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TITLE: An Overview of Raise Boring and Blind Shaft Drilling With Practical Applications and Particular Reference to Design Limits for Accuracy

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AN OVERVIEW OF RAISE BORING AND BLIND SHAFT DRILLING WITH PRACTICAL APPLICATIONS AND PARTICULAR REFERENCE TO DESIGN LIMITS FOR ACCURACY

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ABSTRACT

The current excavation technology of raise boring and blind shaft drilling operations is reviewed. Examples are presented of recent applications of both downhole boring machines and surface-mounted rotary shaft drilling equipment, with comparisons made of operational characteristics, shaft sizes, and accuracy limits of each system. Raise-boring and box-drilling machines are described and current operating practices of these systems are reviewed. The increased interest in "slant hole" or inclined shaft construction is noted, and techniques and equipment for these special shafts are presented.

Practical accuracy limits are discussed for each shaft drilling technique and trade-offs between accuracy, drilling rates, and shaft utilization factors are noted.

Finally, the current status of ongoing research and development efforts will be described, and some predictions made regarding worthwhile improvement trends in shaft construction methods.

Introduction

The traditional method of constructing shafts has been to drill small holes for inserting explosives, blasting to create rubble, and then mucking out the rubble by hoist buckets. This method, which has been essentially unchanged for over a hundred years, is still used with minor variations to build the vast majority of shafts being constructed today, worldwide.

Several factors, however, are bringing about a trend toward mechanized shaft construction methods. Mining labor costs have soared; environmental, health, and safety regulations have had a major influence on construction practices, and it has become increasingly difficult to find the breed of men willing to work in the dangerous conditions of conventional drill and blast shaft sinking.

The trend towards mechanized shaft construction has benefited by the adaptation of equipment that has been used for many years by the oil and gas drilling industry, and also by equipment used for several years by the tunneling industry. These adaptations have resulted in two broad categories of mechanized construction techniques that are commonly described as (1) drilling and (2) boring. Raise drilling and box drilling are also other techiques for mechanically constructing shafts, but they are methods applicable to special situations and will l discussed separately.

Shaft Drilling Equipment

Within the context of this paper, shaft drilling is defined as constructing shafts by using surface rotating equipment derived from the oil and gas industry. Today's shaft drilling technology traces most of its practices to the work done beginning in the early 1960s at the United States Nuclear Test Facility, Mercury, Nevada. Large shafts were (and are) required to test nuclear weapons deep under ground. The urgent need for these deep shafts and the availability of adequate funds provided great advances and extensive experience in the science of shaft drilling.

The first shafts drilled at the nuclear test site used large oil industry drill rigs and the shafts were of modest sizes of 1.2 m to 2.4 m (48 to 96 in). The problems encountered were related to formation stability, cutter wear, penetration rates, and muck removal. The solutions developed during this time period remain valid today. These include air assisted reverse circulation of fluids and fluid additives to promote hole wall stability and efficient cuttings removal, special cutters to reduce bit wear and achieve a reasonable penetration rate, and massive hoisting and rotary table capabilities to permit heavy downhole assemblies to use the pendulum effect to achieve straight vertical holes.

Improvements in all of these operational practices continue to be made by the nuclear test site drillers. However, the most significant recent innovations have been the introduction of special shaft drilling machines and equipment that have the hoisting and rotary torque capacity to drill large shafts up to 5.6 m (20 ft) diameter and 1000 m or more deep. Typical specifications of these machines are hoist capacities of 8.9×10^6 N (2×10^6 lb_f.) and 678 KN-m (500 klb_f-ft) of rotary torque. These capabilities are approximately double the capacities of the largest modified oil industry drilling rigs used heretofore.

Figure 1 is a photograph of a Hughes Model SCS 300 shaft drilling rig, which is representative of a new series of rigs especially designed for shaft drilling projects.

The cutting structure of rotary shaft drilling rigs consists of a support structure (bit body) on which are mounted up to 24 individual cutters. The cutter type is chosen based upon the hardness of the formation being cut. Typically the cutters are of either tooth or disc type. The cutters are arranged in a pattern on the bit body so that all

Fig. 1. Hughes Model CSD 300 Shaft Drilling Rig

areas of the shaft cross section are cut from the center of the shaft to the outer edge. The cutter surface has traditionally been flat in shaft diameters up to 3.6 m (12 ft). However, recent experience with larger 4.3 m (14 ft) diameter shafts indicates that the cuttings removal will be facilitated if the outer edge of the cutting surface is sloped toward the center.

All recently drilled shafts have used a dual string, air assisted, reverse fluid circulation system to transport the cuttings to the surface. In this system the pipe string to the surface is a coaxial system having, typically, a 0.178 m (7 in) pipe positioned inside a 0.34 m (13-3/8 in) outer pipe. The drilling fluid, usually water with perhaps bentonite drilling mud or a polymer added, is introduced into the outer annulus of the drilled hole from the surface. In the annulus between the coaxial pipes is pumped high pressure air and sometimes additional fluid. The inner pipe column receives the expanding air, which creates a flow of the air fluid mixture that in turn carries the cuttings to the surface. A minimum velocity of approximately 0.6 mps (2 ft per sec) is required to carry the cuttings efficiently.

Recently, the trend has been to use disc cutters to achieve a faster penetration rate. Disc cutters create larger chips than tooth cutters, so the fluid velocity up the center pipe must be increased to carry the larger chips. Also, the larger chips tend to clog up a 0.178 m (7 in) inner pipe so the pipe string standard now being introduced by the shaft drilling industry is a 0.51 m (20 in) outer pipe over a 0.34 m (13-3/8 in) inner pipe. This string configuration, being stronger, also permits larger bottom hole assemblies to be used and higher rotary torques to be applied.

Mention should be made of formation stability and shaft liner systems for rotary drilled holes. The reverse circulation system permits drilling fluid to stand in the hole, thereby increasing hole stability during drilling. After drilling to the desired depth is completed, a liner system must be installed in the shaft and cemented into place. Steel liners have been used traditionally; recently, however, precast concrete liner systems have been introduced, and these systems may offer economic advantages over steel liners.

Hole accuracy in drilled shafts is achieved by using massive bottom hole assemblies consisting of, in addition to the bit body cutting structure, heavy "donut" weights, and sturdy rotating or nonrotating stabilizers. The contact force on the cutting structure is maintained at the optimum for the types and numbers of cutters and the majority of the weight of the down hole assembly is carried as tension force in the dual pipe string and supported at the surface by the rig hoisting system. Hence, hole straightness and verticality is achieved by the so-called "pendulum effect." In actual practice, hole accuracies of 0.36 m (14 in) maximum deviation in 600 m (2000 ft) depth are commonly attained. This deviation is approximately 0.03 degree of angular units and is usually entirely satisfactory for mining applications. Even this small deviation may be easily corrected by liner positioning since the steel liner is usually 0.5 m (18 in) smaller diameter than the drilled hole.

Blind Shaft Boring

Tunneling machines have been in extensive use around the world for several decades now, and have become accepted as the preferred method for constructing utilities and transportation tunnels in sizes from 2 m to 10 m (6 ft to 33 ft) diameter and in all formations from soft alluvial ground to hard competent rock. It seems only reasonable that tunneling machines could be adapted to the task of boring shafts, both vertical and inclined. Several companies around the world have produced boring machines designed to bore blind shafts. All of these machines have similar essential components which are, with some variations:

a. cutterhead
b. thrusting system
c. gripping system
d. guidance system
e. muck removal system

The cutterhead of boring machines consists of a full face rotary cutter support body on which are mounted replaceable combinations of tooth, disc, or carbide button type cutters. The cutterhead is driven through a ring gear by multiple electric or hydraulic motors.

The thrusting system applies the required force to the rotating cutterhead by means of several hydraulic cylinders. The thrusting forces are reacted by the gripping system, which is attached to the non-rotating support structure and grips the side walls of the shaft by applying side forces via hydraulic cylinders to grip pads.

The guidance system is usually a laser light beam focused on a target observed by the machine operator. The operator steers the machine by applying differential forces to the thrusting and gripping system hydraulic cylinders.

All of these previously discussed machine components are similar to corresponding systems in tunnel boring machines. The muck removal systems of shaft boring machines have been different from similar systems in tunnel borers, and these systems have given a great deal of problems. The primary muck pickup on most of these machines is by means of chain type conveyors which wipe through the muck at the low point of the face and deposit the muck into a collection hopper at the top of the machine. From this point additional conveyors transport the cuttings to the surface. Up to the present time (1984) none of the mechanical muck removal systems have performed in a completely satisfactory way. The presence of water can cause clogging of the system, for example. One system, shown in Fig. 2, attempts to fluidize the muck by adding large quantities of water, thereby creating a completely hydraulic muck disposal system.

Other muck disposal methods that have been tested with varying degrees of success have been reverse circulation air and air/fluid systems and vacuum systems.

The blind shaft boring machines have the capability of applying very large torque values to the cutterhead; one machine built by Robbins Company had a maximum torque capacity of over 2.71×10^6 N-m (2.71×10^6 ft-lbs), which is over four times the maximum torque of surface mounted rotary drilling machines. This large torque translates directly into a capability of drilling large, up to 10 m (33 ft) diameter, blind shafts, provided of course that the muck handling problems can be solved.

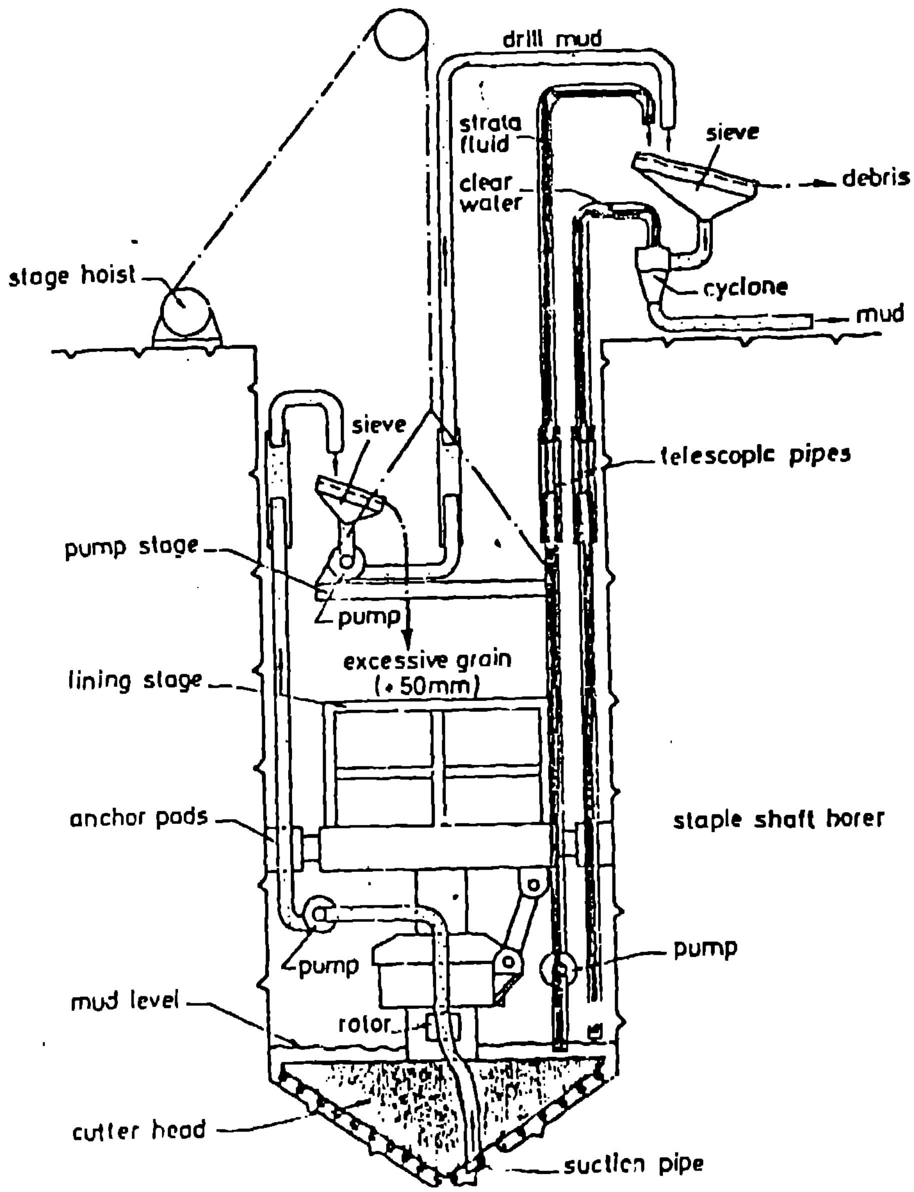

Figure 2. Blind Shaft Borer, Schematic Layout of Hydraulic Muck Disposal System

The other major comparative advantage of shaft boring machines is that absolute directional accuracy can be controlled by the operator, since the machine is being positively steered at all times.

Since the shaft is being bored largely "in the dry," a liner system can be installed above the machine simultaneously with boring the hole. In fact, on one major project the concrete liner construction proceeded more slowly than the shaft could be bored, hence was the pacing item of the shaft construction.

A safety consideration of bored shafts is that personnel must be located in the shaft to operate and coordinate the several systems.

Blind Shaft Construction Considerations

There are numerous situations and combinations of conditions that influence how a so-called "blind shaft" is to be mechanically constructed. Of these many influencing factors, perhaps the two dominant ones are shaft size, i.e. diameter and depth, and geological formation characteristics.

Shafts driven to relatively shallow depths and in unstable formations are most frequently still constructed by the traditional drill-blast-muck out method, with perhaps the formation stabilized by freezing the formation at the perimeter of the shaft. Conversely, deep shafts up to 20 ft diameter in stable, hard formations present ideal conditions for using mechanized construction methods. Boring machines, although not notably successful up to the present time in making vertical shafts from the surface downward, have a great potential for further development toward the capability of making very large 10 m (33 ft) diameter shafts. The only major problem delaying widespread use of those machines is the muck removal difficulties. However, the solution of this problem is believed to be not dependent on shaft diameter.

The drilling of shafts using special surface-mounted rotary rigs has been very successful in the medium diameters up to 3.6 m (12 ft), but bottom hole cleaning and chip removal becomes more difficult at larger diameters. Another factor is the limitation on torque and hoisting forces imposed by the sizes of dual string pipe used by these rigs. Even if the pipe string is increased up to 0.51 m (20 in) diameter from the present industry standard of 0.34 m (13-3/8 in), the torque available will be only 25% of the torque of the larger in-hole boring machines.

If hole accuracy is a strong factor in the final shaft specifications, then boring machines probably have an advantage for vertical holes because they are positively steered by the operator. For inclined shafts boring machines have a good directional accuracy capability, while surface drill rigs have yet to demonstrate an inclined blind shaft drilling capability, although some smaller shafts have been drilled inclined by first drilling a pilot hole as a directional guide.

A site development plan, properly formulated, can result in only the initial shafts requiring blind shaft construction. After the initial shafts and the deep underground tunnels, vaults, and drifts are mined out, the remaining shafts are usually constructed by accurately drilling a small diameter pilot hole from the surface, then raise drilling or box drilling a reamed shaft to the final desired diameter.

Raise Boring and Raise Drilling

Compared to conventional drill-and-blast shaft excavation methods, raise boring offers many advantages, such as safety, increased productivity, less disturbance of formation from its equilibrium state, and smaller excavation crew. In spite of the advantages there are two major limitations, namely (1) it is essential to have underground accessibility for the reaming head (and boring system if a boring machine is used), and (2) raise boring usually is accomplished in an operating mine, therefore close coordination is necessary between the owner and the excavation contractor.

Raise drilling variations are proliferating, so strict terminology needs to be defined. Raise drilling is usually understood to mean drilling a shaft using a surface-mounted rotary drill rig turning a raise bit via a pipe string located in a pilot hole. The pipe string is loaded in tension and torsion by the surface rotary rig, and the cuttings fall by gravity to an underground muck disposal system.

A box drill is a machine located in an underground vault or tunnel that drills a shaft upwards by rotating a full face cutting bit on the end of a large, stiff pipe string. The shaft may be either vertical or inclined but is usually inclined. The shaft length is usually limited to a few meters such as between mining drift levels. The cuttings fall downward by gravity and are disposed of by a muck removal system at the lower level. Usually no pilot hole is drilled for a box drilled shaft.

A raise borer is a blind shaft boring machine designed to excavate a shaft at an inclined angle upward, and the latest designed machines have the capability of making a vertical blind shaft. The cuttings of course fall downward by gravity and are disposed of at the lower level.

Of these three raise techniques, raise drilling is the most highly developed and extensively used, attributed primarily to the fact that modified standard oil and gas drilling rigs can be used, both to drill the pilot hole and to drill the raise itself.

The accuracy of the raise drilled shaft is determined by the accuracy of the pilot hole, so accurate directional drilling practices are applied to the pilot hole drilling.

The current raise drilling record for depth is 690 m (2300 ft) at 3.66 m (12 ft) diameter and the record for diameter is 6.27 m (243 in).

The first blind shaft raise boring was achieved by operating tunnel boring machines to make inclined shaft/tunnels. In Europe tunnel machines made several inclines of approximately 30 to 35 degrees. Recently, machines designed especially for making large diameter. 1.7 to 6 m (6.5 to 19 ft) diameter blind raises have been built by both the Robbins Company and Atlas Copco Jarva, Inc., so we should soon read of these machines' performances in the technical literature.

Current Research and Development Activities

As described above, the shaft drilling technology as practiced today is derived from both the oil drilling industry and from the early tunnel boring machines. Recent improvements in both drilling and boring machines have emphasized two technical areas: (1) increasing drilling rate by using more efficient cutting structures and by increasing effectiveness of bottom hole cleaning and muck disposal capabilities, and (2) increasing capabilities to make larger diameter and deeper shafts by increasing the rotary torque and hoisting force loads of the drill rig.

The first technical problem of penetration rate improvement is being addressed by several organizations and companies. All cutter manufacturers are marketing disc-type cutters, which, while not in any sense a "cure-all," do cut larger chips in medium and hard rock formations and thereby enhance the drilling rates. In conjunction with the disc cutters, the support structures, and particularly the bearings, have been strengthed to promote long service times before replacement is necessary. Some experimental evidence has been accumulated that indicates that cutter life and drilling rate are enhanced if a uniform cutter force can be achieved and maintained, and at least one major manufacturer has marketed a microprocessor-controlled system to measure the transient bit forces and dampen these force transients to achieve a more uniform cutter load.

Bottom hole cleaning is a problem that becomes especially crucial as hole diameters increase above 3.6 m (12 ft). The standard reverse circulation muck removal system loses its effectiveness at the larger diameters and simply increasing the flow rate does not help much. The problem is aggravated by the flat surface cutting face that has been almost universally used. The rotary cutting motion creates a centrifugal force on both the fluid and the cuttings that tend to force the cuttings toward the outer periphery and away from the central pick-up pipe. One solution of the problem is to go to spherical or conical-shaped cutting surface designs, but in the past such conical shapes have been believed to have caused directional instabilities and hole inaccuracies. Perhaps pre-drilled pilot holes will solve this accuracy problem.

An example of an innovative application of a spherical cutting surface and a pre-drilled pilot hole is shown by Fig. 3, which shows the system employed by Zeni Drilling Company to drill two 2.2 m (88 in) diameter shafts of 230 m (750 ft) depth in New Guinea using disc cutters in hard, highly fractured igneous rock.

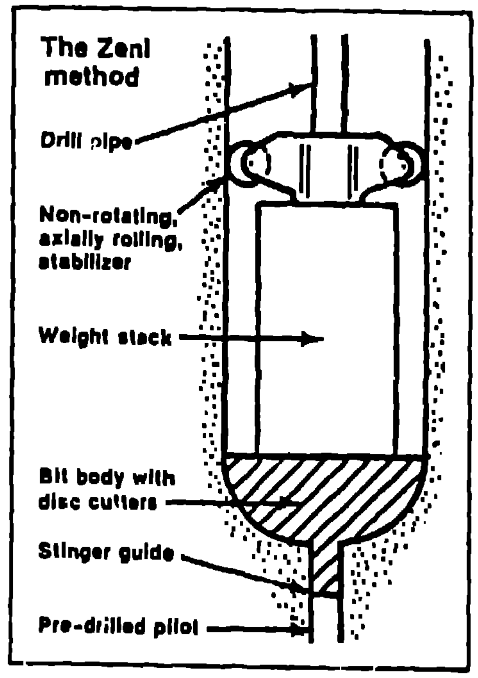

Figure 3. Zeni Method of Shaft Drilling Using Spherical Bit Body and Pre-drilled Pilot Hole.

For boring machines, the manufacturers are each carrying out studies to solve the muck handling problems for their respective models and in at least two instances, blind shaft vertical borers are being marketed.

The second technical problem of achieving larger diameter and deeper shafts must be solved by manufacturers offering larger capacity and higher bit forces, hence higher hoist capacities for surface drilling rigs. A trend toward larger rigs is already evident and given a favorable mining economic climate, will probably continue.

Summary

Several drilling technologies exist and are being extended that permit vertical and inclined shafts to be mechanically drilled. Such shaft construction methods are safer, faster, and economically competitive with the traditional drill-blast-muck out methods in use for hundreds of years. The trend is toward developing larger and more specialized drilling machines for shaft construction. Shaft directional accuracies can be achieved that are consistent with the intended use of the shaft and, in any case, can be as accurate as desired if special techniques are employed and rate of construction is slightly compromised. Research is continuing to improve the cutter life and cutting efficiency, hence to achieve faster drilling rates. Bottom hole cleaning, debris removal, and muck handling systems need to be improved and development is underway to solve these technical problems.