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Investigations for tunnels and storage caverns

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ABSTRACT: This paper describes the methods that have been used in exploration for mines, tunnels and storage caverns. This exploration can be conducted from surface and from underground. The techniques include core drilling: core orientation and logging; rock stress measurement; fluid pressure and permeability testing: geophysical logging and some alternative rock testing methods that are particularly useful in anisotropic rock. The paper also considers the use of open hole drilling as a cost effective way to get a lot of information quickly and at a lower cost than coring. This particularly applies to long directional drilled boreholes which are ideally suited to many tunnel exploration cases.

1 INTRODUCTION

Sigra have been involved in the geotechnical and geofluid investigations for mines, tunnels and underground caverns in rock for 31 years. During this period a number of important lessons have been learned and new techniques developed.

The first and most important lesson is that it is not possible to produce an good design without a thorough understanding of the geology. The extent of understanding must extend beyond the construction areas as potential regional effects must also be characterised and quantified.

The simplest geology is normally associated with sedimentary sequences, but these have their complications. The strata will thin, thicken, have gradational changes and disappear. There are also unconformities to consider.

Igneous rocks may be massive plutonic batholiths, which are often made up of several injection phases. They may be dykes and sills or extrusive events that cover the surface in lava or ash flows.

Metamorphic rocks are often complex as they are frequently made up of varying original material which has been heated, squeezed and recrystalised. They may be subsequently altered.

The complications continue as the stresses will have changed in the rock mass leading to various phases of faulting and jointing. The presence of dykes and faults is an indication of the stress state at the time of their placement. They may be thought of as giant hydrofracture events. The effects of cooling may destress the rock mass substantially. Tectonic events may lead to major regional stress changes while local folds lead to local ones.

Ground fluids may be water that flows freely or is trapped and connate. The groundwater chemistry may vary widely and be acidic, saline or fresh. The fluid in the ground may not be water, but rather gas or oil. In the former case it may be held by sorption within the carbonaceous matter in the rock mass as well as in pore or fracture space. Gas is a major hazard in coal mining and can also be to tunnelling. The storage of most fluid in rock is within pore space, which can be solution cavities, or in fractures. How ground fluids flow will depend on the rock, the fluid and the fluid potential gradient which comprises pressure and gravitation terms.

It is the job of the site investigation or exploration operation to determine all of these factors which may be summarised as regional geology, lithology, structural geology, rock properties, rock stresses, fluid type, fluid pressure, fluid storage, fluid type and the permeabilities. To what extent each of these factors is important is dependent on the nature of the underground construction and its depth. The requirements for pressurised gas storage are very different from those for a drainage tunnel.

2 DRILLING

Following an initial investigation which should include pre-existing geological information, an examination of surficial features, aerial photographic interpretation and satellite imagery the most common approach to ground exploration is by drilling.

The orientation of the drilling needs to be such that lithology changes and structural features are intersected. In flat lying sedimentary ground vertical holes will be best to pick up lithological change but may miss a dyke or a normal fault. In more complex geologies the lithological change may require angled drilling. Drilling along a tunnel alignment has appeal as it provides direct information.

In short holes conventional coring may be used but as the holes get longer wireline coring takes over as the most economical method. This can be used in all orientations, though up hole drilling requires care as does drilling in gassy formations as the risk of having a core barrel ejected by gas exists.

Core drilling is normally undertaken in vertical or angled holes from surface. When it is used at flatter angles the power requirements of the drill rig increase significantly due to friction opposing the rotation of the drill string in the hole. As holes get longer the time involved in retrieving the inner core barrel with the core become higher largely due to hydraulic issues around the drill string and core barrel. These effects combined with the time to make drill bit changes limit the economic length of a horizontal core hole to about 1 km, depending on the drill and the drilling conditions. Directional coring is possible but the core size is small and the process is slow. Typical wireline coring rates lie in the range of 10 to 40 m per day.

On option, where long holes are required, is to consider open hole drilling. If the rock is suitable this can be undertaken using polycrystalline diamond cutter bits (PCDs or PDCs in the oilfield) and drilling can proceed at rates of 100 to 400 m per day. This is an order of magnitude quicker than coring. Virtually all sedimentary rock, some metamorphic and fewer igneous rocks are amenable to the use of this kind of drill bit. Where the rock is very hard and the risk of excessive cutter damage to the PCD bit exists then recourse needs to be made to tricone roller bits but with a substantial reduction in penetration rate. Another advantage of open hole drilling is the ease at which directional control can be achieved. This can be by the use of down hole mud motors or by rotary steering systems.

Downhole mud motors are motors on the end of the drill string that rotate the drill bit and are operated by the drilling fluid that is pumped through the drill string. To be used in directional drilling they are fitted with a bend which is either located between the motor and the bit or behind the motor. In this configuration they never drill straight and the borehole trajectory will be made up of multiple arcs as the drill string is slid forward and its orientation changed. When the drill string is rotated these systems tend to drill increasingly downwards. This can be a severe limitation as the rotation of the drill string is very important in clearing cuttings in flatter trajectories.

Rotary steering systems use the rotation of the drill string to turn the drill bit. This rotation improves cuttings clearance. Directional control is achieved by having pads that push outwards from the drill string. These pads are usually mounted on a non rotating sleeve and their operation is controlled electronically. Such systems have been widely used in oil and gas drilling and have significant potential in tunnel investigation. Hybrid systems that lie between the two methods are being developed.

Under the right conditions it is possible to drill several kilometres horizontally using open hole drilling systems.

The prime limitation on drilling long holes near surface is the drilling fluid pressure gradient required to transport cuttings back up the annulus of the borehole. The longer the hole the higher the pressure gets. This can lead to the hydrofracture of the ground.

Drilling into high fluid pressures always requires the use of a properly cemented standpipe with adequate well control features to permit the withdrawal of the drill string and bit out of the hole and to control outflow. The outlet pressure at the standpipe may need to be controlled so that the drilling fluid acts to support the hole but does not increase to the extent that hydrofracture of jointed rock or liquefaction of soft ground occurs.

3 THE CORE

Engineers and geologists like to see and retain core and it does provide the best samples. Core orientation is essential. Orientation of the core may be gained by using an orientation tool that fits at the top of the inner tube and records its down side. This can only function in non vertical holes. Alternatively, core orientation can be achieved by subsequently logging the hole with an acoustic televiewer (ATV) or optical televiewer (OTV) and matching the structural features logged in the core with those observed on the borehole wall.

The process of logging core should be taken in several stages. The first is to measure the core and determine whether the full length has been retrieved or whether some is lost or gained from the last core run. The second stage is to log the core for its lithology. The third stage is to log the structural features on the core without disturbing them so that their orientation may be determined relative to either the core orientation tool, or some arbitrary line on the core if the approach of using an ATV or OTV image for orientation is to be taken. The fourth stage is to open any joints in the core and to examine them for any infill and their roughness. The final stage is to sample the core for geotechnical testing. This requires the sampler to be competent. It is not a job for the junior person on the site. To sample sensibly requires an understanding of the underground structure to be created along with a concept of the stresses that will be imposed on the structure and that will exist within the rock mass along with the likely failure modes. It is no good taking multiple samples for uniaxial testing if the likely failure mode involves shear on a foliation or bedding plane which is approximately orthogonal to the core. The types of tests that are appropriate are discussed later.

Oriented core provides the basis for analysing structural features usually in the form of stereoplots and joint frequency measurements with orientations. These are a basis for design, not simple numbers from RQD measurements.

4 ROCK TESTING

The standard tests that are applied to rock core are uniaxial compressive testing for strength and sometimes to provide values of axial Young's modulus and Poisson's ratio. Triaxial testing is used for shear strength behaviour but suffers the same limitations in that the test result is highly influenced by the relative orientation of the core to foliation, bedding or any other plane of weakness. The tensile strength of the rock is occasionally measured using the indirect Brazilian test. Very occasionally a joint may be tested for its shear behaviour. It is unusual for testing to properly deal with anisotropy, though so much rock is anisotropic, both in its pre-failure and its failure characteristics.

4.1 Cyclic uniaxial testing

The purpose of conducting cyclic uniaxial testing is to determine at what stress the rock may start to behave in a plastic manner. This is achieved by loading to an initial stress and then unloading and checking whether there was any permanent axial or circumferential offset. This is repeated in a number of increasing load cycles. The test therefore serves to indicate the plastic offset with stress, the axial Young's modulus and the associated Poisson's ratio. The latter two may be highly nonlinear. This test is described in more detail in Gray (2020).

4.2 Triaxial testing for Young's moduli and Poisson's ratios

To be able to interpret the results of the overcore stress measurements it is essential to know the Young's moduli and Poisson's ratios of the frequently anisotropic rock. The method used to derive the different rock moduli involves step loading of a core with first an axial increase in load followed by a confining load increase. This sequence is repeated. After the peak load is reached the sample is then unloaded in decrements. Strain gauges are used to measure strains on the surface of the core. The process enables the determination of the Young's modulus in the axial and transverse directions with the associated Poisson's ratios. (Gray, Zhao and Liu, 2018).

It is quite normal for sedimentary rocks to be significantly stiffer in the direction of bedding compared to across it, though this is not always the case. A similar effect has been observed in altered gneissic rocks where the Young's modulus was five times higher in the plane of foliation than across it. This particular specimen also showed auxetic behaviour, meaning the Poisson's ratio was negative under some stress states. Sedimentary and to a lesser extent metamorphic rocks frequently exhibit significant nonlinearity of their elastic behaviour.

While the need to determine rock properties came from the need to analyse stress from overcores the information from these tests should be incorporated into the models that are used for design. Too often numerical models have very simple isotropic linear rock properties to failure. These bear no relation to the real rock behaviour.

4.3 Shear testing

Most uniaxial and triaxial test specimens will fail in shear but unless by fortuitous circumstances of alignment the shear failure will not be on the plane of greatest weakness. The process of taking a sample and casting it in a test jig and then shearing it is time consuming and expensive. What is required is a quick shear test that will enable the rock to be tested. Gray (2020) has described two tests to do this. Both tests are reliant on the weakest plane being orthogonal to the axis of the core. This is well suited to cores from vertical holes and horizontally bedded strata. The first test is one of simple shear transverse to the core in an arrangement by which the core is supported in two lower saddles and is sheared by the action of an upper saddle pushing downwards. The core invariably breaks at one end and the shear stress readily calculated. The second test was adapted from the Russian GOST standards. It involves placing the core in a holder that is a split cylinder that can be oriented at various angles within a universal test machine. The orientation determines the ratio between normal and shear stress on loading. This test device can be readily used to measure the shear behaviour on the basis of a Mohr-Coulomb envelope. These tests are described in Gray (2020).

4.4 Tensile testing

The indirect Brazilian test to measure tensile strength relies on the core being isotropic and linearly elastic to failure. The tensile stress generated is a function of the line loading of the core and its cylindrical shape. In any rock that does not behave linearly or is anisotropic will complicate the interpretation of the Brazilian test.

The alternative is direct tensile testing. This is more expensive to perform but allows the tensile strength to be directly measured. In bedded or foliated rocks it is particularly useful in measuring the tensile strengths across and along the structural features. If the core is drilled approximately perpendicular to the foliation then it is easy to glue ends on the core and pull directly on these to find the tensile strength. The tensile strength along the bedding may be obtained by cutting a biscuit shaped specimens along the foliations and glueing this into end plates and then pulling the core apart through load on these. Laminated siltstones may show a tensile strength of 6 MPa in the direction of the foliation and 0.1 MPa transverse to it. While civil engineers like to think that they do not rely on the tensile strength of rock most or at least many of their designs in rock would fall down without it. Therefore measuring tensile strength properly matters.

4.5 Point load testing

Point loading imposes a complex loading on to the specimen being tested with crushing, shear and tensile components. The tensile or splitting strength of the rock is most important. While point load testing is often regarded as a lower cost method to obtain an equivalent uniaxial compressive strength this is probably the least useful way to use the test method. While the correlation between uniaxial compressive strength and point load test value is valid for most homogeneous elastic rocks it is not valid when the rock is nonlinear or anisotropic. Point load testing is valuable in determining the anisotropy of the rock. The standard approach to point load testing is described by Ulusay and Hudson (2007). For isotropic rock it recommends testing along the axis and across the diameter of the rock. It recognises that anisotropic rock exists and recommends that in the case of foliated rock testing should be conducted along and perpendicular to the foliation.

Where a stronger foliated rock is of sufficient strength that breaking a sample along a foliation specifically for testing is not practical the alternative is to first test across the sample and parallel with the foliation. Secondly to test in similar material across the core diameter and perpendicular to the test made in line with the foliation.

In foliated rock a number of point load tests are typically regarded as invalid, according to the recommendations of Ulusay and Hudson (2007), because the fracture caused by point loading did not pass through the entire length or diameter of the core sample. This deficiency can be rectified by amending the fracture area to that which really exists and converting this to an equivalent diameter. Taking this approach enables a lot of tests on anisotropic rock to be used where breakage occurs along a foliation and daylights in the core ends.

5 DOWN HOLE GEOPHYSICS

5.1 Deployment method

The question of how to get geophysical sondes up near horizontal holes hundreds of metres long for logging without risking them in the event of local hole collapse has been solved by running the wireline (HRQ) drill pipe back down the hole with a special shoe and latching sub at the inner end. The geophysical sonde is then pumped down the drill pipe towing with it a disposable cable. When it has reached the end of the drill pipe it latched in place with the required portion of the sonde protruding from the end of the shoe. Logging is then achieved by pulling back rod by rod and cutting off the disposable cable and reconnecting each time. Once the system had been developed this is a relatively quick process and recently a 460 m hole was logged easily in two 12 hour shifts. The sonde location is monitored by measuring the position of the drill pipe and reconnecting the monitor after each rod was removed.

If the boreholes are slightly down dip then the problem of keeping the hole water filled does not occur. If they are up dip holes it is possible to keep them water filled if they do not leak. This does require the use of a standpipe and it complicates the process considerably.

5.2 Full wave sonic log

Experience with a sonic log in metamorphic rock has shown a remarkably good comparison between the Young's modulus and Poisson's ratio derived from the compressional and shear waves on and isotropic basis and those derived from laboratory testing. Zones of fracturing and weaker material are shown very clearly by the full wave sonic log.

5.3 Acoustic televiewer

The key to the operation of the acoustic televiewer (ATV) is to have it mounted centrally in the borehole during the logging process. This can be achieved to within 3 mm in a 96 mm diameter borehole. One of the key reasons for the use the acoustic televiewer is for the orientation of structures within the hole so as to enable these to be compared with those measured in core. An acoustic televiewer log can also be used to check on the core orientation sub at the back of the inner tube of the core barrel. The only real problems encountered by the use of an acoustic televiewer in a horizontal hole have been caused by the presence of sand (cuttings) on the base of the hole. These holes had clearly not been flushed out properly despite the rotation of the drill string whilst circulating and withdrawing it. Flushing is extremely important for a range of tests including the acoustic televiewer. Better results could be achieved with a higher flushing rate.

6 ROCK STRESS MEASUREMENT

6.1 Methodologies

Rock stress measurement may be accomplished in a number of ways depending on the rock conditions. The one method by which the full strain tensor can be obtained is by overcoring. However, it can only be used in elastic rock without failure occurring on the hole wall. Hydrofracture can be used but it gives a limited two dimensional picture of stress orthogonal to the hole. Where the larger stress is required it is necessary to have a linearly elastic rock in which the initial hydrofracture closes perfectly before reopening. Hydrojacking may be used on pre-existing joints and provides the stress normal to the joint. This is of direct relevance to pressurised conduits in the rock mass. Borehole breakout observations from an ATV image provide an incomplete picture of stress orthogonal to the hole but provide a direction and may be used with other measurements to get a picture of stress. Core ovality measurement offers the prospect of enabling the determination of the difference between the stresses orthogonal to the hole. Its use requires a core barrel that is running true and has a drill bit that has an internal taper to avoid regrinding the core. It also requires a rock that is sufficiently stressed and with a low enough modulus that the readings from it are big enough to be measured. Overall, the most combinations of stress measurement that can be brought to bear are required. Good point measurements are of limited use if it is impossible to interpolate between them. Interpolation may require the use of lesser accuracy systems to fill in the gaps. Gray (2023) describes these methods in further detail.

6.2 The IST3D overcore tool

The Sigra IST3D is a three dimensional overcore tool that has been operated in vertical holes to 800 m depth and in horizontal ones to 421 m length. The process used for stress measurement is to retrieve the last core run by wireline and then to pump in a countersink bit to grind the core stump. This is then pulled on wireline and a pilot hole-cone drilling assembly is pumped into the core barrel. It is used to prepare the end of the hole for the stress measurement cell. This system is pulled by wireline. The electronics with the cell containing 21 strain gauges are then mounted in the setting tool which is pumped into the cone-pilot hole and glued in place. When the glue has set the setting tool is retrieved and the drill string is pulled back 6 m so that the electronics may record the magnetic field data for orientation purposes. The inner tube assembly is then pumped down the hole and the cell is overcored. During this time strain data is recorded in the electronics. The electronics tool, cell and core are retrieved by wireline. The data is downloaded and the assembly is then placed in a hydrostatic test cylinder to reload the core. This provides a check on the function of the strain gauges. It also provides a basis for determining the Young's moduli of the core, provided that a mean value of Poisson's ratio may be estimated. Figure 1 shows the operation of the tool.

Obtaining the correct rock properties is extremely important. Firstly, any plastic effects must be detected as they may render the test invalid, secondly the rock's properties must be determined with appropriate orientation, hence the test methodology described in section 4.2. Using these core tests results it is possible to calculate the rock stress.

The tool is available in variants to work with PQ, HQ and NQ wireline coring operations. The NQ variant is of particular importance as so much underground exploration drilling is undertaken using this size of hole. Gray and Keloth (2025) describe results of the use of the tool and its predecessor, the IST2D tool, in a mining situation.

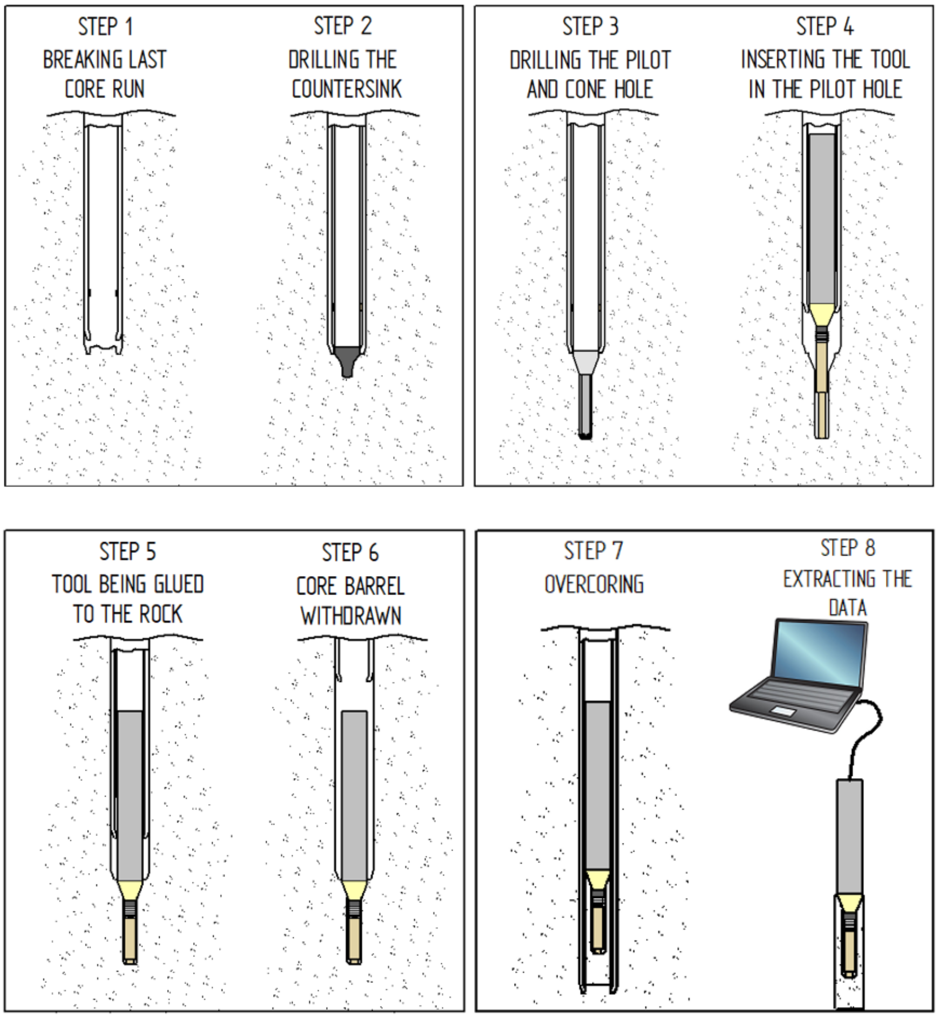

Figure 1. Operation of the IST3D overcore stress measurement system.

6.3 Examining the results

The results of stress measurement in rock are seldom without some surprises. The simplest case of flat lying of sedimentary rocks can be thought of as being under the effect of overburden weight acting in a zero lateral strain environment. To this may be added tectonic strains that load the rock laterally (Gray, 2000). There are multiple exceptions to this simple model due to faulting, folding and erosion but mostly it works, especially on the eastern side of Australia. When stress measurements are made in igneous or metamorphic rocks no such simple model may be applied. The loadings and the strains which have created them are complex

7 PERMEABILITY AND FLUID PRESSURE TESTING

7.1 Test methodology

The two key fluid related parameters that are required for the design of an underground openings are the permeability and the natural fluid pressure within the ground. These enable the determination of fluid influx and efflux during mining and operation.

To obtain these parameters by investigation from a borehole it is necessary to seal a test section and to wait as long as possible for stabilisation of pressure. The test section should then have a flow induced into or withdrawn from it. The test section should then be sealed again and the pressure allowed to recover. The analysis of such a test is based on knowing the flow rates with time and the pressure change following shut in when there is no flow. The analysis is of the transient pressure recovery is with respect to a function of time and flow. This is standard petroleum practice and has many advantages. The most important of these is that the effects of local variations in permeability near the borehole are eliminated from the analysis and static fluid pressure may be estimated. The basis of this is the work by Horner (1951) extended by superposition to the multi flow rate situation. Analysis by type curves (Bourdet, Ayoub & Pirard, 1989) can be used but tend to be less fruitful in a fractured rock situation.

Sigra has recently conducted some testing in 450 m horizontal holes drilled from underground. Two packers were run in hole to test depth on the end of an HRQ drill string with a 29.4 m straddle. The choice of new HRQ rods was made because these can be readily and reliably sealed with thread tape wound on and over the end of their pin thread. Achieving this level of sealing requires extreme cleanliness on assembly. Above the straddle was a main valve which was fully balanced, meaning that changes in pressure in the test zone, or in the rods above the test zone, did not cause it to open or shut. The main valve was opened, connecting the test zone with the drill pipe, by pulling the drill string toward the hole collar and closed by pushing the drill string into the hole. A pump in head that contained pressure transducers and electronics was then pumped to latch on to a spear connection above the valve trailing a geophysical tool wireline. The top of the drill pipe was then sealed around the wireline with a side port for injection or outflow from the drill string. The geophysical wireline carried digital signal information from the transducers monitoring the test zone, packer and in-pipe pressures and a temperature sensor in the downhole tool to a display on a laptop at the collar of the hole.

The test zone was then flushed and the drill string slid into the hole to shut the main valve. The packers were then inflated to by pressurising the drill string. The effect of packer inflation could be immediately seen on screen at the collar of the hole. It manifested as a pressure rise in the test zone between the packers if the tests zone was tight. The pressure rise and the rate at which it dissipated was a good indication of near well bore permeability before full testing started.

The pressure must be allowed to settle in the test zone before the main test. Depending on this pressure, two types of tests were conducted. If the test zone pressure was less than half hydrostatic a decision was made to inject water into the test zone at a pressure to near hydrostatic. If the stable pressure was above half hydrostatic the hole was permitted to flow and the outflow was measured.

Flow monitoring is best accomplished by positive displacement flow meters. Obtaining these can be difficult particularly as the flow rates are usually not known prior to a test. Sigra built one for its own operations that is accurate to 10 ml in 3 litres and can measure flows up to 3.5 litres/second.

At the end of pressure recovery from each test the packers are depressurised and the geophysical cable withdrawn with the pump in instrumentation head. The drill pipe is then shifted to cover the next test interval. The process was then repeated. In new equipment the need to recover the geophysical cable is avoided and a sacrificial cable is used instead. This speeds the process.

7.2 Testing characteristics

The system works well and has been used to measure permeability measurements down to 1×10^{-18} m^2., the equivalent of 1.3×10^{-11} m/s with water at 33°C. It could be used to measure permeabilities six orders of magnitude higher if the high permeability zone could be isolated and the operation at the drill rig were not inundated. The main constraint on low permeability measurement is time. It takes time to achieve pressure stabilisation before flow and though the flow period can be short it takes time to achieve an analysable recovery.

A complication is the time a horizontal hole takes to be drilled. This may allow significant depressurisation. The consequence of this is that full stabilisation is not achieved on shut in before flow. If the flow is by injection the draw down following shut in occurs rapidly but with longer times the pressure starts to rise as the test section starts to recover to the original ground fluid pressure. This can compromise the analysis. It may be best to test sections of a hole at each core bit change so as to avoid depressurisation problems. These are not generally as severe in vertical holes as drilling fluid pressure is frequently similar to the stabilised pressure in the test zone.

It is important to consider how much ground has been tested so as to gain an understanding of the applicability of the measurements. By assuming a porosity-compressibility product it is possible to arrive at a mean effective radius of investigation for each test.

8 CONCLUSIONS

The methods described in this paper may be readily and reliably used with HQ core drilling to beyond 1 km. This means that rock stress may be measured, geophysical sondes run and permeability and fluid pressure determined. The option of drilling directional open holes is discussed as an economic option. This can be used with torque and thrust sensor located behind the drill bit and with a drilling rate sensor on the drill. In this form can provide information at the hole collar on the rock being drilled. Open holes may be geophysically logged to provide important geotechnical information and where uncertainty exists it is quite possible to cut a branch off the main hole and then core the area of uncertainty. Not all situations are suitable for such long hole directional exploration drilling.

The testing of rock core has been discussed with a view trying to get the right measurements being made. This requires careful thought about the underground structure and the modes of loading it may endure. The rock test method needs to be tailored to suit this and the characteristics of the rock which are frequently anisotropic, non-linear and may also behave plastically. Tests which can extract the relevant information are outlined and include cyclic uniaxial, triaxial, shear, tensile and point load testing. The methods suggested are a little different from current practice. Choosing what needs to be tested and how it is tested is not however a job for the inexperienced.

Overall, the paper tries to present a short space the philosophy and technology developed by Sigra as to how obtain the right information for the design for projects in the ground.

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