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Chapter 58

THE ROUTE TO MORE EFFICIENT BLIND SHAFT DRILLING?

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ABSTRACT

The paper describes a variety of existing techniques and equipment which when combined together permit faster and cheaper drilling of shafts in soft to medium strength formations. Drilling fluid circulation, methods of hole stabilisation and bit design, including the advantages of flat bottomed and conical bits, shrouds and skirts, tungsten carbide, long tooth and disc cutters are considered. The principles of rock chip transportation and bottom hole cleaning are described together with a new and very efficient fluid circulation system which was invented by the author.

Blind shafts are holes drilled from the surface with no prior connection existing to any underground workings. Current surface mounted equipment and existing rotary drilling methods would enable holes up to 10 m in diameter to be drilled to depths of more than 1000 metres.

This paper considers a variety of existing techniques which when combined together would permit faster and cheaper drilling of shafts in soft to medium strength formations. The formation of a drilled hole requires only three basic functions.

1) Breaking of the rock at the base of the hole.
2) Removal of the broken rock from within the bore.
3) Support of the shaft wall.

Breaking of the rock at the base of the hole is achieved by cutters attached to a bit body. During the last three or four decades various types of cutter have been developed with a view to increasing the effectivness of rock excavation. The underlying aim of these developments has been to increase the reliability and life of cutters while permitting increased loadings to be applied to them.

Several different companies throughout the world manufacuture cutters but there are only three basic types:

1) Steel milled tooth
2) Tungsten Carbide insert
3) Disc or Kerf cutter

All of these types of cutter have been in existence for many years and while manufacturers have extended the life of the cutter with improved metallurgy and bearings, they have not significantly improved its rate of cutting.

Changes in cutter design that could lead to greater efficiency include:

1) Tooth shapes designed to help transportation of the rock chips to the pick-up point of the bit.

2) Larger diameter cutters which would be less prone to skidding when lightly loaded.

3) Effective scrapers or other mechanisms that would clean the cutter.

Steel Milled Tooth cutters are most suitable for soft ground and they produce large cuttings. This gives the potential for rapid rates of penetration but the performance of the cutter diminishes rapidly once the teeth begin to become blunt.

Tungsten Carbide insert cutters are usually used in harder rocks or in particularly abrasive formations. They require significantly larger bit loadings than the other types of cutter and the rock chips produced are very small. The rate of penetration with these cutters is usually slow, typically a maximum of only a few hundred millimetres per hour, although similar performance is often obtained throughout the life of the cutter.

Disc or Kerf cutters are not normally used for blind hole drilling because they tend to produce large chips which cannot easily be transported across the bottom of the hole and up to the surface. In soft or plastic strata they can produce concentric furrows on the base of the bore with no excavation actually taking place. Because of the relatively wide spacing of the discs on these cutters many more units are required to dress a bit than for tungsten carbide insert cutters when used for hard formation drilling.

In order to advance the hole downward, a force must be applied to the cutters so that the cutting structure (tooth) penetrates the formation. In soft strata the material is displaced by the tooth and subsequently dislodged by the movement of the tooth itself, whereas in harder strata the rock under the tooth is actually crushed and tensile forces are induced in the rock adjacent to the tooth, thereby causing failure of the rock by spalling. The harder the rock, the more force is required to cause tooth penetration and the shorter the tooth penetration the smaller is the chip that is produced.

It will, therefore, be evident that for any particular rock strata the greater the tooth penetration that is achieved then the greater the rate of drilling will be. For many years the force (weight) that could be applied to cutters was effectively limited because of the bearings in the cutters. In the last 10 years or so these difficulties have been substantially overcome and it is now possible to load individual cutters with forces up to 20 tonnes. The materials used in the manufacture of the cutting structure (teeth) of the cutters has also been improved and this has resulted in much longer running times being achieved before cutter replacement becomes necessary.

These improvements mean that in real money terms cutter costs per metre of hole excavated are lower now than they ever were.

The cutters themselves are mounted in saddles which attach to a fabricated steel bit body. Various basic shapes of body have been used, including flat bottomed, conical, hemispherical or a combination of shapes. Recent designs have included flat bottomed with the outside one or two rows of cutters mounted at a slight upward angle to the horizontal so as to form a shallow dish shape.

The various cutter manufacturers favour different shapes of bit body for use with their own cutters and they claim advantages for their own particular favoured shape. Some say that flat bottomed bits drill straighter holes, others that hemispherical bits are best because of their geometrical shape and symmetry.

The author has carried out field trials using flat bottomed and steep conical bits and has found that the latter gave increased rates of penetration in medium to soft formations.

Removal of the broken rock from within the bore is the area in which the greatest improvements in efficiency can be made using existing technology and equipment.

THE GREATEST LIMITATION IN BLIND SHAFT DRILLING IS THE INEFFICIENCY OF ROCK CHIP TRANSPORTATION ACROSS THE BOTTOM OF THE HOLE.

Ideally, the cutter should break a large chip of rock which is instantly dislodged from the bottom of the hole and transported to the pickup point of the bit and conveyed out of the hole with no secondary contact with any other cutter.

This would enable the cutting structures to attack new pieces of rock on each revolution of the bit and for the maximum rate of penetration to be achieved. In practice, the rock chip, even if it is formed by a single pass of a cutter, does not immediately become dislodged. This means that the next cutter passing over that portion of the hole is not presented with fresh rock to cut but instead is running on old rock chip debris. This debris is ground into small pieces which may require several re-grindings before they are small enough to be transported away by the circulating fluid.

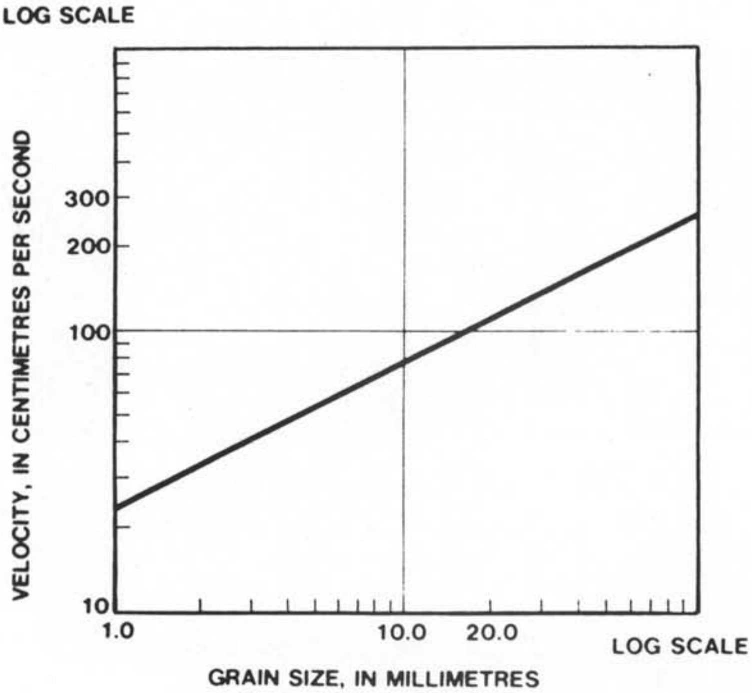
The reasons why the chip is not initially dislodged are inadequacies in the cutter design and insufficient velocity of the circulation fluid over the bottom of the hole where the chip is lying.

Sundberg carried out work to determine the relationship between the horizontal flow velocity of water and the size of rock chip that could be transported. The relationship is found to be approximately linear on a log/log plot and an increase in water velocity by a factor of 2 from 100 cm/sec to 200 cm/sec caused chips that are approximately 3.6 times larger in diameter to be transported. Such a chip could be up to 46 times larger in volume than the chip capable of being transported by the fluid flowing at the original velocity.

In order to encourage the movement of larger cuttings across the bottom of the hole it is necessary to increase the carrying capacity of the fluid.

This can be achieved in several ways:

1) Improve the circulation system to give larger fluid circulation rates.



GRAIN SIZE VERSUS FLUID VELOCITY FROM SUNDBORG DATA.

2) Increase the velocity of the fluid across the very bottom of the hole where the rock chips are lying by restricting its path by skirts or shrouds.
3) Change the physical properties of the fluid by the addition of chemicals.
4) Change the angle of the bottom of the hole.

Circulation Systems

Several types of circulation systems are available for blind shaft drilling applications. They include: Reverse liquid flush, Forward liquid flush, Reverse air or gas flush and forward air or gas flush. It is, however, the reverse liquid flush system that is most commonly employed and which most often provides the best and easiest method of circulation.

Reverse or counter flush circulation is that in which the circulation fluid is passed down the shaft on the outside of the inner drill pipe (either in the annulus between the drill pipe and bore or in the annulus of a dual wall drill pipe). It then crosses the face of the bit and moves up the inside of the drill pipe to the surface. It is particularly suited to large diameter drilling because the downward velocity of the fluid in contact with the wall of the drilled shaft is low thereby causing the minimum erosion of the shaft wall while the upward velocity of the fluid inside the drill pipe is high, thus enabling it to carry large cuttings. Liquid reverse circulation is usually achieved by means of an air-lift in which air is introduced, under pressure, into the drill pipe at some depth below the level of the liquid that surrounds the outside of the drill pipe. The column of liquid within the drill pipe becomes aerated with the consequence that it has a lower average density than the column of liquid on the outside of the drill pipe.

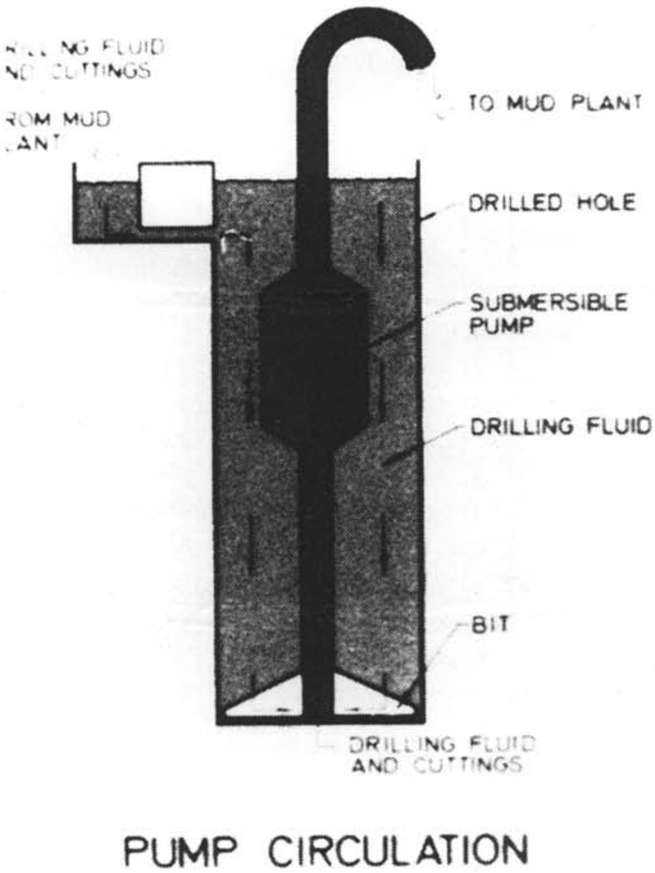
The two columns of liquid and aerated liquid are interconnected at the bottom of the drill pipe at the bit and the difference in pressures between the two columns causes the liquid on the outside of the pipe to flow towards and into the hole at the lower end of the drill pipe. Air-lift pumping has been in use in Great Britain and Europe since the latter half of the 18th Century and is therefore a well established technique.

Reverse flush may also be achieved by reducing the pressure on the inside of the drill pipe by applying a partial vacuum at the top by means of vacuum pumps or inductors. The liquid column outside the drill pipe plus the atmospheric pressure exerts a greater pressure at the base of the bore than does the liquid column in the drill pipe plus the partial vacuum. This imbalance in pressures causes the liquid to flow up the drill pipe.

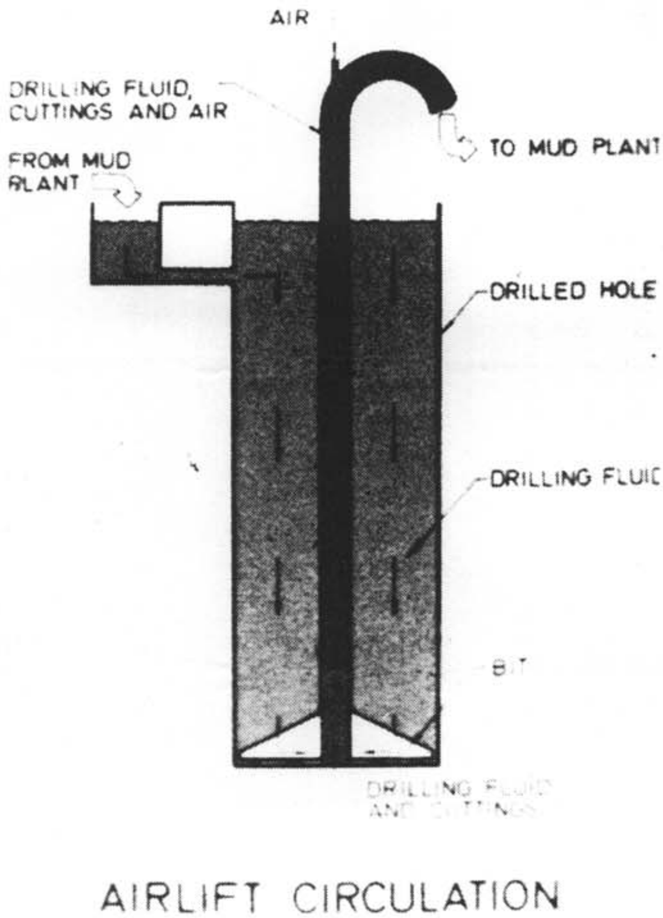
Because the maximum difference in pressure between the inside and outside of the drill pipe is limited to atmospheric pressure when using vacuum pumps, and it is the difference in pressure that causes the pumping forces for the fluid, it can be seen that vacuum induced reverse circulation is not suitable for long lengths of drill pipe with large circulation volumes due to the high frictional resistance of the circulating fluid flowing inside the drill pipe; also rapid rates of penetration are not feasible at depth because the density of the "liquid" column inside the drill pipe increases as more rock cuttings are added to it. As the pressure exerted at the bottom of this column increases so as to approach the pressure at the bottom of the column of liquid in the annulus, the motive force diminishes and circulation rates decrease to unacceptably low levels.

A new form of reverse circulation has been developed and pioneered by the author and is called "Pumped Reverse Circulation". With this system a submersible pump is installed down the shaft as part of the drill string. The pump is situated within the chamber of a closed vessel. The only entry to this vessel is from the drill pipe below and the output from the pump is connected to the drill pipe above.

When submerged in the fluid in the shaft the vessel fills with liquid and when the pump is activated it starts to pump liquid from within the chamber. This reduces the pressure in the chamber to less than the pressure outside the chamber and a flow is created. Because the vessel can be submerged to a depth which is only limited by the mechanical properties of the pump seals and the physical length of the power supply apparatus, the potential difference in pressure between the inside and the outside of the pump chamber could be many or even tens of atmospheres. Such a pressure difference would be sufficient to cause large flow rates through long lengths of drill pipe even when the fluid is laden with large quantities of cuttings.



PUMP CIRCULATION



AIRLIFT CIRCULATION

Another advantage of this system is that the drill pipe is full of liquid and solids only, with no air or gas being required. Therefore, for any particular velocity in the pipe the maximum quantity of liquid is flowing, whereas with the air lift or air injection system the pipe is occupied by liquid and air, so that for the same fluid velocity less liquid is being moved. This is a disadvantage as it is usually the velocity of the drilling fluid across the face of the bit that is the limiting factor in rock chip transportation, not the upward velocity of the fluid in the drill pipe.

Large circulation volumes, however, require large diameter drill pipes. The largest, readily available size of pipe has a bore diameter of approximately 300 mm. The maximum volume that can be circulated through this size of pipe using an air lift system with the ideal conditions of a deep air injection point is found in practice to be about 15 cubic metres per minute. This is almost identical to the circulation volume achieved by the author at both shallow and deeper depths using the "Pumped Reverse Circulation" system with 300 mm bore pipe. It has been calculated however that with different pump characteristics a volume of over 20 cubic metres per minute would be possible.

Skirts and Shrouds

The cutters used on large diameter bits are mounted in saddles. This causes the cutter to stand off from the bit body by up to 450 mm and the volume of "open space" between the bit body and the bottom of the hole influences the velocity of the circulating fluid across the bottom of the hole for any given fluid circulation rate.

In general, a large under-bit volume results in a low average velocity for the fluid across the bottom of the hole. The under-bit volume can be decreased by fitting shrouds to the bit body. These shrouds blank in the areas between the cutters. Care must be taken by the bit designer to ensure that the bit body retains its dynamic balance and that the clearances between the shrouds and the bottom of the hole are not so reduced that they scrape or cause obstructions to the transportation of particularly large rock chips which from time to time may be formed in the normal course of drilling.

The fluid may be directed to flow close to the surface of the bottom of the hole by skirts or baffles fitted at suitable locations on the bit body, usually between the cutters on the perimeter of the bit or close to the centre of the bit. These two locations are places where the "resultant" velocity of the circulation fluid is likely to be at its lowest.

The skirts consist of metal or rubber sheets which extend most of the distance from the bit body to the bottom of the hole. They cause the fluid path to be restricted to the small space between the bottom of the hole and the skirt. This causes the circulating fluid to have an increased velocity over this section of the hole which is the purpose of the exercise.

When a bit is being rotated in the hole it imparts a rotational or tangential velocity to the fluid surrounding the bit. If that fluid is being circulated by a reverse circulation method it will have a radial velocity from the outside of the bit towards the pick-up point of the bit. The "resultant" velocity of the fluid is a function of the tangential and radial components. In practice the fluid flows in an erratic spiral from the outside of the bit inwards towards the pick-up point.

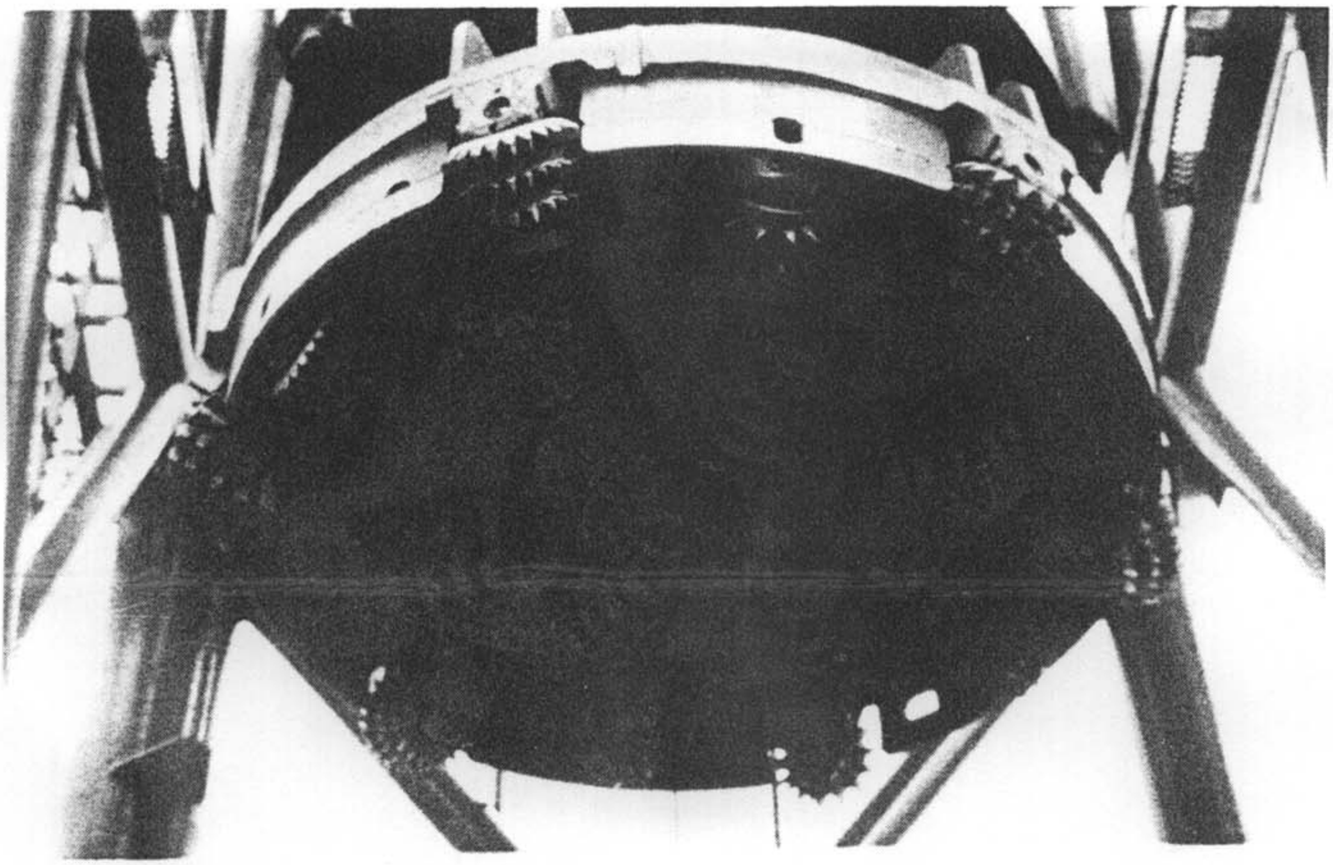
On the outside perimeter of the bit the radial component is low and the tangential component is likely to be high but this depends upon the physical characteristics of the particular bit and the speed of rotation. A skirt placed on the perimeter will greatly assist in increasing the radial component of the flow over this part of the hole.

Near to the centre of the bit the tangential component is small, irrespective of the speed of rotation of the bit and the "resultant" velocity is determined largely by the radial component. For bits fitted with a central pick-up a skirt placed near to the centre of the bit may significantly increase the velocity of the circulating fluid at the critical location.

The "resultant" velocity may often be able to be increased by speeding up the rotational speed of the bit. Several factors limit the permissible speed of bit rotation. Amongst these are the reduction of reliability and the risk of failure of the cutter bearings and the ability of the drilling rig's rotary system to operate for long periods of time at high speeds and torque. The input horsepower of the rotary system is directly proportional to the speed of rotation for a fixed torque and sufficient horsepower for high rotational speeds may not be available except on the very largest of rigs.

It is usual to limit the speed of rotation of large diameter bits, due to the loadings on the cutter bearings, so that the perimeter speed does not exceed 115 m per minute.

A combination of the highest practical rotational speed together with bit shrouds and correctly placed skirts will result in an increased velocity for the circulating fluid across the bottom of the hole.



2.44 m bit with skirts and shrouds fitted with milled tooth cutters

Mud Properties

Changes to the physical properties of the circulation fluid may further improve the bottom hole cleaning. Sundberg's work was carried out on the horizontal transportation of rock chips by water. If the viscosity of the circulating fluid is increased then the rock chip carrying capacity of the fluid is also increased. If the density of the fluid is increased then this improves the carrying capacity of the fluid but it becomes more difficult to dislodge the rock chip in the first place with fluids of higher density. Other problems may also arise with high weight drilling fluids and therefore, overall, it is thought to be better to use circulating fluid with low density but with a viscosity greater than water.

Bottom Hole Angle

Changes to the angle of the bottom of the hole will assist in rock chip transportation if the surface over which the rock chips are to be moved is inclined downwards from the horizontal. It requires less applied force to move a particle down a slope than across a horizontal surface. Therefore for any given force, the steeper the angle of the inclined surface over which the particle is to be moved then the larger is the particle or rock chip, that may be moved across it.

This fact has been used by the author to improve rock chip transportation under large diameter bits. He has built steep conical bits for use in medium to soft formations where large rock chips can be produced by the cutters. He has found that these large chips are capable of being moved down the inclined surface of the hole to a pick-up tube located in the centre of the bit, whereas chips of comparable size would not easily move across the bottom of the hole formed by a flat bottomed bit.

It has been found in a 2.44 m diameter hole that by using all of the above techniques to improve rock chip transportation (ie. large flow rates of up to 15 cubic metres per minute with a shrouded, skirted steep conical bit rotated at the maximum speed with light-weight medium viscosity drilling fluid), then chips larger than those that can be generated by standard milled tooth cutters are capable of being transported.

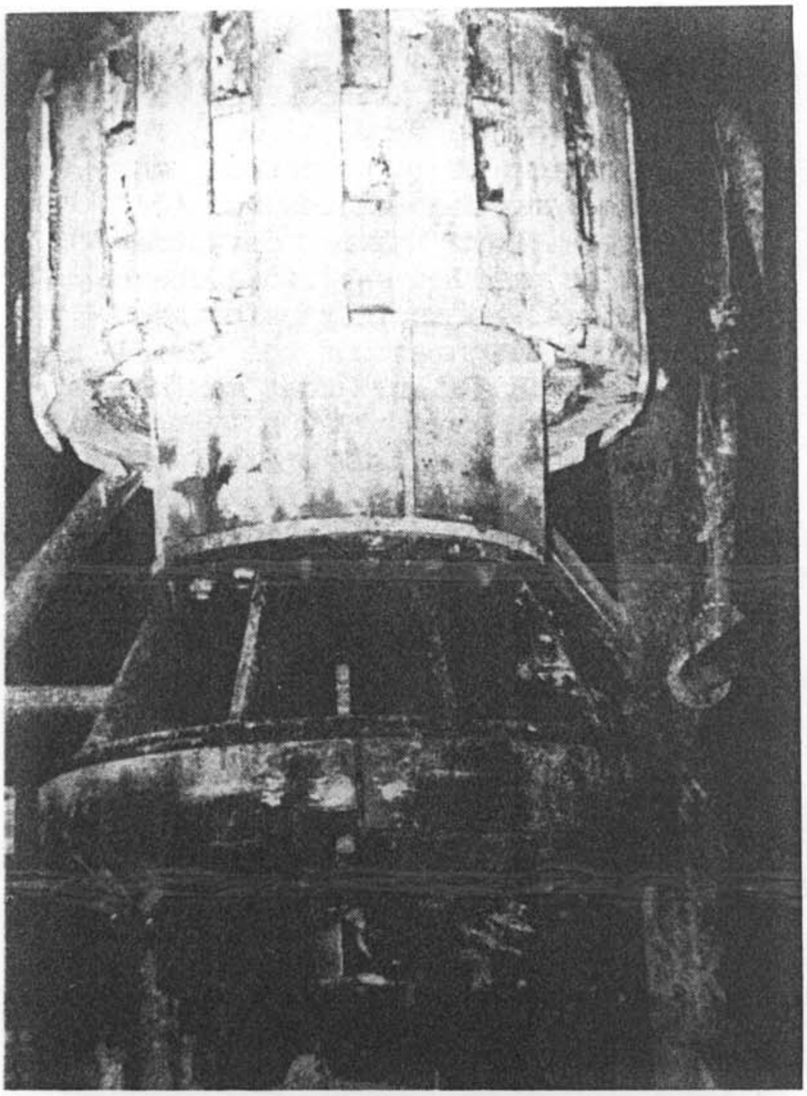
This has enabled disc or kerf cutters to be used in such circumstances. As a general principle more overall energy is required to break rock into small pieces than into larger ones and for the greatest efficiency and fastest rate of drilling the rock should only be broken down into the largest size that can be readily moved across the bottom of the hole.

Disc or kerf cutters are designed to produce larger chips than do milled tooth or tungsten carbide insert cutters, but kerf cutters have seldom been used in blind shaft drilling because of the difficulty that is experienced in generating any chips at all with them when they are fitted to the conventional flat bottomed bit. Even when chips were produced they were often too large to be effectively transported out of the hole. An additional problem is that more disc cutters are usually required than milled tooth cutters to dress any particular size of bit and more force is needed on each cutter in order to achieve the required penetration before rock failure occurs and any chip at all is produced.

More force per cutter and more cutters per bit results in much more weight being needed for a bit fitted with disc cutters than for a similar-sized bit with milled tooth cutters. It was often impractical to use kerf cutters, with the limitations on bottom hole assembly and drill string weight that existed with the lighter duty drilling rigs that were used for blind hole drilling in the past.

The steep conical bit shape offers another advantage over the flat bottomed bit shape in that it provides an inclined free face to which the rock may fracture and break. When disc cutters are used on an inclined face the amount of furrowing that may take place before rock failure occurs is reduced. This opens up the possibility of using disc cutters in strata for which they were previously considered unsuitable.

In hard or particularly abrasive formations it is possible to use disc cutters fitted with tungsten carbide inserts. These provide the advantages of larger rock chip size and increased life for the cutting structure of the disc.



Conical Bit fitted with disc cutters

The drilling of large diameter holes at increased rates of penetration seems therefore to be an achievable goal. It is nonetheless essential that these holes be drilled on the line and in the direction required. Most large diameter drilled holes are specified as vertical holes. The methods by which blind drilled holes may be kept vertical fall into three categories:

1) Steering of the drill bit
2) Guiding of the bit by a pilot hole
3) Using the pendulum effect and stabilisation

Steering of the drill bit is widely used on small diameter oil, gas and geothermal wells where whipstocks or bent-sub mud motors are used to drill deviated or directional holes. No equipment is known to exist for use in large diameter drilling which would be equivalent to the bent-sub mud motor. Some attempts have been made over the years to move the drill pipe off the centre line of the shaft so as to cause the bit to drill at an angle slightly inclined to the centre line of the shaft. Such a system was used during drilling of a shaft at Schinnen for the Dutch State Mines in 1950 (Colliery Engineering, December 1951) when an off-centre stabiliser was used.

The use of these devices is hard to monitor and control, and the rate of change of angle of the hole is also very slow. The system is not compatible with high rates of penetration and efforts have been directed more to keeping the shafts vertical rather than correcting them once they have deviated. Nonetheless, the author believes that as drilled shaft diameters become larger and shafts deeper, there will be an increasing need for the driller to be able to correct the alignment of the drill bit so as to form straight shafts that will allow the maximum size of casing to be installed.

The author has carried out theoretical studies and design work on the equipment and techniques necessary to allow 6 m diameter bits to be steered in rock but no practical tests have yet been undertaken.

Guidance of the bit by a pilot hole is the oldest and one of the surest methods of directional control used in the blind shaft drilling industry. The early holes were formed by drilling small holes which were reamed to larger and larger sizes using multiple passes of hole openers of increasing diameters.

A similar system is used today except that the pilot hole is often opened up to the final diameter required in a single pass. The type of bit used for this operation is very similar in design to other blind shaft drilling bits except that it is fitted with a central heavy duty stinger or guide pin which fits into the pilot hole and restrains the larger bit from wandering off centre. This method of working allows for most of the weight of the bottom hole assembly to be applied to the drill bit, thus enabling rigs of any particular size to drill holes of a larger diameter than would otherwise be possible.

One of the disadvantages of the system is that it is difficult to drill the pilot hole to the degree of vertical accuracy normally associated with blind shaft drilling. If a specialist slim-hole rig is used to form the pilot hole these problems can be overcome and the economies associated with the use of a smaller size of shaft drilling rig than would otherwise be required may be sufficient to allow for the extra costs associated with the mobilisation and use of the slim-hole rig.

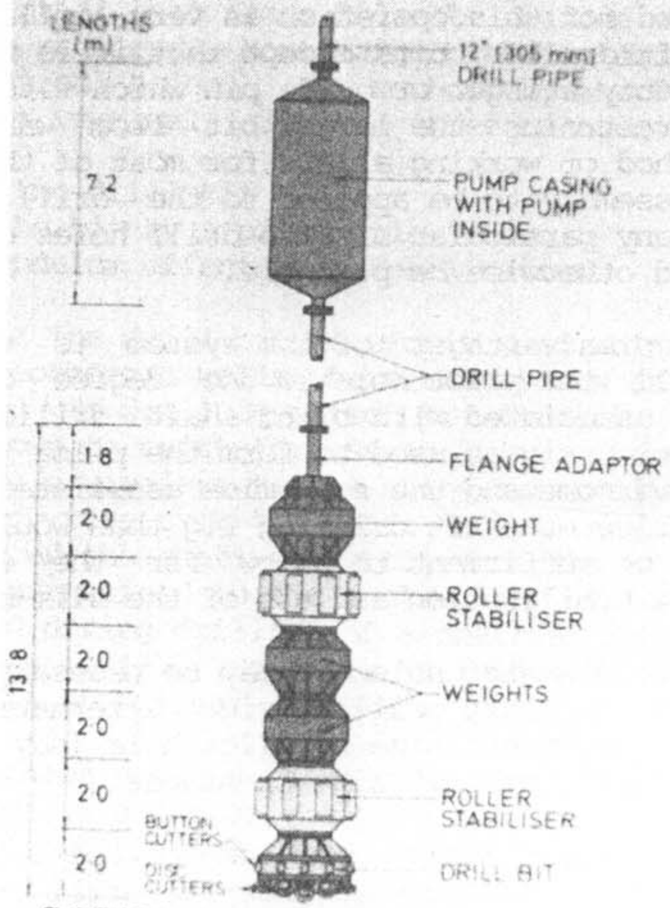
For very large diameter holes it may be necesary to use two or more passes with the shaft drilling rig. Alternatively it may be used to form a convenient size of pilot hole (say 2m) which could then be reamed to the full size in stages.

The pendulum effect occurs when some of the weight of the bottom hole assembly is held back so that the drill string is in tension and thereby tends to hang vertically. If the bit is displaced from the vertical the gravitational or pendulum effect provides a force which acts to bring the bit back on line.

It is usual to use large amounts of weight in the bottom hole assembly in the form of drill collars or drill weights situated above and near the bit. These weights are often interspersed between stabilisers which may themselves be heavily weighted.

More weight is provided than is needed to be applied to the bit. This allows some of the weight to be held back by the rig which causes both the pendulum effect to occur and the drill string to operate in tension. This is a very desirable condition as it prevents stress reversals in the drill pipe which could lead to fatigue failure of the pipe or pipe connections.

The greater the weight of the bottom hole assembly the greater is the weight that can be held back and this results in a larger pendulum effect, which should enable a straighter hole to be drilled. The diameter of any drilled shaft is, however, always small in relationship to the depth of the shaft and the permitted tolerances of the shaft from the vertical are also very small.



BOTTOM HOLE ASSEMBLY (Current)
For 2·44 m diameter

Because of the shallow angles involved, the resultant corrective force available from the pendulum effect is tiny in comparison to the excess weight employed and the deeper the shaft the smaller the angle of deviation will be for any particular horizontal displacement of the bit. It is therefore necessary to provide large amounts of excess weight in the bottom hole assembly in order for the pendulum effect to provide corrective forces of a significant magnitude.

Another benefit of having a heavy bottom hole assembly is that it acts as a flywheel. This tends to smooth out the bumps and jerks that result from the cutters running over different types of rock, or dipping strata. The rotary table of the rig is thereby protected from most of these shock loads and this leads to a longer life for this unit. Notwithstanding the above it is doubtful that shafts could be drilled straight in non-homogenous materials using the pendulum effect alone.

Stabilisation of the drill bit and bottom hole assembly is required in order to provide directional control for the bit. If strata conditions are encountered which tend to displace the bit from the desired centre line then some form of restraint must be available to the bit to prevent such a displacement occurring. This restraint is provided by stabilisers.

The bottom hole assembly should be provided with at least one and preferably several stabilisers. Sometimes the bit body itself is stabilised. This is because the nearer the lowest stabiliser is to the bit, the more effective will that stabiliser be in limiting the horizontal displacement of the bit from the centre line of the piece of shaft just drilled. If another stabiliser is mounted higher up the bottom hole assembly then the two stabilisers will work together to keep the whole of the bottom hole assembly central within the bore. Stabilisers work by bearing against the shaft wall thereby limiting the horizontal movement or displacement of the stabiliser and these other items of bottom hole assembly attached to it.

There are two basic types of stabilisers used, rotating and non-rotating stabilisers. The names refer to whether or not the outer part of the unit is capable of remaining static when the bit is being rotated. The rotating stabiliser does not possess this ability and is often fitted with rollers mounted on vertical axles so that they can roll around the shaft wall as the bit and bottom hole assembly is rotated. Sometimes these rollers are equipped with a cutting structure so that the stabiliser also acts as a reamer, opening up the hole to the required diameter as part of the overall drilling process, or to do so in the event of the gauge cutters on the bit becoming worn or if the ground should swell after initial extraction.

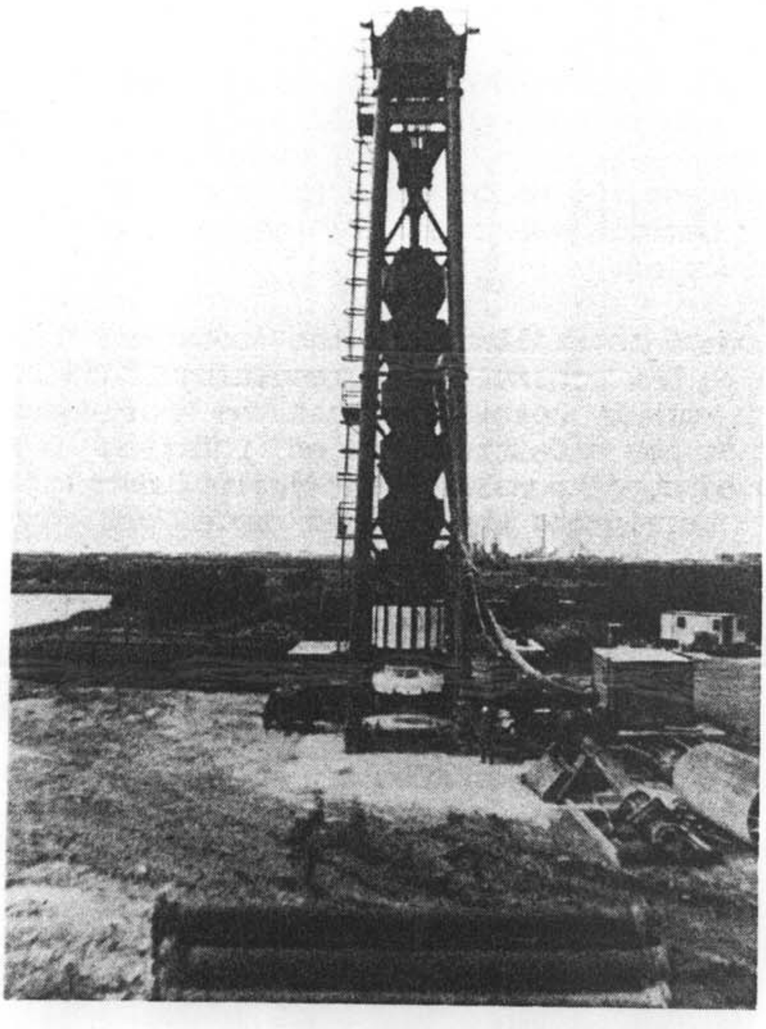
In soft ground the action of the rollers of the rotating stabiliser may cause damage to the shaft wall resulting in overdig. Since stabilisers only work by bearing against the shaft wall it can be appreciated that the effectiveness of rotating type stabilisers in such ground conditions is greatly, if not entirely, dissipated thereby permitting the bit to move off vertical.

The non-rotating stabiliser has an outer shell or a number of pads which because of the design of the unit can remain stationary even when the core of the stabiliser is rotated. In some designs these pads may be spring loaded so that they press against the strata. The pads will remain stationary so long as the frictional resistance between the pads and the strata exceeds the internal friction of the bearing arrangement between the outer shell or pads and the inner core of the stabiliser.

The outer section will therefore remain in contact with the shaft wall (without rotating) while the central core revolves with the remainder of the bottom hole assembly and the bit. This type of stabiliser causes much less damage to the shaft wall in soft formations and is therefore more effective at controlling the displacement of the bit.

The benefit that accrues from using multiple stabilisers particularly in soft formations, is that adequate stabilisation is often provided to the bit and bottom hole assembly even if overdig or damage to the shaft wall occurs opposite one of the stabiliser units. The more stabilisers that are used in the assembly and the larger the bearing surface between the stabiliser pads and the shaft wall, then the smaller is the unit loading for any particular bit displacement force. This smaller unit loading results in less damage occurring to the shaft wall which allows the stabilisers to perform their function better and a straighter shaft to be formed.

By using multiple point stabilisation and holding back the excess weight in the bottom hole assembly it is often possible to drill shafts with an accuracy of better than 1 part in 1000.



"Titan" drilling rig with bottom hole assembly.

CONCLUSION

By using a selection of the above techniques it should be possible to drill shafts up to 4 m in diameter at average rates of penetration of 20 m to 25 m per day in sedimentary rock having crushing strengths upto 100 MN/sq. m.

The excavation of blind holes at these rates of advance is not consistently obtainable by any other means currently available; but the drilled hole usually needs to be lined.

The lining or casings for blind shafts are often made from steel plate sometimes reinforced by heavy steel stiffening rings. The casings can be installed in quite long lengths at rates up to 100 m per day and then cement grout is placed in the annulus between the casing and the drilled hole. The provision, running and cementing of these casings is VERY expensive.

It is the cost of these casings, more than any other element, that is restricting the development of shaft drilling. If a significantly cheaper method of shaft lining could be developed, then shafts formed by the blind drilling method would often be the quickest, cheapest and certainly the safest method of shaft construction.