Directional Drilling for Tunnel Investigation and Associated Testing Techniques

I. Gray
[1]*Sigra Pty Ltd, Brisbane, Australia*
E-mail: ian@sigra.com.au

ABSTRACT: This paper examines the suitable directional drilling options available for tunnel site investigations. It examines the different drilling methods, borehole survey systems and testing that may be conducted within the hole for lithology, ground fluid and geomechanical parameters. The use of open hole drilling coupled with suitable borehole geophysics is compared with core drilling. The issues of drill string mechanics and drilling hydraulics are considered. The latter is frequently the limitation in shallower boreholes.

KEYWORDS: Tunnelling, Site investigation, Directional drilling.

1. INTRODUCTION

The conventional site investigation method for tunnels typically involves drilling a number of boreholes from surface, from which core is taken to be logged and tested for geotechnical parameters. In addition, downhole testing is often undertaken, which may include the measurement of ground fluids and stress. It sometimes includes borehole geophysics.

In shallow tunnels with predominantly vertical variation in geology, vertical drilling is generally the most effective approach. However, when either the proposed alignment is deep, the surface inaccessible, or where the geology changes rapidly through the tunnel alignment, there are good reasons to consider directional drilling in the alignment of the tunnel.

Advances in directional drilling technology have been driven by the petroleum industry. It has been adapted and modified to suit mining, and of late there is a trenchless technology drilling industry serving civil engineering needs. Between these capabilities, the technology currently exists to conduct tunnel site investigation by directional drilling successfully and economically, provided the process and its limitations are understood. The prime limitations are borehole stability, borehole hydraulics and limitations of drill string mechanics. Directional drilling options include open hole drilling used with geophysics to obtain information on the rock type, and directional coring for direct sampling.

Accompanying any drill hole there should be a range of test techniques to obtain geotechnical and ground fluid parameters. These testing techniques have to be changed to deal with off vertical holes.

2. TYPES OF DRILLING

The drilling of virtually all boreholes is achieved by the rotation or sliding of the drill string or a combination of the two. The exception is where the hole is created by a cable tool which operates by the action of cutting, or bailing tools being raised and lowered on the end of a rope.

Rotation of the drill string serves the primary purpose of transferring cutting energy to the drill bit. Sliding of the drill string must be used with some other means to cut into the formation to progress the borehole. This can be achieved by a down hole motor powered by drilling fluid, mud jetting to erode the formation, or a down the hole hammer to break hard rock. Most sliding techniques are used with some rotation to open out the hole.

The drill bits used with rotation may be some form of drag bit, usually with tungsten carbide inserts, or increasingly with poly crystalline diamond cutters (PCD or PDC). Drag bits cut by digging into and shearing the material at the end of the hole. Where the rock is harder, a roller cone bit is commonly used, where the cutting action is achieved by studded, rolling elements that cause small bearing capacity failures of the bottom of the hole. This type of bit needs far less torque but greater thrust to make it cut.

The cutting of core is normally achieved using either impregnated diamond or surface set diamond drill bits at the end of a core barrel. These bits cut in a similar manner to drag bits. All, except the simplest core barrels, contain an inner tube to hold the core. This is supported on bearings so that the outer part of the core barrel may rotate while the inner tube does not. The inner barrel normally contains a core catching arrangement to grip and break off core when the core barrel is pulled back. Triple tube core barrels use an additional split tube within the inner tube of the core barrel. This enables the core to be removed from the inner tube while supported by the splits. The core barrel retrieval may be achieved by withdrawal of the drill string between each core run or by wireline. In the latter case the inner barrel is withdrawn through the drill string by a wireline. This process can be used in vertical or angled holes.

Percussion drilling is used to create open holes in hard material. The rock breakage here is achieved by impacting the rock surface at speed with a hammer embedded with tungsten carbide buttons. Most of the cutting is achieved by rock breakage on the rebound, though some may occur by bearing capacity failure on impact. To cut effectively the hammer bit must be rotated so that the buttons on the bit strike a different part of the hole at each blow. In short holes the hammering action may be delivered from the top of the hole but in holes of any length, down hole hammers are used. Most down the hole hammers are driven by compressed air.

Down the hole mud motors are driven by the drilling fluid passing through the motor which applies rotary motion and torque to the drill bit. In most of these the motor is a positive displacement device that works as a progressive cavity pump operated in reverse. It contains a power section composed of a helical rotor that rotates within an elastomeric stator housed in the body of the motor. The helical rotor is coupled to the drill bit. Mud motors may be used in combination with drill string rotation to provide extra cutting energy at the drill bit, or may be used for directional drilling with the inclusion of a bent housing below the motor power section.

3. METHODS OF DEVIATING THE BOREHOLE

3.1 Wedges

One of the oldest means to deviate a borehole is by using a wedge system. A wedge consists of a long steel ramp that is concave. The Wedge is orientated to a desired azimuth then anchored within the borehole. The anchored wedge forces the drill bit and drill string to deviate from the original hole trajectory. Wedges continue to be used to this day, especially in core drilling in mineral exploration. Here the boreholes may be deep and there is a need for additional ore sampling to the single hole. The choice is then made to pull back and set a wedge. Coring can then proceed on a changed trajectory and another sample obtained. This process has uses in tunnel investigation to provide geotechnical samples and to enable investigation of a bigger area than a single hole can provide.

3.2 Hole Jetting

Jetting was traditionally used in the petroleum industry to change the direction of boreholes in softer formations. The process requires a drill bit (usually a roller cone) fitted with an eccentric jet through which the drilling fluid was forced at speed. If the drill string was held stationary the jet would erode to the side of the hole face creating a pocket, and subsequent rotation would lead to the drill string preferentially following the path of the erosion. To achieve a significant hole deviation multiple erode and rotate cycles are required.

3.3 Deflecting Bits

These are used to push through soils and weak rock. They are of eccentric design that may include an angled blade, eccentric jets, eccentric teeth or even an eccentric roller. They are used by the civil directional drilling industry to create boreholes for services in soils and soft rock. They are generally pushed through the ground to build angle and rotated to enlarge the hole or to drill a straight section. Sometimes they are oscillated to build angle in a particular direction.

3.4. Dual Pipe Drill Strings

Another method used predominantly in the civil directional drilling industry involves the use of an external drill string, akin to a casing, along with an internal one. The external drill string has a bend at the end that can be pointed in a particular direction, or tool face. The inner component of the drill string can then be rotated within it to cut in the direction of the tool face. Both inner and outer sections are advanced together. Both the inner and outer sections may be rotated together to produce a straighter trajectory. The drilling fluid may be pumped up the inner drill string and return between it and the outer string. Alternatively, it may be pumped down the annulus between the inner and outer strings and returned up the outside of the outer string.

3.5 Positive Displacement Mud Motors (Mud Motors)

. Most directional drilling in rock is achieved through the use of mud motors which revolutionised directional drilling in the 1960s. In directional drilling form these are constructed to include a bend, so that the drill bit cuts at an angle to the main body of the motor. To drill in a particular direction, the bend is oriented to a particular tool face angle, fluid is pumped through the mud motor so that the drill bit is rotated, and the mud motor is advanced by sliding the drill string into the hole. If the desired trajectory of the hole is not in this build direction, or at the rate required, then multiple changes of tool face angle are required to keep the hole roughly on course. If the drill string and mud motor are rotated, then the borehole invariably cuts a downward trajectory.

3.6 Rotary Steering Systems (RSS)

Rotary Steerable systems developed by oilfield service companies are the current state of the art in directional drilling technology. To achieve much faster drilling rates, longer and smoother boreholes with fewer cuttings clearance problems, the oil industry has in part changed from the use of mud motors for directional drilling to rotary steering systems. In these the drill string is rotated and the drill bit is either pushed or pointed in a particular direction by a bottom hole assembly. To do this the bottom hole assembly includes ~~a~~ either a non-rotating sleeve which incorporates pads that push on the borehole wall, or a system to bend an internal shaft connected to the drill bit to point the bit in the desired direction. Pistons to control the pads or bend the internal shaft are actuated by on board electronic and hydraulic systems which act to guide the drill on a designed path. The system invariably includes electronics to communicate from the hole collar to the bottom hole assembly. The downhole electronics will also include orientation sensing systems and may include geophysical options to gather information on the rock being drilled, and thus enable the borehole to be guided into the correct petroleum bearing formations. Rotary steering systems have been used to drill 12 km laterally at rates up to 1 km per day. Rotary steering systems from the oilfield are expensive but cost efficient in the right application.

3.7 Directional Hammers

For a down the hole hammer to cut, the drill bit must be rotated so that the buttons strike new rock each time they hit. This is achieved by drill string rotation in normal straight drilling. Directional hammering systems require the bit to cut at an angle to the drill string. This is achieved through the use of a bent sub in the drill string. The problem with this is that the drill bit needs to be rotated. Though bit rotating systems have been patented, they have not become commercially available. Directional drilling with a hammer has therefore been achieved by oscillating the drill string and hammering over an arc to preferentially drill in that direction.

3.8 Directional Coring

Directional coring is usually accomplished by coring as straight as is possible for the maximum distance and then making changes where necessary. This coring is normally achieved by wireline core withdrawal rather than conventional recovery. Direction changes may be brought about by the use of a mud motor or the use of a directional coring system. The section drilled by a mud motor does not retrieve core. Directional coring may also be used to deviate the hole and to retrieve core. Directional coring systems work by deflecting the orientation of the core barrel so that it points in a preferred direction. The core cut by such systems is much smaller than could be cut using conventional or wireline core barrels.

4. BOREHOLE SURVEY SYSTEMS

Directional drilling requires the borehole orientation to be determined. It also requires the orientation of the directional drilling component (tool face) to be able to be set. There are three basic types of survey systems that may be used. They are:

4.1 Magnetometer and Accelerometer Systems

These operate by measuring the earth's magnetic and gravitational fields with triaxial magnetometers and triaxial accelerometers. The gravitational field always points downwards while the magnetic field points at various angles depending on the location of the measurement. It is possible from these measurements to determine the inclination and azimuth of the borehole from magnetic north and the tool face angle of any directional tool. Multiple point measurements are made along the length of the borehole and the borehole orientation determined by some means of integration or more simply the fitting of a uniform curvature between these tangential measurements.

4.2 Gyroscope Systems

Gyroscope systems come in many forms. They all measure change in orientation from some initial state.

The original gyroscope consists of a rotating wheel within gimbals which tends to hold its direction while the tool in which it is mounted rotates. Thus, the difference in orientation between the tool and the rotating mass may be measured (usually optically). Gyroscopes of this form tend to be fragile and need careful shock protection.

Micro-electrical-mechanical (MEMS) gyroscopes measure the rate of change of rotation to which they are subject. Their output has to be integrated to obtain a change in orientation. This process is subject to error and therefore these devices tend to have lower accuracies than other gyroscope systems. MEMS gyroscopes do however have the benefit of being resistant to shock, vibration and high temperatures without losing their calibration. They have very low power requirements. These factors allow them to be installed near the drill bit to conduct surveys while the drill string is static, such as during a drill pipe connection.

Fibre optic gyro systems use the Sagnac effect. In these a laser light is pulsed in two directions through a fibre optic coil and the phase shift between each direction is used to detect the rate of angular change of the coil. The output of these devices needs to be integrated to provide information on orientation change. Currently these devices tend to be more accurate than MEMS types. Laser ring gyroscopes also use the Sagnac effect but are too large for drilling applications.

No gyro system is suitable for use during rotary drilling where the angular rate of change is too great for use in their current form.

4.3 Incremental Deformation Systems

These systems measure the incremental deformation of a drill string or borehole by optical means. They comprise a tube with three points of contact within the drill string or hole. Within the tube are two or three transparent rings which are photographed by a camera located at one end of the tube. The relative displacement of the rings gives an offset while the orientation of this offset is determined with respect to a floating bubble which shows the up position and is also photographed. The system is designed to be inserted into a hole or drill string and advanced stage by stage to take multiple offset measurements. The initial orientation and position of the borehole has to be surveyed and the offsets can then be added to it to obtain the final hole position. This type of system can be used with considerable accuracy but seems to have fallen into disuse.

5. GETTING INFORMATION FROM THE DRILLING TOOL

To be able to obtain borehole orientation information or to be able to retrieve geophysical information requires some means to record and convey it to the hole collar. The original means for doing this was to record the information mechanically or photographically and to retrieve the tool used to gather it mechanically between measurements. The modern extension of this is to record the information into electronic memory devices and to retrieve these mechanically. Mechanical retrieval is slow but may be greatly sped up by the use of wirelines such as are used to retrieve wireline core barrels. Even with this it is still a very tedious process. Alternatives have therefore been sought.

The first of these is the use of wirelines that carry electronic signals as used in geophysical equipment. While these can permit the very fast transmission of data, they have to be removed from the drill string to permit drilling. They are therefore only marginally better than record on board devices for directional tool orientation.

The oilfield has adopted the use of mud pulse telemetry for much of its work. This uses an electrically actuated flow restrictor located in the bottom hole assembly to digitally change the back pressure in the drill pipe. This pressure change is monitored via a pressure transducer at surface and decoded. The rate of transmission is however only about 10 bits per second. The system can however be used with any drill pipe.

An alternative to mud pulsing is the use of electromagnetic telemetry. Here an electrically isolated section of the bottom hole assembly transmits low frequency waves into the ground. This information is picked up as a signal between earth points and the drill string. The reliability of the system is dependent on the ground through which communication is being made.

A variant of this is regularly used in horizontal directional drilling for services. Here the holes are shallow and communication can be made through the ground to a receiver that is held roughly above the transmitter located in the bottom hole assembly. In its simple form the receiver is hand held and is moved over the bottom hole assembly to maximise the signal and thus approximately locate the position of the transmitter below. In more advanced systems the signal being transmitted carries information on the orientation of the bottom hole assembly. This can be used by the driller to orientate the drilling tool to progress in a specific direction.

Another method of communication was one where a downhole transmitter tapped on the drill string and the noise was detected at surface by an audio receiver. This method had a range limitation of about 600 m in the form developed. Beyond this signal attenuation became too great.

The obvious solution to drill string communications is to use wired communication within it. Electronic communication while drilling with limited rotation can be made through wire located loosely within the drill string. This method is frequently used in horizontal directional drilling for civil purposes. Where more reliable communication is required and drill string rotation is at speed there is a need to fit a suitable wired communication system. Specifically wired drill pipe has been developed for oilfield applications. This incorporates a conductor and inductive coupling at each tool joint. Repeater systems need to be incorporated at some tool joints to overcome signal attenuation. The system is only available in a limited range of drill strings and is expensive.

An alternative system is used in the coal mining industry. In this, a rigid conductor is centrally mounted within the drill string between spiders located at each tool joint. Electrical connection of the conductors occurs as the tool joint is made up. The connection is sealed and transmission is through the single conductor and the drill string itself. In its current form the system has enabled drill holes up to 1.6 km in length to be drilled before drilling fluid pressure loss and other factors make the system untenable. The use of this system prevents the drill string from being used for wireline core recovery.

6. BOREHOLE FLUID MECHANICS

Drilling fluid flow is required to clean the cuttings from the drill bit and to carry them out of the hole. It also serves to cool the drill bit and frequently to lubricate the drill string within the hole. The pressure of the drilling fluid on the borehole wall can also be used to support the hole against collapse.

In the case of most drilling methods, the drilling fluid passes down the drill string and back along the annulus between the drill string and the borehole wall. An exception is where drilling includes advancing a casing, in which case the bulk of the fluid returns between the drill string and the casing. Another exception is that of reverse circulation drilling. The most common form of this is with hammer drilling, where the air passes down the outer annulus of a dual drill string and returns with cuttings up the centre tube. This method is used principally in ore body sampling.

In more normal drilling the fluid is required to lift the cuttings up a near vertical hole. Therefore, the upward flow velocity must be greater than the slip velocity of the particles through the fluid. In addition, the particles that are contained within the drilling fluid should not settle back during stoppages to drilling, such as during the addition of a drill pipe. This means either that the fluid flow rate is sufficiently fast that virtually all cuttings are discharged between rod changes, or that the drill fluid should be sufficiently viscous that the settle back rate of cuttings is low. The problem with highly viscous fluids is that the differential pressure to move them along the hole is high. Also, the use of viscous fluids leads to laminar flow which has less of a hole cleaning capability than turbulent flow. This is why many drilling fluids have additives that make them become less viscous with increasing shear. The ideal drill fluid is in many cases one which is highly viscous when it is not being pumped (sheared) and thins to allow turbulent flow when being pumped up the annulus.

In directional drilling in near horizontal holes, cuttings removal becomes more complicated. No matter how viscous the drilling fluid is, the cuttings being transported within it will settle on the bottom of the hole when they are not being pumped. Indeed, without the rotation of the drill string, such as in the case of sliding the string to drill with a mud motor, a cuttings bed will tend to form in the base of the hole. This has serious consequences for hole cleaning and friction between the drill pipe and the hole. If a cuttings bed forms and either a large cutting is formed, or part of the borehole wall sloughs away, it is very easy for a partial blockage in the remaining space at the top of the hole to occur. This situation may become rapidly worse as cuttings build up behind this, with the consequence that the drill string becomes locked into the hole by a collar of compacted cuttings. Under these situations the fluid pressure upstream of the blockage will rise rapidly.

In the case of boreholes lying typically from 25 to 55 degrees from horizontal a cuttings bed may form if the drill string is not rotated and then this bed will slump and slide down the hole to form a blockage.

Drill string rotation tends to agitate the cuttings and prevent the formation of a cuttings bed even in horizontal boreholes.

To move drilling fluid along a borehole requires a differential hydraulic potential. This potential comprises pressure plus density x depth x gravity terms. In the static situation, the fluid pressure in the borehole is dependent on the depth from the borehole collar and the pressure at the collar. When pumping starts this fluid pressure is augmented by the pressure required to move the fluid.

There is always the risk that there will be drilling fluid loss into the ground. This may be by seepage into permeable ground or by hydrofracture of the ground around the hole, with accompanying fluid loss. In the latter case the fluid loss may be to surface. This is a major risk with shallow directional holes in weak material.

The conundrum is therefore to achieve high enough flows for turbulent flow to move the cuttings while keeping the pressures low enough to avoid fluid loss and hydrofracture.

7. DRILL STRING MECHANICS

A drill string is a structural member that is subject to axial loads, bending, shear and torque. It must withstand these loads without failure.

In normal, near vertical, drilling, the drill string weight in the hole provides the bulk of the force on the drill bit. The weight of the drill string is frequently augmented by the use of heavy drill pipe, called collars. These collars are also stiff and can carry some compressive load with minimal buckling. Pushing the drill string will induce buckling. This occurs because the drill string is long and slender. The extent of buckling is limited by space within the borehole for the drill pipe to deform to.

In boreholes which are near horizontal there is a need to push the drill string to advance it. For buckling to occur the drill pipe must deform up the wall of the borehole against gravity. For each drill string, hole size and inclination, there is a specific axial load for the onset of sinusoidal buckling. If pushed beyond this axial load, the drill string will enter a helical buckling mode. This may be accompanied by a lock up of the drill string within the borehole. Under these conditions no amount of pushing will advance the drill string. Rotation of the drill string overcomes the problems associated with buckling while sliding.

A theoretical weightless drill string that has balanced moments applied at each end will form a constant radius curvature. As a consequence, there would be no friction between it and a hole of the same profile. Real drill strings have weight and the boreholes are never of constant curvature hence there are varying shear forces and bending moments along them. These, and any torque required to rotate the drill string, need to be taken into account in designing a borehole profile. This is the art of what is known as torque and drag modelling. To be useful it has to be verified, by frequent measurements while drilling, the force required to push the drill string into the hole, pull it out, or rotate it. With these real inputs it is possible to determine the friction existing along the borehole. Practical testing also indicates whether there are problems in moving the drill string in and out of the borehole. It is possible to push a drill string relatively easily into a hole with multiple directional changes and not be able to withdraw it due to the difference in load, and hence friction, that develops on the inside of the bends between the drill string and the hole in each mode of sliding.

Rotating the drill string changes its behaviour significantly from that of sliding. Friction opposes the direction of movement, thus the friction acting on a rotating drill string is principally opposing its rotation rather than sliding motion. If a drill string is being rotated it is much easier to slide along a hole than if it is not. The reasons for this are also associated with a change in friction of a drill string that is rotating on the borehole wall in fluid.

Boreholes should be designed so that plastic failure of the drill string does not occur at any stage. The exception to this is the oilfield technique where coiled tubing is used to drill a hole using a mud motor. In this case the drill string is a coil of steel tube that is deliberately plastically deformed to go into and come out of the hole.

The principal concern with drill string failure is associated with fatigue of the tool joints associated with rotation of the drill string. Drill string rotation in boreholes that are curved leads to an oscillating state of stress within the drill string and this is generally magnified within the tool joints because of their dimension and shape. It is therefore normal to limit the curvature of a borehole so as to limit fatigue loading. The degree of curvature may be thought of as the angular change per unit length. This is frequently described as dog leg severity and traditionally measured in degrees per 30’ length, a hangover from the oil industry.

To summarise, drill string mechanics and limitations are very different between rotating and sliding drilling systems.

8. TESTING METHODS

The methods to gain information from a borehole already discussed revolve around core retrieval and the use of geophysics. This leaves the measurement of rock stress and ground fluid associated properties to be measured by in-hole testing.

8.1 Borehole Geophysics

Borehole geophysics is extensively used in mining to determine rock type and rock properties. In sedimentary rock the typical suite of tools includes natural gamma, resistivity and density sondes. These three tools deliver the bulk of information on the formation type and group. In some cases, a neutron tool may be added to provide information on porosity. In igneous and metamorphic rock applications, electro-magnetic tools such as induced polarity or magnetic susceptibility may be used.

Geotechnical information is obtained from the sonic log, calliper log and either acoustic or optical televiewers. The sonic log may be a simple compression wave speed device or may also measure shear wave velocity. The most advanced tools measure shear wave velocity in different directions within the hole. From the sonic log it is possible to get information relating to the rock modulus and Poisson’s ratio. The calliper log gives an indication of where the hole has drilled or collapsed to be oversize. This is a direct indication of weak material within the borehole. Acoustic televiewers scan the wall of a liquid filled borehole using ultrasound. They develop an image of the borehole in terms of travel time and amplitude of the returning pulse.

Where the borehole is not liquid filled the acoustic televiewer cannot be used and needs to be replaced by an optical televiewer. Televiewers provide a 360-degree view of the borehole along its length and enable the acquisition of information on rock structure such as bedding and joints. An Optical televiewer can also be used to complement data from an acoustic televiewer, especially in areas of core loss within a borehole. Their use in combination with coring means that the orientation of joints can be determined without the need for orientated core. Acoustic devices can also be used to detect borehole breakout. This occurs when stresses within the rock lead to compressive failure of the borehole wall. The width and depth of this failure zone are an indication of the ratio of stress at the borehole wall over rock strength. As the borehole is likely to be drilled in the alignment of the tunnel this is a very useful finding.

Virtually all borehole geophysics is measured by lowering the sondes on a wireline winch and logging on their withdrawal from the borehole. This is not a convenient system for holes that at an inclination where gravity will not convey the tool down the hole. Logging directional boreholes requires some alternative means to convey the tools down the hole and for data storage and retrieval. The options are to run the geophysical sondes on the end of the drill string, but this places them in danger of damage during deployment down the hole. An option is to run the tools within the drill string while running into the hole and to pump them out when at the end of the hole. This type of operation is suited to tools that record on board and do not require human interaction to operate them. Another option is to use a tractor system to convey the tools along the hole trailing the geophysical cable behind the tool. This method always comes with the risk of the tool being jammed in the hole.

With the exception of the optical televiewer or the calliper log all borehole geophysics relies on the borehole being liquid filled. This requires managed pressure drilling systems to maintain fluid in holes that would naturally drain.

8.2 The Measurement of Rock Stress

The approximate determination of rock stress by borehole breakout has been discussed. Another way to gain an idea of the stress difference between the major and minor stress in rock is by measuring the core for ovality. Core that is cut as a cylinder deforms as the bit progresses over it and the in situ stress is relieved. Provided that core regrinding does not occur within the bit, the difference in stress perpendicular to the core hole for a linearly elastic rock is directly related to the difference in diameter of the core and the Young's modulus and Poisson's ratios of the rock. These measurements need to be related to orientation of the core.

Hydrofracture may be used to measure stress but is limited by complications associated with measurement and analysis. There are real complexities in running packer systems up a near horizontal hole, inflating them and fracturing hard rock. These involve packer pressurisation, deflation and the measurement of the orientation of any fracture created. The determination of anything except the minimum principal stress by hydrofracture is difficult.

Another option to the hydrofracture of intact rock is hydrojacking. This involves straddling a rock joint with packers and pumping water into the straddled zone to open the fracture. Once the fracture is opened, pumping is stopped and the pressure is allowed to decay until the fracture closes. This fracture closure pressure represents the stress across the joint. This is a measurement that is directly useful in investigation for tunnels that will carry water at pressure, such as head races in hydro-electric projects.

Overcoring is another method to measure rock stress. It works by measuring the change in diameter of a pilot hole or the change in strain on the wall of the pilot hole while it is overcored. Overcoring has been undertaken for many years in short holes drilled from underground openings. For the last 24 years overcore equipment has been available that will enable this to be undertaken to 1000 m depth in water filled boreholes at a near vertical inclination. Options now exist to run this in horizontal holes provided they are being drilled using an HQ type wireline coring system.

Any stress measurement is a point measurement and some means must exist to interpolate between measurements along a borehole. Either borehole breakout or core ovality measurements serve the purpose of determining where changes in rock stress occur.

8.3 The Measurement of Ground Water Parameters

The ground water parameters that matter in tunnelling are how much water the tunnel will make and what pressure will it develop should a lining be used to seal it out. Also of importance is the nature of any water make – does it come from porous rock, flow in fractures or does it come from hitting a limestone cavern with a limited volume?

The process of determining the flow from porous or fractured rock requires the measurement of permeability, storage behaviour, and as part of this process, the near wellbore loss terms. The frequently used approach of packer testing to obtain Lugeon values fails to measure any of these parameters and should not be used. A process of sealing a test section, waiting for its pressure to stabilise, flowing out of or into the test section and then sealing the section again should be undertaken. This follows oilfield drill stem test practice and will enable the measurement of fluid pressure and permeability separated from near well bore loss terms.

The only measurement of storage parameters that can be made from a test in a single hole is whether the pressure has dropped between the initial and final pressure stabilisations thus indicating a volumetric change.

More detailed information on in situ storage behaviour can only be obtained from in hole testing if some form of adjacent piezometer can be monitored. Information on water storage is otherwise limited to porosity measurements obtained from geophysical logging of the borehole, or to a limited extent by the visual examination of core or the measurement of its porosity.

The determination of fracture width associated with fluid flow is most important in any design of a grouting pattern.

8.4 Gases

Rocks may contain varying gas types. In carbonaceous rock methane, carbon dioxide and sometimes higher hydrocarbons are typically present. In other rocks it is possible to additionally get hydrogen and radon. The process of gas storage in rock may be by adsorption, typically of hydrocarbons, into carbon rich material, or in the pore space of the rock.

The risks with gases are the immediate complications they may cause with drilling, namely blowouts, or in the case of wireline coring, the ejection of the inner tube on recovery. When tunnelling there is a need to deal with the gases, as these may lead to ventilation issues which if not addressed may cause poisoning and asphyxiation. Gas at pressure may also lead to outbursts of rock and gas. These are serious, violent events that continue to plague coal mines but also occur in some other rocks and potash deposits. The sudden emission of ignitable gases also poses an explosion risk.

Where the potential exists for gases to be present it is necessary to measure for gas. There are two methods that are readily available during the drilling process. The first is to monitor the drilling fluid for gas emissions and types. This is part of what the petroleum industry would describe as mud logging. The second is to take core or cuttings and to seal them in pressure vessels and to volumetrically measure any gas release and to follow it by analysis of the gas. This method is suitable for gases held by adsorption but not free gases held in fractures or pore space.

9. PRACTICAL CONSIDERATIONS AND OPTIONS

Whether to attempt site investigation for a tunnel by the drilling of a directional hole will be dictated by economics, site access, equipment availability and geology.

9.1 Weak Ground

The presence of weak material such as soil or gouge material associated with faulting will be of immediate concern as this will be a major limitation on any drill hole. Hitting such material will require hole stabilisation measures.

In their simplest form these will mean keeping the borehole pressurised with drilling fluid. Here the drilling fluid is likely to be a bentonite mud which will form a filter cake on the borehole wall thus preventing fluid loss into the ground. Maintaining a pressure to support the hole requires that there is gravitational pressure head in the hole or that one is created by the use of managed pressure drilling systems which maintain a controlled pressure at the borehole collar. The use of such systems will also help prevent overpressure leading to fracturing and fluid loss.

The use any form of managed pressure drilling system requires a standpipe or well head at the collar of the hole. This should be capable of taking any pressure that is required. This requirement is universal for any serious drilling operation.

In the case where fluid pressure is inadequate to support the borehole or cannot be maintained to support the hole, then the use of casing is an option that should be considered. The length to which casing can be installed is dependent on friction and capacity of the drilling machine used to install it. Ideally it should be installed through a well head of some form and with a closed end so that mud pressure can be maintained during its installation. It is common under such conditions to need to install multiple casing strings, one inside the other, so as to reach a reasonable distance.

The use of viscous muds and adequate flow rates to drill can easily lead to excessive flowing pressures within the borehole. These, combined with initial static heads, can lead to hydrofracturing of the ground. This is a problem with drilling at shallow depths and in soils in particular.

Invariably the most difficult holes to drill are those in mixed ground. Where hard rock, boulders, gravel and finer material are present, each really requires its own approach to being drilled. Having to cope with all of them in a single hole becomes very difficult and may require the use of multiple drilling systems which may not be readily compatible.

9.2 Drilling in Rock

9.2.1 Drilling with Core Recovery

The immediate question that should be asked is whether the recovery of core is imperative. If it is, and the tunnel is of any length, then wireline coring is the most likely option as it offers very considerable time saving over conventional core recovery requiring pulling of the drill string to retrieve core.

The use of wireline coring does however pose an immediate limitation in that it is not possible to maintain pressure within the borehole above hydrostatic while retrieving the core. This may eliminate its use in cases where dewatering must be controlled. If adequate care is taken to observe water pressure and make values through the well head prior to wireline core retrieval, then problems may be detected. In this case the drill string may be withdrawn through the well head under controlled pressure conditions and a cementing string inserted into the borehole to conduct a cementing operation over a specific troublesome fracture, thus enabling the recommencement of wireline coring. Where water make cannot be controlled by cementing, coring can only be continued using conventional coring systems.

Normal wireline coring systems have no directional control systems. At best they will drill a relatively straight hole. The deviation of this can be monitored by survey systems that are conveyed by wireline. These may be included in the head of the inner tube, in which case they can be read each time the core is retrieved but they will only monitor inclination. Alternatively, they may be pumped down separately by wireline to record hole azimuth as well as inclination. In this case they will be either contain gyroscopes or magnetometers. In the latter case they will normally be pumped out of the core barrel so as to operate free of its influence on earth's magnetic field.

Corrections to the direction of the borehole can be made in three ways. All require pulling the drill string. The first option is to run back into the hole with a mud motor and to correct the hole trajectory fairly quickly, but with the loss of the core from this section of hole. The second is to use a directional coring system that will recover core of smaller size than that originally taken. This method will achieve the change of direction much more slowly than can be achieved with a mud motor because the cored sections are short. The third way is to set a wedge to deviate the hole.

Each correction to direction will bring with it a curvature in the hole through which the more normal coring process will have to continue. These dog legs should be kept to a minimum so as to reduce the subsequent fatigue loading on the rotating drill string.

The drill power and torque required to turn a drill string is considerable if we consider HQ coring (60.9 mm core for HQ-3 in a 96 mm diameter hole) ; the torque required to rotate the drill string over 1 km of horizontal hole with a coefficient of friction of 0.25 is about 1250 Nm. The power required to rotate the drill string at 700 rpm is 91 kW and the pull out load is 28 kN. The comparative values for 1 km of NQ coring (45 mm core for NQ-3 in a 75.7 mm diameter hole) are 655 Nm, 48 kW and a pull out load of 18.8 kN. The important figure here is the pressure loss associated with the passage of drilling fluid along the annulus. If the drilling fluid is water which is being pumped at 80 litres per minute the pressure at the drill bit is 4.4 MPa. This is likely to be too high for shallow holes. The other limitation on longer holes is the torsional capacity of the tool joints. Where the hole has curvature, the fatigue loading of the tool joint may become paramount. Designing directional holes requires a good understanding of the drill string and the application of torque and drag modelling. Wireline drill rods have inherently weak tool joints because they are generally of uniform internal and external dimension through the tool joint.

At the best, wireline coring will be limited to about 50 m per day in 1000 m length holes.

9.2.2 Open Hole Drilling

Drilling in the absence of core withdrawal is likely to be more than an order of magnitude quicker than wireline coring. The easiest rocks to drill are those which will cut using polycrystalline cutter bits. These comprise most of the sedimentary, a number of metamorphic and a few igneous rocks. These bits can typically cut at 0.1 to 1.0 m/minute, depending on the rock being drilled. The prime limitation on drilling rate is the ability to control the trajectory of the hole. This means taking borehole surveys and adjusting the hole trajectory. It is quite easy to achieve 300 m in a shift, and 1 km per 24 hour day has been repeatedly achieved in the right conditions using the best equipment.

To get this sort of productivity it is necessary to have good hole cleaning and preferably rotary steering as opposed to down hole motors. The problem is the cost of oilfield rotary steering systems and the size of drilling equipment required to operate them. New, lower cost systems are however becoming available for mining and civil engineering purposes.

If an open hole is to be drilled, then the means to determine what rock the hole passes through needs to be determined prior to drilling.

Some useful information can be gained from the measurement of penetration rate and the thrust and torque on the drill bit. This can be readily measured using a torque and thrust sub and suitable electronics. The next most easily used systems are geophysical sondes that have low data rates and can either record on board in memory or by transmission up a communications system in the drill string.

The most valuable geotechnical information is likely to come from the use of acoustic televiewers and sonic sondes. These require interactive use and therefore fast two-way communication through the drill string. This can be achieved.

10. CONCLUSIONS

Drilling directionally controlled boreholes as part of site investigation for tunnels can be a very cost-effective option under the right circumstances. The methods used for this can be an extension of the core drilling options currently used or a step into the realms of oilfield drilling technology. There are also a number of intermediate options becoming available. The choice of what to do requires a leap of faith from one which is dominated by core recovery to one that is based on open hole drilling with suitable borehole geophysical measurement to determine what is needed.

The petroleum industry made this leap many years ago and the mining industry is becoming increasingly dependent on information from geophysics. However, there are circumstances where core simply must be obtained. One option is to drill an open hole, examine the geophysics, and decide where core must be then taken. Then to do this by either side tracking off the main hole or by running a wedge and then taking a core.

Making the right decision requires a detailed knowledge of what can be achieved by the various techniques and having the right technology to drill and get the information required.