Rotary Drilling of Large Diameter Vertical Holes

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ABSTRACT

This paper describes the basic principles of rotary drilling and the problems that are involved in utilizing these principles to drill large diameter holes. The functions of the drilling plant and the factors that influence the design of its component parts are discussed.

A study of drilling practices is given with emphasis on how various factors affect the drilling speed and efficiency. Specific recommendations are made for the selection of techniques that should be employed to result in the lowest drilling cost.

References are made to particular projects where shafts were drilled utilizing equipment and practices that yielded satisfactory results. The functions of the drilling fluid are outlined. The conditions to be considered in designing the shaft lining are mentioned and installation procedures described. Remedial measures are offered for various drilling problems. The paper ends by citing the advantages of the rotary drilling method of shaft construction.

INTRODUCTION

The method of drilling holes into the earth by utilizing a rotating, hollow drill stem and circulating fluid through a drill bit began at the turn of the century. One of the first major improvements was the invention of the rolling cutter type bit by Mr. Howard R. Hughes in 1909. Since that time, drilling methods have continually improved and the techniques have developed into a professional science. Rotary drilling of large diameter holes is a more recent innovation. Until about 1955, large hole drilling in the United States was limited to diameters of about 36 inches. Now that several holes, ranging from 40 inches up to 90 inches in diameter, have been successfully drilled, industry has lost some of its skepticism and several large diameter holes have been drilled.

The mining and construction industries have used these drilled shafts for various purposes. The trend toward better mine ventilation has increased the need for relatively small, economically constructed shafts and the drilled shafts have been used mostly to accommodate ventilation equipment. Other uses have been ore removal shafts, exploration shafts, personnel shafts, emergency escapeways and underground storage cavern access shafts. In some cases, two shafts, drilled side by side, have been used for ore removal, allowing balanced hoisting to be achieved from a single headframe and hoist (1). Due to the risk involved in sinking a large diameter shaft through unconsolidated materials, quite often two smaller shafts, drilled close together, are more economical.

In the construction of underground storage facilities, it has been found that a 42 inch finished diameter has been large enough to permit the entry of workmen and machinery and the removal of stone and, at the same time, small enough to permit effective sealing later against the pressure of the stored product (2). In the first 10 years of development, about 29 underground storage systems were constructed (3). Many of the access shafts were rotary drilled and the cavern construction, being similar to a mining operation, has kindled the thinking of the mining industry and inspired the drilling contractors to expand their services into the realm of large diameter drilling.

The result has been similar to a backward step in the development of drilling practices because the equipment and the techniques used in oilwell drilling are inefficient when applied to large hole drilling. Thus, the drilling contractor, desiring to drill big holes, has had to revise his thinking and go back to the basic concepts of rotary drilling in order to develop new tools and methods.

The basic principle of rotary drilling involves the use of some type of tool which is placed in the hole to cut or break the formation into chips. These chips are moved away from the cutting tool and out of the hole by circulating a fluid through the drill stem which will carry the cuttings to the surface as circulation is continued. The main problems involved are to provide sufficient downward and rotational force on the bit or cutting tool so that it can generate chips and to circulate enough fluid to carry these chips out of the hole with a minimum of regrinding. Most of the other problems associated with rotary drilling might be classified as a part of or resulting from the cutting action or the circulating system. The ultimate purpose of all the equipment, techniques and personnel involved is to make the bit drill. Descriptions of some of the machine elements and drilling technology are outlined below to illustrate their application to shaft boring.

THE DRILLING PLANT

The main components of the drilling plant are divided into five categories; that is, prime movers, hoisting equipment, drill string equipment, circulating equipment and rotating equipment:

1. The prime movers are the source of power for the hoist, the rotary and the fluid circulating pumps. Usually all of these items are powered from a single source consisting of several engines unitized and compounded together with provisions for transmitting power to either or all of the power requiring elements at the same time. Load requirements vary according to the type of operation being performed. For example, while actual drilling operations are in progress, the rotating and pumping equipment are in use and the hoist is idle and when the drill string is being hoisted out of the hole, the pump and rotary are idle. Thus, it isn't necessary to have sufficient power to perform all of these operations at the same time although the available intermittent horsepower should be such that slow hoisting rates are obtainable while the pump is in use for short periods when lifting the bit off bottom or during certain fishing operations.

2. The hoisting equipment consists of the hoist, the derrick and the block and tackle system. The principle function of these machine elements is to provide the means of removing equipment from or lowering equipment into the hole. Drill string and casing loads are often quite heavy; thus, the mechanical advantage gained by wreathing several wire rope lines through the blocks is utilized. The companion components of the hoisting system, that is, the blocks, hook, hoist, etc., should be of about equal capacity. Conventional equipment, up to 450 tons capacity, is commonly used in the oil drilling industry and is suitable for handling most of the loads involved in large diameter drilling. The horsepower required for hoisting is a function of the speed and the load. As an example, to lift a 500,000 pound load out of a large diameter hole at a rate of 50 feet per minute, the theoretical horsepower would be:

$$hp = \frac{500,000 \text{ lb.} \times 50 \text{ ft./min.}}{33,000 \text{ ft.-lb./min./hp}} = 757 \text{ hp}$$

This calculated requirement does not include friction losses which might be as high as 30 percent, depending on the efficiency of the power transmission elements between the engines and the load. Peak loads are usually encountered when running casing, where a relatively slow hoisting rate can be tolerated. Thus, the horsepower, which is adequate for normal drill string hoisting, will usually satisfy peak load requirements. The torque capacities of the clutches and other machine elements and the strength of the block and tackle system are usually the limiting factors.

3. The drill string equipment consists of the bit, the drill collars (or weights which are used to exert a downward force on the bit) and the drill pipe from which the drill collars are suspended. All of these members are hollow, facilitating the circulation of the drilling fluid.

   The factors influencing the design of the drill pipe for large hole drilling are the torsional and tensile loads to which it will be subjected, the bending and vibrational stresses and the diameter of the fluid passage which will permit large volumes of fluid to be circulated with a minimum of pressure. The tensile requirement is the total weight of the drill string equipment plus a reasonable allowance for shock loads or for pulling on a drill string which is stuck in the hole. The tensile strength of the drill string members is usually as much as the pulling capacity of the hoisting equipment.

   Torsional requirements are difficult to calculate due to the numerous variables that determine the amount of torque required to rotate the drill bit. Torsional values obtained from empirical formulas have compared favorably with laboratory and field measurements and torque values can be extracted from published graphs with a fair degree of accuracy (4).

   Bit design is a science of its own. Several of the leading rock bit manufacturers are marketing rolling cutter bits with a wide selection of types designed to cut a particular type of formation (5). Designs, which have been tried and proved in oil and gas well drilling, are now used on large diameter bits.

   Drill collars of varying designs are in use. They should be as short as possible, yet heavy enough to provide a sufficient downward force on the cutters and constructed in pieces small enough to facilitate easy handling and assembly. The weight run on the cutters should never be more than the weight of the drill collars after deducting the buoyancy of the drilling fluid displaced. During drilling, all of the drill pipe should be in tension since drill pipe is essentially a tube of medium wall thickness and has but little resistance to bending by column action (6). By keeping the neutral stress point in the drill collar section rather than in the weaker drill pipe section, many drill string failures can be prevented.

4. The circulating equipment for use in drilling large diameters is one of the factors limiting the hole size which can be drilled efficiently. Fluid circulation rates in oil well drilling are usually such that the velocity of the fluid returning from the bottom of the hole to the surface is 150 feet per minute, or higher. This velocity can be obtained by circulating about 400 gallons per minute in small holes. To obtain the same velocity in a 90 inch diameter hole, the driller would have to increase his pumping rate 120 times and circulate about 48,000 gallons per minute. It can readily be seen that some sacrifice of efficiency is necessary. Centrifugal type pumps are being used to circulate large volumes of fluid. Although they do not operate with good volumetric efficiencies, like positive displacement, piston type pumps, the centrifugal units will provide large volumes if delivered at low pressures. To keep the pressure drops and horsepower requirements as low as is practical, the internal diameter of all the elements through which the fluid must travel should be as large as possible, yet be as light as possible to facilitate handling.

   While drilling a 60 inch diameter shaft in Ontario, Canada, good cutting removal and an acceptable rate of penetration was obtained while circulating 6,000 gallons per minute with a return velocity of 43 feet per minute (7). In some cases, lower velocities have yielded acceptable penetration rates. A rule of thumb for a minimum G.P.M. flow rate of 50 times the diameter of the hole in inches has been offered by some sources (4). The corresponding annular velocities are very low and would not provide efficient cutting removal; however, these low velocities are acceptable for jobs of short duration when suitable pumping equipment is being repaired or is not available.

   When the diameter of the bore hole is such that it is impractical to handle the large volume of fluid required, reverse circulation offers a means of obtaining cutting removal. In this method, the direction of fluid travel is reversed and the cuttings are lifted away from the bit by fluid traveling upward through the inside of the drill string. This is accomplished by means of an air-lift. Reverse circulating by air-lifting a relatively small volume of fluid will yield a high velocity inside the drill pipe permitting the removal of large cuttings from the bottom of the hole. Tests have indicated that a reverse flow of 2,400 gallons per minute can be accomplished with 600 C.F.M. of air (8). Experimental work which has been done with the air-lift, reverse circulation method is limited. In actual practice, if the drilling rate is such that the column of fluid inside the drill string is loaded with cuttings, making it considerably heavier than the fluid in the annulas, the rate at which the dense fluid can be lifted with a given volume of air will be considerably less than the flow rate which would be obtained if the density of the fluid inside and outside of the pipe were equal. Also, it is questionable as to whether a reverse flow of a relatively small volume of fluid will provide adequate washing and cleaning action on the bit cutters. In spite of these possible disadvantages, it is believed that reverse circulation will ultimately lead to the successful drilling of holes larger than eleven or twelve feet in diameter.

5. The rotating equipment consists of the rotary machine, the kelly or grief stem and the swivel. These items are expanded versions of conventional oilfield equipment. The swivel and kelly must have a large internal diameter to avoid restrictions to fluid flow.

   The rotary table should be of special design due to the torsional load to which it is subjected when rotating the large diameter drilling tools. Some conventional oilfield tables are suitable for the smaller ranges of large diameters, although they do not have openings large enough to provide passage of large drill collars or bits. The size of the opening, however, is not a serious problem as the table can be removed when the tools are hoisted out of the shaft. The torsional stresses and the vertical load are of prime importance.

DRILLING PRACTICES

Drilling practice involves the selection of a combination of weight on the bit, rotary speed and hydraulic action. The best combination of these three factors is the one that results in the lowest drilling cost. At this stage of the development of techniques, the large diameter driller does not have the variety of selection that is available in oil well drilling.

For a fixed circulation rate and rotary speed, the rate of penetration of rock bits in most formations is in direct proportion to the weight applied to the bit cutters (9). The optimum weight on the bit, or the one which results in the minimum footage cost, varies inversely with formation drillability. Thus, the optimum weight increases as formations become harder (drillability decreases). The large diameter driller, if he is properly equipped, can use optimum weight on the bit in soft formations, but it is impractical to provide sufficient weight to obtain optimum conditions in the hard rock formations. As an actual illustration of the relationship between weight and formation drillability, while drilling a 60 inch diameter hole in Ontario with 70,000 pounds of weight on the bit, the penetration rate varied from as high as 40 feet per hour through some of the glacial drift formations to as low as 1 1/2 feet per hour through hard limestone formations. The limits on the practicability of applying optimum weight on large diameter bits in hard formations are determined by the torsional strength of the drill string and rotating elements, the hoisting capacity and the economics of the drilling company's investment in drill collars.

Selection of an ideal rotary speed is not available to the big hole driller because the peripheral velocity of the outer diameter cutters must be kept within a range which will result in a reasonable life of the cutter bearings. Shock loads on cutters, cutter teeth and the drill string must also be kept within reasonable limits. The rate of penetration of a rock bit under field operating conditions varies in a decreasing function with the speed of rotation; that is, the response of penetration rate to increases in rotary speed decreases as the rotary speed is increased (9). The range of speeds available to the big hole driller are relatively low; however, the actual velocity of the outer diameter cutters on a large diameter bit will be very high compared to that of the cutters near the center.

A rule of thumb R. P. M. of 120/d where d equals the hole diameter in feet has been suggested (4). The corresponding cutter velocities are within the limits of good practice for hole diameters in the range where rotary drilling is practical.

The hydraulic horsepower available at the bit is almost nil in large diameter drilling. Due to the necessity of circulating large volumes of fluid to lift the cuttings off bottom, the major portion of the horsepower available from the pumps is consumed in pressure drops through the drill string. Thus the advantages to be obtained from hydraulic horsepower expended by jetting action on the bottom of the hole are very limited. The horsepower required to push the fluid through the drill pipe could be decreased and the jetting action increased by the use of larger drill stem. However, there is a practical limit to the size of drill stem that can be efficiently handled.

The hydraulics of rotary drilling presents a real economic and operating problem to the drilling contractor. It is impractical to provide enough positive displacement pumps to obtain a suitable annular velocity in a large hole so the pressures must be kept low enough to utilize centrifugal or turbine type pumps, necessitating the use of large drill pipe. The contractor must weigh the advantages of having a good hydraulic program against the loss of time and efficiency of handling larger equipment, the investment required and the cost of moving heavier equipment from one job to another.

Some big holes have been drilled with annular return velocities considerably less than 10 feet per minute. Under these conditions, it is necessary for the bit to regrind the cuttings several times and to maintain a very viscous fluid to carry these reground chips out of the hole. Both of these factors retard the drilling rate and decrease the useful life of the cutters. In actual practice, annular velocities in the range of 25 to 40 feet per minute have yielded acceptable rates of penetration while circulating with a low viscosity drilling fluid.

DRILLING FLUIDS

In addition to providing a means of transporting the cuttings from the bit to a surface disposal system, the drilling fluid performs many other functions which are important to the success of the drilling operation. Cooling of the bit is one of the most essential functions of the fluid and most any type of fluid will perform this function. Other functions of the drilling mud are as follows:

1. The hydrostatic pressure exerted by the column of fluid in the hole tends to hold loose formations in place and prevent them from caving. Some formations disintegrate or become loose when wet. When drilling through such formations, it is essential that the fluid properties are such that a film or gel type seal or cake will be formed on the wall of the hole, thus preventing the intrusion of large amounts of water into the formation.
2. The hydrostatic pressure and wall building characteristics of the fluid must prevent water or gases contained in the formation from entering into the bore hole.
3. The lubricating qualities of the fluid facilitate the ease of movement of tools into and out of the hole. Sometimes, corrosion inhibitors are used in the fluid to retard corrosion of the drill string and circulating equipment.
4. The fluid must have ability to hold solids in suspension and prevent them from settling to the bottom of the hole.
5. The fluid must have qualities permitting excess solids, sand and cuttings to settle out in a fall out sump on the surface, facilitating recirculation of the fluid.

Control of the drilling mud, so that it will best perform the above functions, sometimes requires the services of a specially trained technician. In some formations, a very light, low viscosity fluid will suffice while another formation will require the driller to exercise very close control of the fluid properties by the addition of clays, chemicals, water and barites.

LARGE DIAMETER DRILLING PROBLEMS

The problems associated with large diameter drilling operations are similar to those encountered in oil field drilling. The remedial measures are sometimes different due to the size of the operation. Good planning, technical advice and close attention to the operation are essential to reducing the risk of down the hole hazards.

Loss of circulation can be costly due to the large volume of fluid in use. The probability of encountering fluid loss zones is usually fairly well established from exploration drilling that has been done prior to drilling the shaft. In cases where cluid loss is to be expected or where no prior drilling has been done, extra provisions should be made for preventative and remedial measures. A large volume of fluid should be on hand and the hydrostatic pressure should be kept as low as down the hole conditions will permit.

Excess sloughing of formations into the bore hole must be avoided. This problem is usually easy to remedy by maintaining a suitable drilling fluid. However, the cost of mud materials to maintain such a large volume could be a major portion of the overall project cost. A well planned program should include provisions for a casing to be set through the loose surface formations and other hazardous zones. In addition to reducing the risks involved while drilling is in progress, such casing provides additional support to the final shaft lining in the critical places.

Deviations of the bore hole from vertical are considered to be a problem by some. Usually the specifications and the working agreement between the contractor and the owner limit the inclination from vertical to a very close tolerance. When suitable equipment is used, large diameter drilling lends itself to good control of hole deviation. Sometimes the tolerance is held to such a low angle that there is no practical means of measurement until the job is completed and the drilling fluid is evacuated from the shaft.

In rotary drilling, the principal method used to maintain a vertical direction of the bore hole is to place the heaviest drill collar assembly possible just above the bit so as to obtain the best available plum-bob effect to aid in overcoming the tendency of the bit to drill perpendicular to the slope of the formations. In small diameter holes, space limitations will not permit the use of a suitable plumb-bob. In large diameter holes, where more than a hundred thousand pounds of drill collars can be placed in a very short length just above the bit, the plumb-bob action is very effective and becomes increasingly effective with increases in deviation. Experience indicates that this method of control is satisfactory and hole inclination is not a problem.

Handling of large drilling tools and casing is a problem. More time is required than in handling of oil field tools. Other factors being equal, the contractor who has the most efficient equipment handling system, the most alert and best trained personnel and the experience is the one who can do the best job at the lowest cost.

SHAFT LINING

Most drilled shafts require a lining for shaft support during use and to seal off formation water or gases and to prevent unconsolidated formations from caving. The most common method of lining rotary drilled holes is to lower a steel casing into the bore hole and fill the annular space between the casing and the wall of the hole with cement. The design and installation of the shaft lining is a very important and expensive part of the overall project.

The factors to be considered in designing the shaft lining are the ability of the various formations to stand without support, the pressure head of any formation water, gases or hydrocarbons, the grouting method that is to be used, the length of time that the shaft is to be in use and the purpose for which the shaft is to be used.

Some shafts require very little, if any, support and a thin wall casing with low density, high yield cement to seal off formation water is adequate. Others require more support and the combined strength of the casing and cement must withstand the external pressure of formation water, squeezing shales and sloughing formations. Some sources have indicated that a design collapse pressure of 130 psi is sufficient to withstand these rather unpredictable loads (10).

Some formations have a tendency to disintegrate and slough when they become wet. This often occurs while drilling is in progress due to wetting of the formation by the drilling fluid. It stands to reason that an angle of repose would eventually be established and subsequent caving would be from the top of the cavity. If water bearing formations are sealed off so that no fluid can come into contact with these zones, caving would eventually stop. In this event, the design pressure for the shaft lining need not exceed the overburden pressure due to the thickness of the hazardous zone. This would apply to loose sands as well as to sloughing shales.

Formation sampling and analysis and a knowledge of the thickness of each strata is a prerequisite to good casing design. For shafts drilled to shallow depths or for very small diameters, the design problems are practically nil. In most cases, economics will dictate that a thin walled casing be used with a high strength cement with the casing serving mostly as a form for the cement. Thick walled casings are expensive and often too heavy to be lowered into the hole by the hoisting equipment. Strength obtained from an additional thickness of cement is cheaper than that obtained from steel. Thin walled casing with external stiffeners has been used and offers a practical and economical means of gaining additional strength when it is required (10).

In the deeper shafts, the casing load sometimes exceeds the safe capacity of the hoisting system. Experienced contractors have their own set of standards and ideas for overcoming this problem and usually desire to retain their trade secrets. Generally, these ideas involve floating the casing in the hole or lowering it in by sections, comprising a load that can be safely handled, or by using hydraulic jacks. Usually the casing can be fabricated in rail car lengths which are welded together as they are lowered into the bore hole.

Cementing procedures are similar to those used in the oil fields in that the cement, of the desired specifications, is pumped through grout lines to the bottom of the casing and the slurry displaces the drilling fluid as it rises to the surface. In the deeper shafts, stage cementing is sometimes necessary to avoid collapsing the pipe. A plug of some type is used to prevent entry of the grout into the bottom of the casing.

SHAFT DRILLING COSTS

Drilling cost is a composite of many variables and can be estimated only after careful analysis of conditions and a predetermined plan of procedure is established. The factors influencing the cost are: the hole diameter, depth, formation drillability, down the hole drilling hazards, labor and rig operational cost.

In its range of practical diameters, rotary drilling compares very favorably to other methods. Actual drilling cost has varied from about $4.50 up to $13.00 per cubic foot of material to be evacuated.

APPLICATIONS OF THE ROTARY DRILLING METHOD

Cable tool drilling and core drilling with steel shot has been used in the mining and construction industries. Material presented here deals only with the conventional rotary drilling method which has its own variety of applications.

In the beginning, most large hole drilling utilized the hole opening method, that is, opening the hole in stages by drilling a hole of a certain diameter and reaming it to a larger diameter and repeating this procedure until the desired diameter is obtained. The trend has been away from this method and most recently drilled shafts have been opened to the full diameter by one pass of the drill bit. There is yet a controversy as to whether or not to drill a pilot hole. The purpose of the pilot hole has been to serve as straight guide for the big bit and as a sump to receive any cutters, tools or other objects that might be lost in the bore hole while drilling is in progress and, in some cases, to provide information about the formations that are to be penetrated. The method explained in this paper does not favor the drilling of a pilot hole because: (1) It is very time consuming and expensive to drill a pilot hole and maintain the deviation tolerances usually required by the mining industry. In some cases it is impractical and the expense is not justified. (2) If the pilot hole is not perfectly vertical, the large bit, having a tendency to drill vertical, will not follow the pilot and then the advantages gained by having a guide and a junk catcher are nullified. (3) Stratographic information is usually available from exploration or core drilling that is done prior to the commencement of shaft drilling.

Another variation is to drill a pilot hole into an existing mine and then ream it to the desired diameter, allowing the bit cuttings to fall through the pilot hole into the mine where they can be removed by underground equipment. This method eliminates the necessity of circulating large volumes of fluid and appears to be very practical where conditions permit its use.

ADVANTAGES OF THE DRILLING METHOD

In the diametrical range, where it is practical, rotary drilling offers many advantages over conventional shaft sinking methods. Usually there is a big saving in time, affording an opportunity to meet market demands and expedite mine development. Formation water presents no problem to drilling and is easily sealed off from the finished bore by airtight casing surrounded by cement. The hazards to personnel working below ground are eliminated as it isn't necessary for anyone to enter the shaft until it is completed and ready for use. The economics of rotary drilling are favorable, especially through wet formations where freezing would be necessary for conventional methods. A steel inner lining lends itself to easy installation of shaft hardware such as ladderways, service lines, partitions, etc., which may be welded to the steel pipe.

As of this writing, plans are in the making for shafts up to 11 feet in diameter and for smaller diameter shafts to depths of 2,500 feet.

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