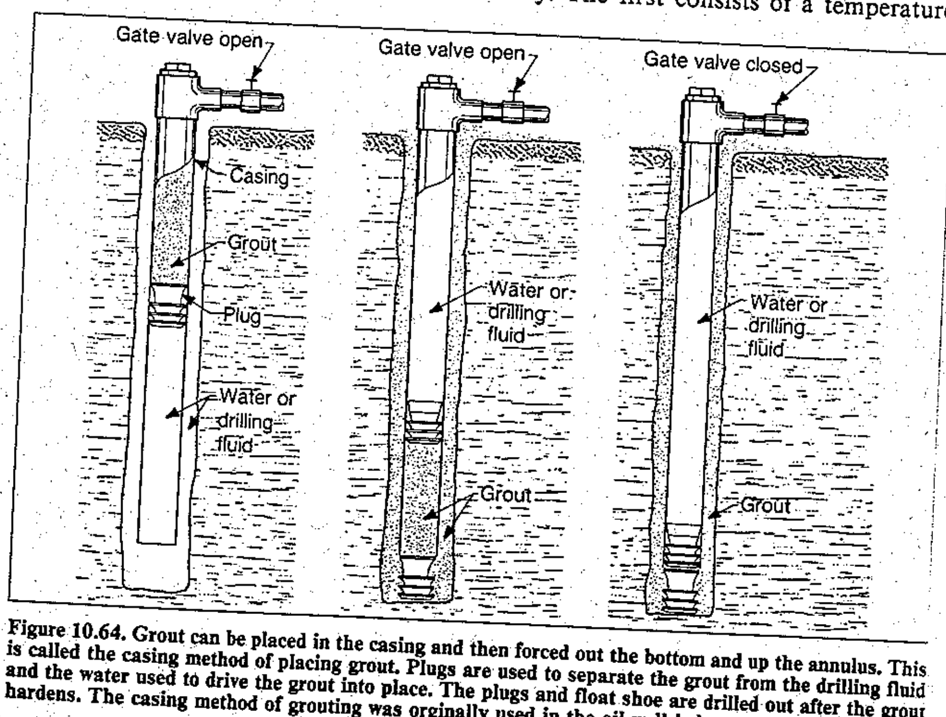


Figure 10.64. Grout can be placed in the casing and then forced out the bottom and up the annulus. This is called the casing method of placing grout. Plugs are used to separate the grout from the drilling fluid and the water used to drive the grout into place. The plugs and float shoe are drilled out after the grout hardens. The casing method of grouting was orginally used in the oil-well industry.

survey that measures the heat produced during the setting of the cement. The temperature survey should be conducted within the first 12 to 24 hours for good results (Smith, 1976). The second method involves mixing a short-lived radioactive tracer into the cement. The radioactivity is then checked to verify the position of the cement. Disadvantages of this method include its high cost, special requirements for handling radioactive materials, and interference with other types of geophysical logs relying on the natural radioactivity of the formations.

Abandoned and improperly constructed wells provide vertical openings or channels through which contaminated water may gain entry into usable fresh-water aquifers. Grouting of abandoned wells is discussed in Chapter 18 in connection with sanitary protection of groundwater resources.

Installation of Bentonite Grout

Bentonite (essentially montmorillonite) is widely used as a grouting material, especially for monitoring wells and water wells where surface contamination may occur, because of its low cost and ease of placement. Commercial bentonite used for grouting is available in either pelletized or granular form. When either of these forms are mixed with water, they begin to hydrate within seconds. Thus, it is impossible to place the granular form by dropping the particles into the annulus. Even pellets dumped down the annulus will begin to stick together and to the walls of the annulus within a few feet of the surface, and therefore may bridge high above the intended depth. It is possible to freeze the pellets first and then carry them to the drilling site in a cooler containing dry ice. In this condition, the pellets will settle a greater distance before sticking. The pellets can also be cooled with liquid nitrogen; in this case, an icy outer layer forms which further protects the pellets so that they may fall 40 ft (12.2 m) or more before hydration begins. In general, the pellets should always be tamped into place to eliminate any bridging that may have occurred.

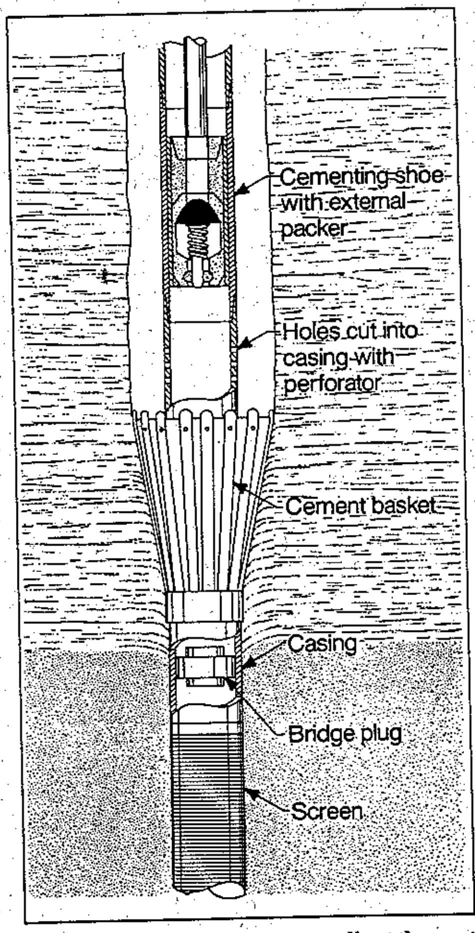


Figure 10.65. A cementing shoe can direct the grout out into the annulus above one or more cement baskets mounted at any position in the casing string. The grout passes through holes cut into the casing by a mills knife or other kind of perforator.

A much better practice is to pump a prepared bentonite slurry by means of a tremie pipe, using a Moyno pump [40 to 60 gpm (218 to 327 m^3/day)] or diaphragm pump [60 to 100 gpm (327 to 545 m^3/day)]. If the mixture of bentonite (usually granules) and water is used, only 1 lb (0.5 kg) of bentonite can be mixed per gal (3.8 ℓ) of water because the resulting viscosity will be at the limit of pumping capacity. After being placed, grout with this concentration of bentonite may eventually shrink 25 percent, even though the ground around the grout usually remains somewhat moist. This is a highly unsatisfactory shrinkage rate. Virtually no shrinkage will occur in grout mixed at concentrations of 1.5 lb (0.7 kg) bentonite per gal (3.8 ℓ) of water. This concentration can be pumped only if the water has been pretreated with 1 qt (0.9 ℓ) of polymer per 100 gal (380 ℓ). The polymer prevents the clays from hydrating immediately, and once the particles are evenly distributed in the water the viscosity remains low enough so the slurry can be pumped for about 20 minutes. The granular bentonite should be mixed gently into the water with a paddle, not a mixer or pump; these latter devices will break up the particles and cause the viscosity of the slurry to increase prematurely.

Bentonite grouts should be mixed in batches so they can be pumped before the slurry becomes too viscous. Ideally, the diameter of the suction hose should be as large as possible. In most cases, the slurry reservoir is above the pump intake so that hydrostatic pressure created by the reservoir makes the pump operate more efficiently. The pump and all piping should be flushed with clean water after each batch of grout is pumped into place. The volumes of bentonite, polymer, and water for various annulus sizes, per 100 ft (30.5 m) of depth, are given in Table 10.7.

Bentonite grout has several advantages over cement grout. It has a faster setting time, no heat of hydration, a lower hydrostatic pressure (specific gravity is 9.2 for the grout given in Table 10.7), and the cost is one-third that of cement. Also, bentonite will adhere to both walls of the annulus, whereas cement will adhere firmly only to the soil.

There are several limitations on the use of bentonite grout. Bentonite grouts cannot be used when the borehole is underreamed, because the "set" taken by the grout is not sufficient to withstand the vertical hydrostatic pressures. Thus, the grout may eventually flow into the underreamed section. Another limitation is that bentonite grout should not extend so close to the ground surface that it can dry out and shrink because of low soil moisture. Cement is always used at or near the top of the borehole. The presence of salt water will cause bentonite grout to flocculate and thereby lose viscosity. Organic acids can also destroy the impervious character of the grout seal.

Table 10.7. Amounts of Bentonite, Water, and Polymer Required to Grout 100 ft (30.5 m) of Three Common Annuli

	Bentonite		Water		Polymer*	
	lbs	kg	gal	ℓ	qts	ℓ
2-in (51-mm) pipe in 4-in (102-mm) hole	75	34	50	189	0.5	0.5
4-in (102-mm) pipe in 6-in (152-mm) hole	112	51	75	284	0.75	0.7
5-in (127-mm) pipe in 8-in (203-mm) hole	225	102	150	568	1.5	1.4

*Concentration of polymer recommended by Baroid for their product EZ-Mud®.

PLUMBNESS AND ALIGNMENT

A water well should be both straight and plumb, although in practice any borehole of substantial depth may not be perfectly straight or perfectly plumb. A straight well is one in which each casing section is joined to adjacent sections in a manner that maintains perfect alignment. A borehole that is plumb is one whose center does not deviate from an imaginary vertical line running from the ground surface to the center of the Earth (Figure 10.66). A well bore may be straight, but not plumb; if the borehole is plumb, however, it will be straight. Some tolerance or deviation in straightness (alignment) and plumbness is normally allowed in practice. By custom, a deviation from plumbness of two-thirds the well's inside diameter per 100 ft (30.5 m) of anticipated pump setting is allowed and thought to be reasonable, considering the inherent difficulties of drilling in earth materials (American Water Works Association, 1984). The U.S. Environmental Protection Agency (1975c) has suggested that wells should be constructed so that the borehole deviation from plumbness is 1 degree or less per 50 ft (15.2 m) when using drift indicators. Table 10.8 shows the allowable limits of deviation for various depths.

Of the two factors, straightness of the well bore is the most important, because it determines whether or not a properly sized turbine pump can be installed in the well to the desired depth. If the well is out of alignment beyond a certain limit, the pump cannot be set. A pump can be installed without difficulty in a well that is straight but out of plumb. Too much deviation from the vertical may affect the operation and life of some pumps, however, so plumbness does need to be controlled within reasonable limits. In general, turbine pumps require reasonably straight well bores, whereas submersible pumps can be set in well bores that are more out of alignment.

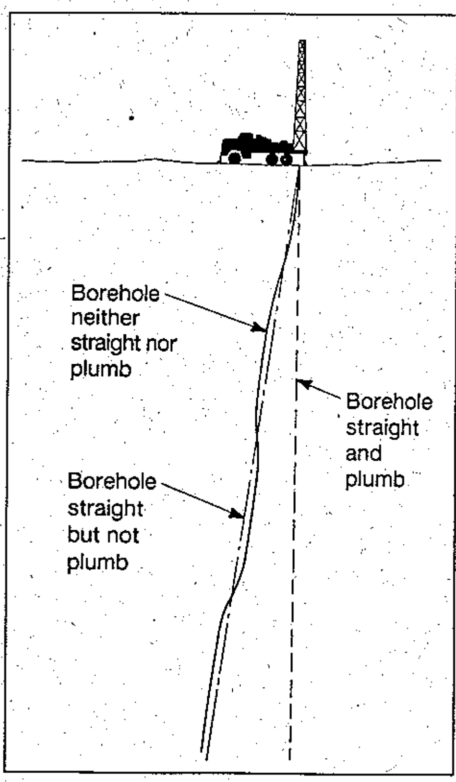


Figure 10.66. A plumb borehole is one that follows a vertical line from the ground surface to the earth's center. A straight borehole is one in which each succeeding casing joint (or length) is aligned with the preceding joint.

Some conditions that cause wells to become misaligned and out of plumb are (1) character of the subsurface material (faults, boulders in the borehole, inclined strata), (2) too much or too little weight on the drill bit, (3) trueness of the casing and drill pipe, and (4) the pull-down force applied to the drill pipe in rotary drilling. While the force of gravity tends to make the drill bit cut a vertical hole, the varying hardness of different materials being penetrated deflects the bit from a truly vertical course. In glacial drift, the edge of a boulder can deflect a cable tool or rotary bit. In cable tool drilling, a boulder may deflect the well casing, causing the hole to drift increasingly as the well is deepened.

When drilling by the rotary method, too much force applied at the top of the drill stem will bend the slender column of drill pipe. This tends to cause the bit to cut off-center. Heavy drill collars in the lower part of the drill stem help to put weight just above the bit, which overcomes the tendency to drift off a true vertical course. They are also more rigid than ordinary drill pipe, and thus help keep the lower part of the drill string straight. Large stabilizers are also used by many drillers to keep holes straight.

Obviously, any variation in the straightness of casing results in a corresponding misalignment of the well. Sections of pipe may be slightly bowed, or the center line of the threaded or bevelled ends may not exactly coincide with the center line of the

Table 10.8. Well Deflection Limits for Drift Indicator Survey

Depth (ft)	Depth (m)	Allowable Deviation (ft)	Allowable Deviation (m)
50	15.2	0.4	0.1
100	30.5	0.9	0.3
150	45.7	1.3	0.4
200	61.0	1.7	0.5
250	76.2	2.2	0.7
300	91.5	2.6	0.8
350	107	3.1	0.9
400	122	3.5	1.1
450	137	3.9	1.2
500	152	4.4	1.3
600	183	5.2	1.6
700	213	6.1	1.9
800	244	7.0	2.1
900	274	7.8	2.4
1000	305	8.7	2.7
1100	335	9.6	2.9
1200	366	10.5	3.2
1300	396	11.3	3.4
1400	427	12.2	3.7
1500	457	13.1	4.0
1600	488	14.0	4.3
1700	518	14.8	4.5
1800	549	15.7	4.8
1900	579	16.6	5.1
2000	610	17.4	5.3
2100	640	18.3	5.6
2200	671	19.2	5.9
2300	701	20.1	6.1
2400	732	20.9	6.4
2500	762	21.8	6.6

pipe. Commercial tolerances permit certain deviations in the straightness of pipe and the accuracy of threads. These must be considered in specifying the allowable deviation of a completed well.

Most careful drillers check the hole alignment several times when drilling a deep well. This is especially common in cable tool drilling. Time and money can be saved by taking steps to correct the misalignment just as soon as a deviation is discovered. In rotary drilling, the alignment is checked at preselected intervals during drilling [every 100, 500, or 1,000 ft (30.5, 152, or 305 m)]. In many wells, however, the alignment may be checked only after the well has been completed.

In recent years, special deviation instruments have been developed to measure the mislignment that occurs during drilling. A deviation survey is conducted along with the standard suite of logs after the maximum hole depth has been reached. Two typical battery-powered deviation instruments are shown in Figure 10.67. Special centralizers are fitted to the inclinometer to keep it centered within specially grooved plastic or aluminum casing placed in the well. Readings from the downhole inclinometer are transmitted to the surface indicator console where the readouts are given directly as displacement. Other drift indicators are entirely mechanical; a timer is set at the surface, the indicator is lowered at a certain rate into the casing or into drill pipe, and at a predetermined time the timer actuates a mechanism that punches a hole in a paper target inside the indicator. The location of the hole in the target indicates the inclination of the borehole. This type of drift indicator is run inside the drill pipe in rotary drilling, or inside the bailer in cable tool drilling. Drift angles of 1.5 to 90 degrees can be determined with this instrument to an accuracy of 0.1 to 0.5 in per 100 ft (2.5 to 12.7 mm per 30.5 m), depending on the deviation from the vertical. The deviation device is especially useful in deep holes where other methods of determining plumbness or straightness are not accurate or are too time consuming.

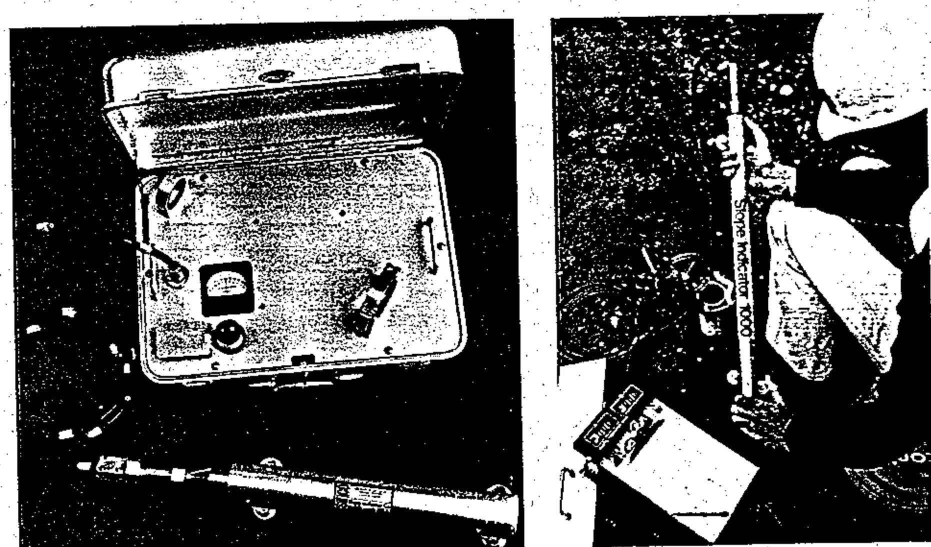


Figure 10.67. The alignment of well casing can be determined by lowering an inclinometer down the well casing inside a specially grooved plastic or aluminum casing. The grooves keep the instrument centered and aligned in the casing. This device can sense a deviation from vertical up to 12 degrees. The deviation instruments shown here are battery-powered. *(Slope Indicator Company)*

Several other more advanced instruments used in oil field work may be applicable to water well drilling, but generally only experienced surveying personnel are equipped to use them effectively. Some instruments can be installed in the drill string and provide continuous information on hole deviation and direction as drilling proceeds. One wireless unit transmits data on hole deviations to a surface recorder by means of pressure surges transmitted through the drilling fluid stream. Downhole instruments equipped with a gyrocompass are widely used to check inclination of the borehole. If computer assisted, these instruments can yield data on dogleg severity and borehole direction at the well head. Magnetic multishot instruments record data on film that can be used for complete directional surveys. To record data the lights in the instrument are turned on, thus exposing the film (a shot is taken on the multiple-shot discs), while the operator records the time and depth of each survey station. Over 1,000 records may be obtained from one run into the hole. The instruments can be hung on a wireline in the borehole or be installed inside a drill collar.

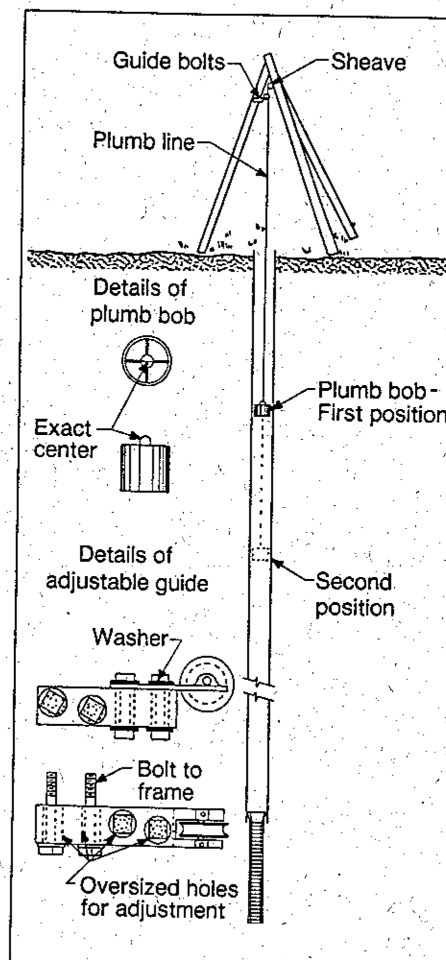


Figure 10.68. The straightness and plumbness of a well can be determined by using a small tripod mounted over the top of a well bore and a plumb bob suspended in the casing.

Plumbness of shallow wells can be checked with a special plumb bob, and straightness can be tested with a 40-ft (12.2-m) cylindrical dummy* that is slightly smaller than the inside of the well casing. However, the deviation from plumbness and straightness may be measured by a plumb-bob test alone, as suggested below.

The device used to check the straightness and plumbness of a well is shown in Figure 10.68. The plumb bob, suspended on a wire line, is a short cylinder with an outside diameter about ¼ in (6 mm) smaller than the inside diameter of the casing. It must be suspended from the exact center of the device. The plumb bob should be heavy enough to stretch the line taut. A ⅛-in (3-mm) stainless steel wire cable makes a suitable line because of its flexibility and resistance to corrosion.

The line may be suspended from the derrick of a drilling machine or from a tripod so that the plumb bob will hang in the exact center of the well casing. The guide block

*The typical dummy is 40 ft long because standard casing joints are 20 ft. Other lengths of dummies may be used if the casing lengths are increased. The dummy must extend two casing lengths to be functional.

is mounted so that the vertical distance from the center of the small sheave to the top of the casing is exactly 10 ft (3 m). The guide is then adjusted horizontally so that the plumb bob hangs in the center of the well casing.

The test is started by lowering the plumb bob 10 ft. If the wire line moves away from the center of the well in any direction, the distance it has moved off center is measured. The plumb bob is then lowered another 10 ft, and the distance the wire line has now moved off center is measured. This procedure is repeated until the well has been checked to the desired depth. If the casing is exactly round, the measurement to the wire line can be made from the edge of the casing. If the pipe is not exactly round, a plastic template like that shown in Figure 10.69 may be used to measure the displacement of the wire line.

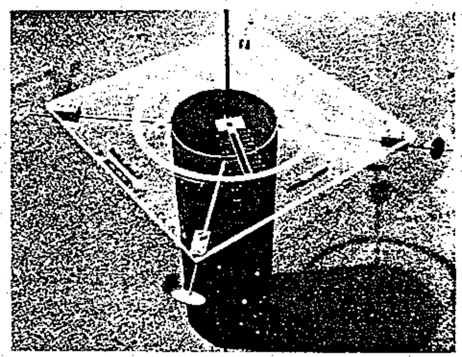


Figure 10.69. A plastic template placed on top of the well casing can be used to measure the displacement of the wire line connected to the plumb bob. *(Water and Power Resources Service, 1981)*

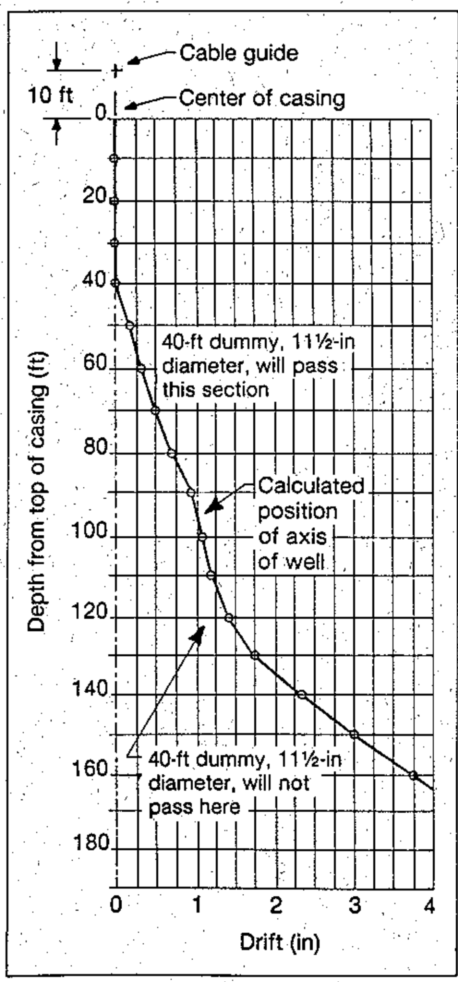


Figure 10.70. A graph of this well shows that it is out of plumb and not straight for much of its length.

The well is plumb to the depth of the suspended bob as long as the plumb line passes through the center of the template positioned on the top of the casing. Any drift of the well causes the wire line to move off center. Drift at any depth is the measured displacement of the plumb-bob line multiplied by the total length of the line and divided by the fixed distance between the overhead pulley and the top of the pipe. Suppose, for example, that the line is suspended 10 ft above the top of the pipe and it moves ¼ in off center when the plumb is lowered 10 ft into the well. The casing drift, in this case, is ¼ in × 20 ft/10 ft = ½ in. If the rate of drift is the same for each 10-ft interval between any two depths, it means that the well is straight between these points, but out of plumb. A crooked section is revealed by different values of drift for successive 10-ft intervals.

The calculated values of drift may be plotted against depth to obtain a graph of

Table 10.9. Relative Performance of Different Drilling Methods in Various Types of Geologic Formations

Type of Formation	Cable Tool	Direct Rotary (with fluids)	Direct Rotary (with air)	Direct Rotary (Down-the-hole air hammer)	Direct Rotary (Drill-through casing hammer)	Reverse Rotary (with fluids)	Reverse Rotary (Dual Wall)	Hydraulic Percussion	Jetting	Driven	Auger
Dune sand	2	5	Not recommended	Not recommended	6	5*	6	5	5	3	1
Loose sand and gravel	2	5	Not recommended	Not recommended	6	5*	6	5	5	3	1
Quicksand	2	5	Not recommended	Not recommended	6	5*	6	5	5	Not recommended	1
Loose boulders in alluvial fans or glacial drift	3-2	2-1	Not recommended	Not recommended	5	2-1	4	1	1	Not recommended	1
Clay and silt	3	5	Not recommended	Not recommended	5	5	5	3	3	Not recommended	3
Firm shale	5	5	Not recommended	Not recommended	5	5	5	3	Not recommended	Not recommended	2
Sticky shale	3	5	Not recommended	Not recommended	5	3	5	3	Not recommended	Not recommended	2
Brittle shale	5	5	Not recommended	Not recommended	5	5	5	3	Not recommended	Not recommended	Not applicable
Sandstone—poorly cemented	3	4	Not recommended	Not recommended	Not applicable	4	5	4	Not recommended	Not recommended	Not applicable
Sandstone—well cemented	3	3	5	Not recommended	Not applicable	3	5	3	Not recommended	Not recommended	Not applicable
Chert nodules	5	3	3	Not recommended	Not applicable	3	3	5	Not recommended	Not recommended	Not applicable
Limestone	5	5	5	6	Not applicable	5	5	5	Not recommended	Not recommended	Not applicable
Limestone with chert nodules	5	3	5	6	Not applicable	3	3	5	Not recommended	Not recommended	Not applicable
Limestone with small cracks or fractures	5	3	5	6	Not applicable	2	5	5	Not recommended	Not recommended	Not applicable
Limestone, cavernous	5	3-1	2	5	Not applicable	1	5	1	Not recommended	Not recommended	Not applicable
Dolomite	5	5	5	6	Not applicable	5	5	5	Not recommended	Not recommended	Not applicable
Basalts, thin layers in sedimentary rocks	5	3	5	6	Not applicable	3	5	5	Not recommended	Not recommended	Not applicable
Basalts—thick layers	3	3	4	5	Not applicable	3	4	3	Not recommended	Not recommended	Not applicable
Basalts—highly fractured (lost circulation zones)	3	1	3	3	Not applicable	1	4	1	Not recommended	Not recommended	Not applicable
Metamorphic rocks	3	3	4	5	Not applicable	3	4	3	Not recommended	Not recommended	Not applicable
Granite	3	3	5	5	Not applicable	3	4	3	Not recommended	Not recommended	Not applicable

*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 position of the axis or center line of the well bore. Figure 10.70 is a graph for a well that is both out of plumb and crooked. The graph indicates that the casing is straight and plumb to a depth of 40 ft (12.2 m). The deflection at the 40-ft level is caused by a dogleg in the casing. From this point to a depth of about 90 ft (27.4 m), the casing is straight but out of plumb. Below 90 ft, the rate of drift gradually increases and the casing is neither straight nor plumb.

CONCLUSIONS

Selection of the best drilling method for a particular job requires an understanding of the geologic conditions and the physical limitations of the drilling rig. In addition, the value of experience cannot be overestimated, for many drilling difficulties occur because either the driller is unprepared to handle the wide range of subsurface conditions or has pushed the rig beyond safe operating limits. Good record keeping, patience, and a willingness to learn are some important characteristics of good drillers; the age of the machine or the particular drilling method used are of secondary importance in drilling successful wells. Table 10.9 gives the drilling performance of different drilling methods in various geologic formations. The relative performance differences between drilling methods, however, will also depend on the experience of the driller, the presence of geologic anomalies at the site, and the pressure conditions affecting the groundwater.