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Dealing with groundwater in underground mining

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Abstract

This paper examines the process of dealing with water in underground workings, with an emphasis on doing this before flooding inflows are encountered. To do this, suitable drilling and test processes that enable the nature and magnitude of the problem to be understood are discussed. These include testing from surface and from underground. The suitable test processes involve transient analysis techniques taken from the oil and gas industry and applied in boreholes drilled from the surface or underground. These techniques enable the pressure of the water and the permeability to be established along with characteristic fracture widths. They include forms of drill stem tests (DSTs) and diagnostic fracture injection test (DFIT) procedures common in petroleum but rarely used in mining. The latter enables the fracture opening and closure pressures to be determined. The result of the testwork is an understanding of the rock mass and its fluid connections.

Armed with this information, scenarios to deal with water inflow are considered. These include the use of very high pressure, high flow rate grout pumping systems, which can be used to pump cement to seal off working areas, particularly during development. These pumping systems are essentially the hydraulic fracturing pumps used in the petroleum industry. Their use is to open fractures at pressures higher than the rock stress and to force grout into these.

In many cases grout sealing is not appropriate and the paper considers drainage options for these. These options include directional drilling. Here the flow rates and total stored fluid volume are important considerations.

Keywords: *groundwater, testing, control, grouting, drainage, hydrofracturing, directional drilling*

1 Introduction

Dealing with groundwater is often an extremely challenging part of underground mining. The consequences of failing to do so can extend from inconvenience to sudden inrushes of water that stop mining and risk lives.

From an economic viewpoint the cost of groundwater control can be major. This can be split into capital costs such as boreholes, pumps, sumps and grouts to operational costs, of which energy can be a major factor. Water is dense and lifting it a long way is expensive.

The wettest mine on Earth is apparently Konkola in Zambia, which pumps reported volumes of 300,000 m^3/day (Hague & Germishuys 2003) to 436,000 m^3/day (Hamilton 2016) from a depth of about 1 km. Ignoring any pumping or efficiency losses, the power required to pump 300,000 m^3/day from 1 km depth is 34 MW. The consequence of a power supply failure to operate pumps in such a wet situation is that the mine will rapidly fill with water. The energy cost of this pumping is huge. The Konkola copper orebody continues dipping to greater depths, extending into the planned Mingomba project with 247 Mt of 3.6% copper (Jamasmie 2023). Mingomba is considerably deeper than the adjacent very wet Konkola mine. To be able to deal with such challenges as these, new approaches are required. Fluids (gases and liquids) need to be looked at holistically with rock stresses, rock types and structural geology if these types of deep, wet orebodies are

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to be mined successfully and economically. Table 1 contains information on wet mines as gathered by Hamilton (2016). Many of these are in carbonate sequences or other sedimentary deposits.

In some mines the requirement is to reduce fluid pressure in pores or fractures and thus improve stability through increased effective stress and the increased friction resulting from it. The spacings of such drainage holes for this purpose are essentially independent of permeability provided no flow-induced back pressure occurs within them. In these cases the drainage system needs to be monitored by direct pressure (piezometric) monitoring as flow monitoring alone can be quite misleading. The effectiveness of drainage holes is influenced by the build-up of mineral deposits or, in some cases, the growth of algae or bacteria which block flow into these. In some cases the effectiveness of drain holes may be restored by chemical treatment or high-pressure water jet cleaning.

Table 1 10 of the wettest metal mines (Hamilton 2016)

Project	Company	Commodity	Location	Geology	Mine workings	Inflow (m^3/s)
Konkola	Vedanta	Cu	Zambia	Carbonates, sandstone	UG	5.1
Pomorzany	ZGH	Zn, Pb	Poland	Carbonates	UG	3.8
Christmas Creek	FMG	Fe	Western Australia	Iron formation, dolomite	Pit	3.5
Cloudbreak	FMG	Fe	Western Australia	Iron formation, dolomite	Pit	2.9
Grasberg	Freeport	Au, Cu	Indonesia	Carbonates	Pit, UG	2.2
Leeville	Newmont	Au, Cu, Ag	Nevada USA	Carbonates, metasediments	UG	1.6
Viburnum Trend	Doe Run	Pb, Zn, Cu, Ag	Missouri USA	Carbonates	UG	1.5
Hope Downs	Rio Tinto	Fe	Western Australia	Iron formation, dolomite	Pit	1.2
Konkola North	Lubmbe	Cu	Zambia	Metasediments	UG	1.2
San Vincente	SIMSA	Pb, Zn	Peru	Carbonates	UG	1.1

The options for dealing with groundwater are to drain it before mining, drain it as part of mining, block it or avoid it. Draining it means understanding where it is coming from and how much of it there is to deal with. Blocking it can mean grouting or freezing while avoiding it may mean sterilising reserves.

How any of these methods of controlling groundwater in mining may be applied depends on the geology and the source of the water. This may be from direct infiltration or from a substantial aquifer system such as the Great Artesian Basin in Australia. In the latter case the consequences of drainage may be untenable because of the effects on depressurising the aquifer system and depleting the water resource.

Other aquifers may be saline or hold toxic minerals that may not be discharged. The nature of water-bearing rocks is not limited to porous sedimentary deposits. Karstic rocks typically contain vugs which may become large solution cavities and drainage pathways, as in underground cave systems. Preferential leaching of some minerals may also lead to porosity and permeability. This might occur in a feldspar where the plagioclase is more soluble than the orthoclase and is therefore preferentially leached, leaving rock that is highly porous. The various chemicals in groundwater influence how they act upon the rock. These might be associated with geothermal effects.

In many instances the prime carriers and store of groundwater are fault systems where there is broken rock that has not become an impermeable fine gouge or where the zone of the fault has not become filled with mineralisation.

Drainage associated with mining will affect surrounding groundwater with potential impacts on its use and on subsidence from the consolidation of soils affected by the drainage.

Again, the Konkola mine is a good example of the complexities of the interaction of multiple water sources, structural geology and surface subsidence (Chella & Mutambo 2019).

Drainage may of course simply change how water is abstracted as the mine itself may in many cases be regarded as a giant well. This is the case in caving operations where water control is essential. Avoiding mud rushes in such operations is, however, crucial to safety; for example, the Palabora copper mine block cave in South Africa (Maloma 2016).

Gaining an understanding of groundwater should be an integral part of exploration from the earliest stage. The understanding of ground fluids is not possible without an understanding of the geology of the mining area. The incorporation of a groundwater testing and monitoring program into the exploration drilling operation is likely to be cost-effective provided it is designed correctly. Such investigation must include an examination of groundwater chemistry and isotopic tracers including those for radionuclides, particularly radon gas, which may complicate matters significantly.

There are several stages of groundwater exploration that may be conducted depending on the nature and risk associated with groundwater. These are the basic geological investigations in which the determination of aquifers, aquicludes, faults and open jointing is determined. It also includes single-hole testing, multi-hole testing and full-scale drainage tests which involve single or multiple pumped or injected wells and piezometers. It may also advantageously include the use of sequentially pulsed tests which can be used to define permeability and storage behaviour against a background of changing water head.

Exploration and monitoring will generally need to continue once a mine with groundwater issues is operating. In deep mines this will generally be conducted by drilling from underground. Drilling into ground with high water pressures and potentially high water flows requires the use of proper well control systems so that large influxes do not occur. In addition, it means being able to measure where the water is coming from within the hole, and what potential flow rate and volume may be encountered in mining. If the water flow is likely to be significant it will also require a means to deal with it, both at the local scale of the borehole and in terms of the total mining operation.

Another aspect of groundwater that should be considered is what will happen to it following mine closure. What will the abandoned mine do to the regional groundwater situation? Will it fill up and become a mixing chamber of groundwater from various sources and from reactions of water with the broken rock or will it be a store of clean useable water? These scenarios are widely different.

2 Fundamentals of ground fluids in rock

Ground fluids may be stored in pores, fractures (including faults) or solution cavities. In the case of gases, they may also be stored by solution in fluids or by sorption into the rock itself. The former is particularly the case where the gas is carbon dioxide as it is highly soluble. The case of sorption is common in carbonaceous rocks where methane or other hydrocarbons are frequently generated by the rock and to some extent remain within it. Coals and shales are typical examples of these. A porous sandstone or limestone could be regarded as an example of a porous rock that might well provide significant storage of fluid. Such rocks frequently form aquifers or are the basis of petroleum reservoirs. The fluid contained therein may be exchanged as part of a flowing system or may be connate. Such porous rocks are generally of sedimentary origin and are interspersed with less permeable strata which forms seals or aquicludes. Seals may also be created by fault boundaries. Fault boundaries may also be open and allow connection through the rock mass. This is dependent on the nature of the faulting.

In rock that lacks porosity, such as those of igneous or metamorphic origin, the storage of fluids is within fracture systems. Fractured porous sedimentary systems display dual porosity behaviour. In these the major permeabilities are generally determined by the fracture systems. Such fractures may be faults or multiple joint sets. In some cases rock which lacks significant porosity gains it through solution once fluid movement is established.

The permeability of rocks is to some degree influenced by the effective stress state. In softer fractured rock this effect can be extreme. For example, in cleated coals the permeability can drop an order of magnitude with a change in effective stress of 2 to 5 MPa (Gray 1987a). In deeper stiffer rocks subject to higher stresses this behaviour may also be expected but at much higher stress levels. The term 'effective stress' needs careful definition as rocks do not behave like soils and the fraction of the fluid pressure that acts within the rock mass is less than unity. This fraction is dependent on the degree of fracturing within the rock mass and the closure behaviour of the fractures under stress. Because the fractures have direction the effective stress characteristics of the rock are also directional (Gray et al. 2018).

In hydrogeology, reference is generally made to storage through the terms 'storativity' and 'specific yield'. However, these terms only apply to laterally extensive aquifers. Both refer to the amount of water released per unit area per unit change in hydraulic head and typically are applied to aquifers. In the case of storativity, the term includes the effect of rock compression as the fluid is withdrawn and the increase in the volume of fluid due to the expansion of the water. Specific yield describes the volume of water released by drainage accompanying the lowering of the phreatic surface of the groundwater.

The 2D concept of storativity is not appropriate in the context of deep underground mining, which is really 3D unless there is a very specific aquifer that is being intersected. Rather the concept of the product of porosity and compressibility should be used as it deals with storage in 3D. The concept of specific yield still has some validity but should be thought of as what fraction of the total porosity will drain of water as the phreatic surface is lowered within the rock mass. The specific yield of rock mass containing large solution caverns is very different from that of a fine-grained sandstone with 5% porosity. In the former case virtually everything will drain from the cavern provided it is connected to the rest of the rock mass. In the latter case most water will be retained by capillary pressure effects. For example, capillary pressure effects cause smaller pores to retain water more effectively while larger cavities release water more readily. In short, more water is held in big holes and a bigger fraction comes out them more readily than from small ones.

Similarly the concepts of hydraulic conductivity and how it is measured need rethinking. The use of permeability is more appropriate, especially when the storage term is in terms of porosity-compressibility products. Permeability is the constant in Darcy's law equation, which equates the apparent velocity of fluid transport to the potential gradient by a linear relationship. The potential gradient is composed of a pressure plus an elevational potential gradient term. If large enough openings and a high enough potential gradient exist then Darcy's relationship may not hold and the transition to turbulent flow may take place. This would typically occur in an open fracture zone such as the one intersected during shaft sinking at Resolution Copper mine in Arizona, USA (Goodell 2014). In this case the water flow reached 2,700 m^3/day.

The practices of petroleum reservoir engineering are in many ways more general and comprehensively suitable for the purpose of dealing with fluids in the ground than the general hydrogeological approach used in civil and mining engineering. The problem with the petroleum engineering approach for most hydrogeologists is the use of mixed imperial units and the jargon of that industry. Much can, however, be gained by studying the petroleum reservoir engineering approach.

The biggest difference between the hydrogeological cases and that of petroleum is where recharge takes place. Such recharge may be that of a confined aquifer fed from a long distance away or, in the case of deep mines, the local fracturing and faulting that connect the workings to surface water. Another major difference between conventional hydrogeology and petroleum engineering in mining is that the ground is being broken by the mining process and connections are being made that previously did not exist.

3 The groundwater exploration process

3.1 Single hole tests and near wellbore effects

Much of the mineral and geotechnical exploration process will be by core drilling. It is therefore logical that as much of the groundwater exploration as possible should be accomplished utilising the same drillholes. This means having the appropriate tools and methods to do so. Because exploration drilling is substantially conducted by wireline coring it is highly desirable that these tools should work as part of this process.

Near wellbore effects are caused by variations in permeability around the borehole. The idealised head (pressure) distribution around a pumped well with near wellbore loss is shown in Figure 1. Lowered permeability around the wellbore may be due to blockage from drilling fluids which form filter cakes by the plugging of fractures by fines developed during drilling, the hole not intersecting adequate fractures in the rock mass, or fracture closure by stress concentration around the wellbore. The effects of differing fluids also matter. A viscous drill fluid will not change the permeability around the wellbore but it will change the response of a test. In other cases the drilling fluid may be incompatible with the ground fluid chemistry and cause clays to react and block fractures or pores. Raised permeability around the wellbore may be brought about by washing out of fractures or by raised fluid pressures tending to open pores and fractures.

The near wellbore effects can be very high. It is not uncommon for the pressure loss around the wellbore to account for 95% of the pressure drop between that in the hole and that in the ground being tested. This means that to be reliable the testing methodology and analysis must eliminate these near wellbore loss effects from the assessment of the permeability of the rock mass. One of the complications associated with dealing with near wellbore effects is that they change during flow. If an injection test is being conducted there is a high probability that the wellbore losses will increase during the process with a filter cake build-up on the borehole wall or by fines being driven into the fractures. Production tests tend to flush out fractures and remove filter cake, thus lowering near wellbore losses, but the lowered pressures will increase the effective stress within the rock mass, sometimes dramatically reducing its permeability.

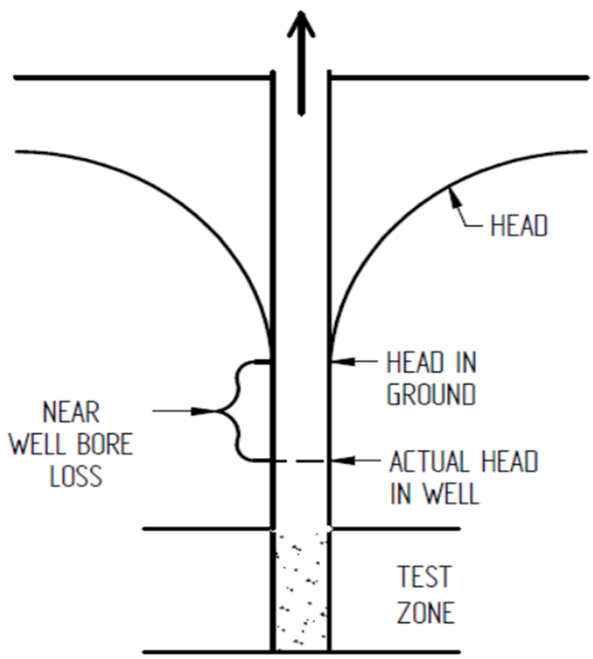

Figure 1 Showing head (pressure) distribution around a pumped well with near wellbore loss

3.1.1 Packer testing

Testing for groundwater was, and in many cases still is, conducted by the totally inappropriate packer test where the values delivered are in Lugeons. This test involves injecting into a section of a borehole between packers at a pressure of 10 atmospheres. This continues until the flow supposedly stabilises. The numerical value, in Lugeons, derived from this test is the stabilised flow rate in litres/minute divided by the length of the test zone. The test takes no account of the original pressure (head) that existed, nor does it deal with near wellbore effects. Above all it fails to take account of the need to examine transient effects which are an essential part of deriving meaningful permeability values. Generally all the test delivers is a flow number that has more to do with the head difference before and during the test and the near wellbore effects. It can provide information on whether there is a gaping void or whether the wellbore is tight and really nothing else. There are several variations on how the packer test should be conducted (International Organization for Standardization 2012), most of which involve injecting in a regimen of stepwise pressure increase and decrease. However, unless the pressure is raised to the level of hydrojacking or hydrofracture, they yield no more information and take a lot longer to do.

3.1.2 Drill stem tests

What is required is a test that is suitable for use in a cored borehole and which is immune to wellbore loss effects. The drill stem test (DST) has been used for many decades by the petroleum industry, albeit in a rather different form. In the original petroleum form the DST is conducted by running a compression packer on the end of an empty drill string into the hole. A drill pipe extension in front of the packer comes to rest on the bottom of the hole, forcing the compression packer to set. After a period of pressure stabilisation the drill string is rotated to open a valve so that fluid flows from the test zone ahead of the packer through the valve and into the drill string. After a flow period the drill string is further rotated and the valve is closed, allowing pressure to build up. The benefit of a test that produces fluid from the rock mass is that once the drilling fluid has been flushed out, the test is being conducted with the fluid contained in the rock and not something introduced to it.

The critical measurements in a DST are the flow when the valve is open and the pressure build-up when it is closed. By focusing on the pressure build-up during the period when the valve is closed it is possible to solve for the permeability of the formation under test and to calculate the stabilised fluid pressure without any influence from near wellbore effects. As with any single hole test it is not possible to determine directional permeability, nor the storage behaviour of fluid in the rock mass. However, if there is some other basis to estimate the storage characteristics that exist then it is possible to estimate both the wellbore loss and the effective radius of the test. If the latter is too small the test is probably meaningless. Having no flow does not necessarily mean zero permeability. If a pressure difference between the formation and the tool exists it can mean that there is no connection and the permeability is undefined.

There are several variants of tools to conduct DSTs, however, the author has used one that has been specifically developed to work with HQ coring operations. It works in the manner shown in Figure 2.

The sequence in the DST operation is as follows:

- A – The wireline DST tool is lowered through the HQ drill string to rest on the landing ring.
    a. A head seal is placed at the top of the drill pipe.
- B – The DST tool is shown landed and locked into the core barrel.
    a. Compressed air is used to push down the water level in the drill string. Overflow at the top of the hole occurs.
- C – The packers are inflated.
    a. Compressed air is bled off.
    b. The test zone is allowed to come to equilibrium.

- D – The valve is opened by raising the drill string so inflow can take place.
- E – The valve is closed by lowering the drill string so that a pressure build-up can take place.
- F – The packers are deflated by pulling on the wireline.
    a. The tool can be pulled out of the hole.

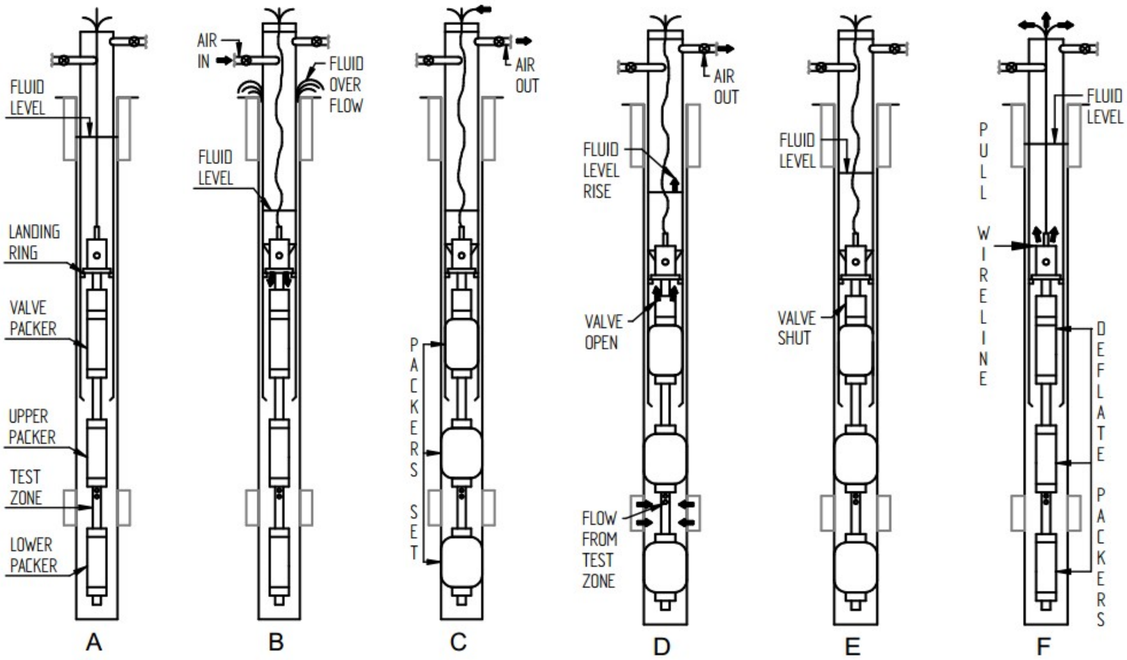

Figure 2 Step by step diagram of the operation of the wireline drill stem test tool

Water inflow can be monitored by a change in pressure of the in-string pressure transducer, while the flow of displaced air and any gas produced can be measured on the gas flow meters. Any gas flow can be detected as the difference between water inflow to the string and gas flow out of the string. The period of inflow is limited, either by time constraints on the test, or by an endeavour to restrict the head rise in the drill string to approximately one third of the difference in head between that existing in the string and bottom hole before the valve is opened. After this flow period the main valve is closed by lowering the drill string. The test zone pressure is then recorded and allowed to approach equilibrium. The flow and build-up process may sometimes be repeated. This is especially the case if the initial flow period inflow rate is variable.

The key to the success of the test approach is the downhole valve, the surface read out and the ability of the system to withdraw fluid as opposed to injecting it. Other variants exist, including a closed chamber tool where production is into a chamber which is under vacuum until opened to inflow. This solves the problem of needing to use compressed air to drive down the fluid level and enables fluid to be collected but it has a limited volume. In another version the packers are attached to the end of the drill string and the inflation and communications lines are raised and lowered through the drill string. This version is particularly useful for testing multiple sections in a hole without pulling the drill string each time. Its limitation is that the packer spacing and hence the length of the test zone cannot be changed between tests.

Figure 3 shows the results of a DST of a sedimentary formation. The packer pressure is in pink, the test zone pressure is in dark blue and the in-pipe pressure is in red. The packers are set and the test zone is allowed to come to equilibrium. At time A the valve is opened and the pressure drops dramatically, with very little inflow shown by the negligible rise in the in-pipe pressure following the opening of the valve. On shutting the valve the pressure climbs very rapidly before curving over to asymptote to the formation pressure. The valve is opened at time B and closed with similar results. To the casual observer the low flow would indicate very low permeability. This was not, however, the case as the low flow was caused by very high near wellbore losses.

The rapid pressure build-up when the valve was closed occurred because the pressure drop adjacent to the wellbore vanished when flow ceased.

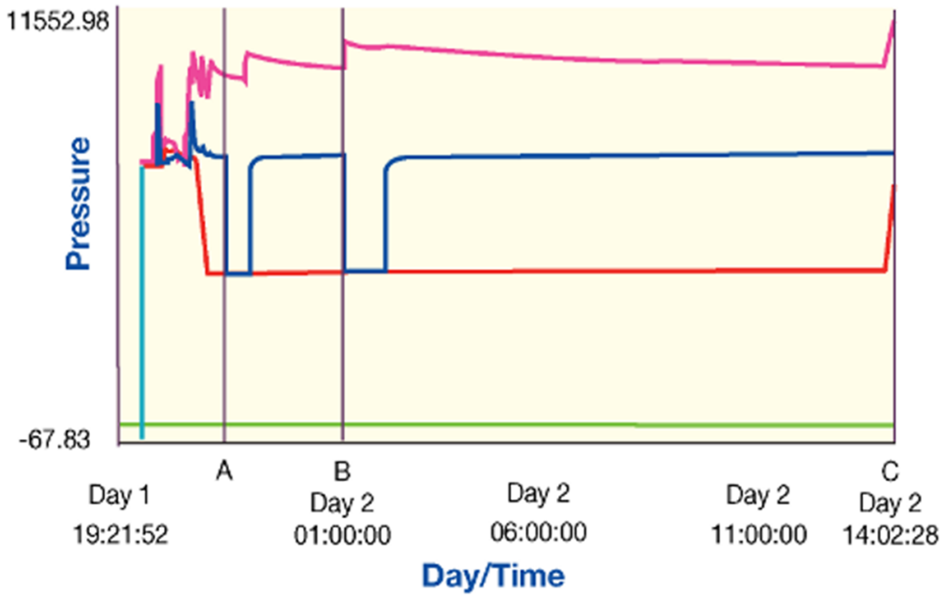

Figure 3 Two flow period drill stem tests showing pressure (kPa) versus time

A quite different example of a test plot is shown Figure 4. In this case the test is conducted across a zone in slightly fractured granite at 650 m depth. Following the test zone being set the zone pressure climbs slowly to reach 6.5 MPa, corresponding to this depth. The valve is then opened and there is a low, and declining, inflow shown (as in Figure 5). Following valve closure the pressure in the test zone rises but only to about 6.1 MPa. It is also possible to see that the pressure rise following shut-in at approximately 13:30 hours (Figure 4) is not instantaneous as in the previous case. This is because the near wellbore loss and permeability are both low. The time markers A, B and C in Figure 4 are simply markers used in the processing software.

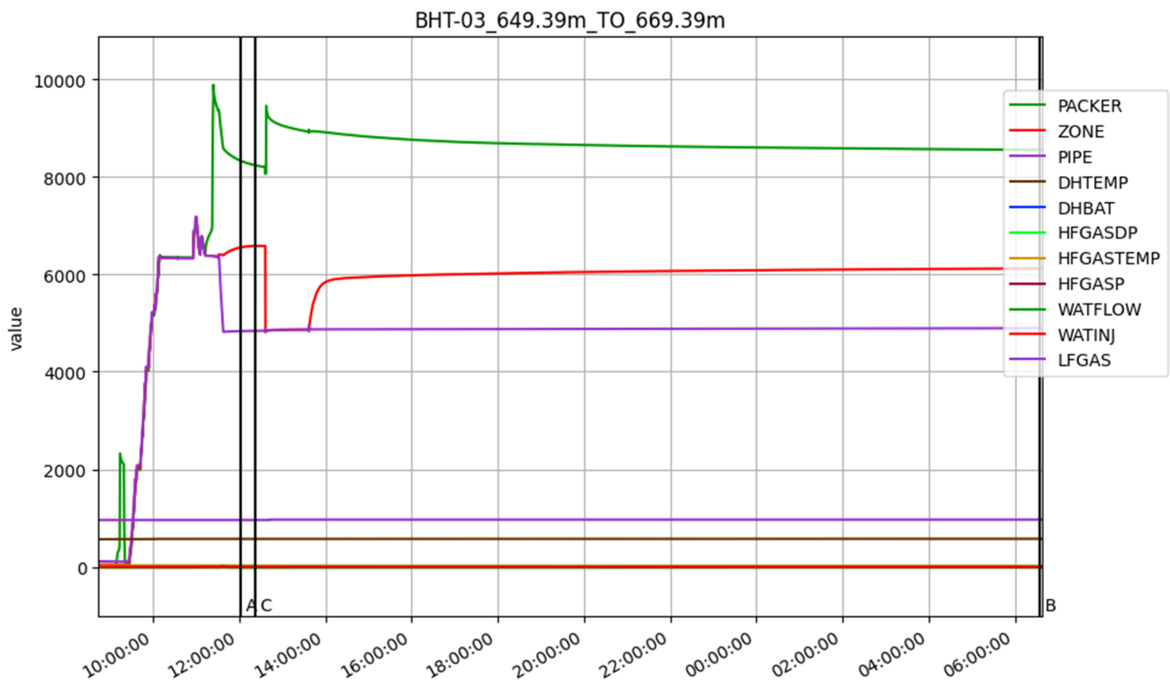

Figure 4 Drill stem tests in fractured granite. Test zone, pipe and packer pressures are in kPa. Time is in hh:mm:ss

Figure 5 shows a rapidly declining flow rate with the negative values indicating inflow to the test zone. The change in equilibrium pressure before and after flow is the result of the depletion of fluid from the fractured zone. Indeed it is quite possible that the fractured zone was initially pressurised by the drilling process and the test simply relieved some of this pressure. The fractures being tested may not have been water filled prior to drilling.

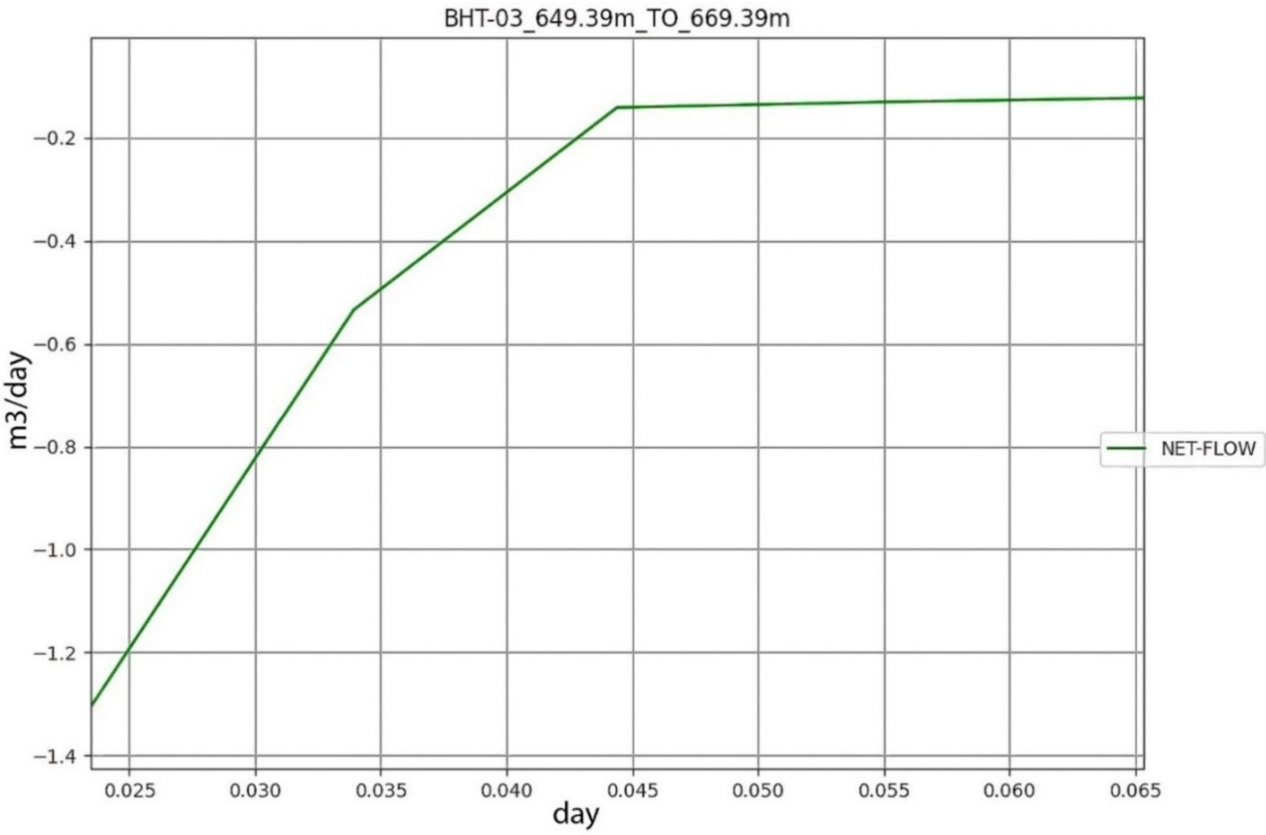

Figure 5 Flow rate

3.1.3 Analysis

The analysis of such tests is not simple but can yield a great deal of information. The analysis processes of the petroleum industry are useful but need suitable interpretation and modification as the nature of the ground being tested for mining purposes tends to be different from the layered sedimentary sequences of petroleum reservoirs. Historically key publications in this area are those of Horner (1951), Dake (1978), Gringarten et al. (1979), Agarwal (1980), Bourdet et al. (1983) and Bourdet et al. (1989). The curve methods of analysis from the latter three publications are not necessarily the best way to analyse fractured rock masses; sometimes a simpler method, which is the multi-rate analogue of a Horner build-up plot, reveals more about what is going on around the hole.

Knowing the apparent fracture width provides a basis for estimating storage within fractures and the width up to which a grout particle may be pumped.

The basis of pressure build-up or drawdown testing following a flow period (Horner 1951) is shown in Equation 1.

$$p_{r_w,t} = p_i + \frac{q\mu}{4\pi kh}\left(\ln\left(\frac{(T+\Delta t)}{\Delta t}\right)\right) \tag{1}$$

where:

$p_{r_w,t}$ = the pressure after shut-in at the test zone.

p_i = the initial reservoir pressure.

q = the uniform flow rate (-ve = flow from formation into the well).

h = the formation thickness.

k = the permeability of the formation (length^2).

μ = the dynamic viscosity of the fluid.

T = the flowing time.

Δt = the time after shut-in.

This has been extended by superposition techniques to the case of a multi-rate test as shown in Equation 2.

$$p_{r_w,t} = p_i + \frac{\mu}{4\pi kh}\sum_1^n\left[q_i\left(\ln\left(\frac{t-t_{i-1}}{t-t_i}\right)\right)\right] \tag{2}$$

where:

q_i = the flow rates at each interval starting at time t_{i-1} and finishing at time t_i.

t = the time from the start of flow.

The analysis of the test shown in Equation 2 is by a multi-flow rate method based on examining the post-shut-in pressure build-up. Figure 6 is a plot of the function of:

$\sum_1^n\left[q_i\left(\ln\left(\frac{t-t_{i-1}}{t-t_i}\right)\right)\right]$ on the x axis and labelled mflowHorn in Figure 6 with zone pressure on the y axis.

The permeability may be derived from the slope of the plot, m, as shown in Equation 3.

$$k = \frac{\mu}{4\pi mh} \tag{3}$$

where:

m = the slope of the plot.

The plot derived from the test in Figures 4 and 5 is shown in Figure 6. Here the later times are progressing to the right as the flow is into the well (negative).

If the zone being tested had been a homogeneous radially symmetric aquifer or reservoir the plot of Figure 6 would have been a straight line with permeability as a function of the inverse of the slope. Figure 6 shows at least two straight line periods corresponding to different fractures or fracture groups and the final picks of pressure at A and B used to extrapolate to the final stabilised pressure value.

To analyse this test for mean effective radius of investigation and near wellbore loss we must estimate a value of the porosity-compressibility product. In this case we have chosen a value of 1×10^{-11} Pa^{-1}. Using this value the near wellbore loss (skin value) was negative, meaning that the fractures had more permeability near the wellbore than the fractures generally. The mean effective radius of investigation is estimated to be 27 m. The latter value is not too sensitive to the value of the porosity-compressibility product and indicates that a useful volume of the rock mass has been tested.

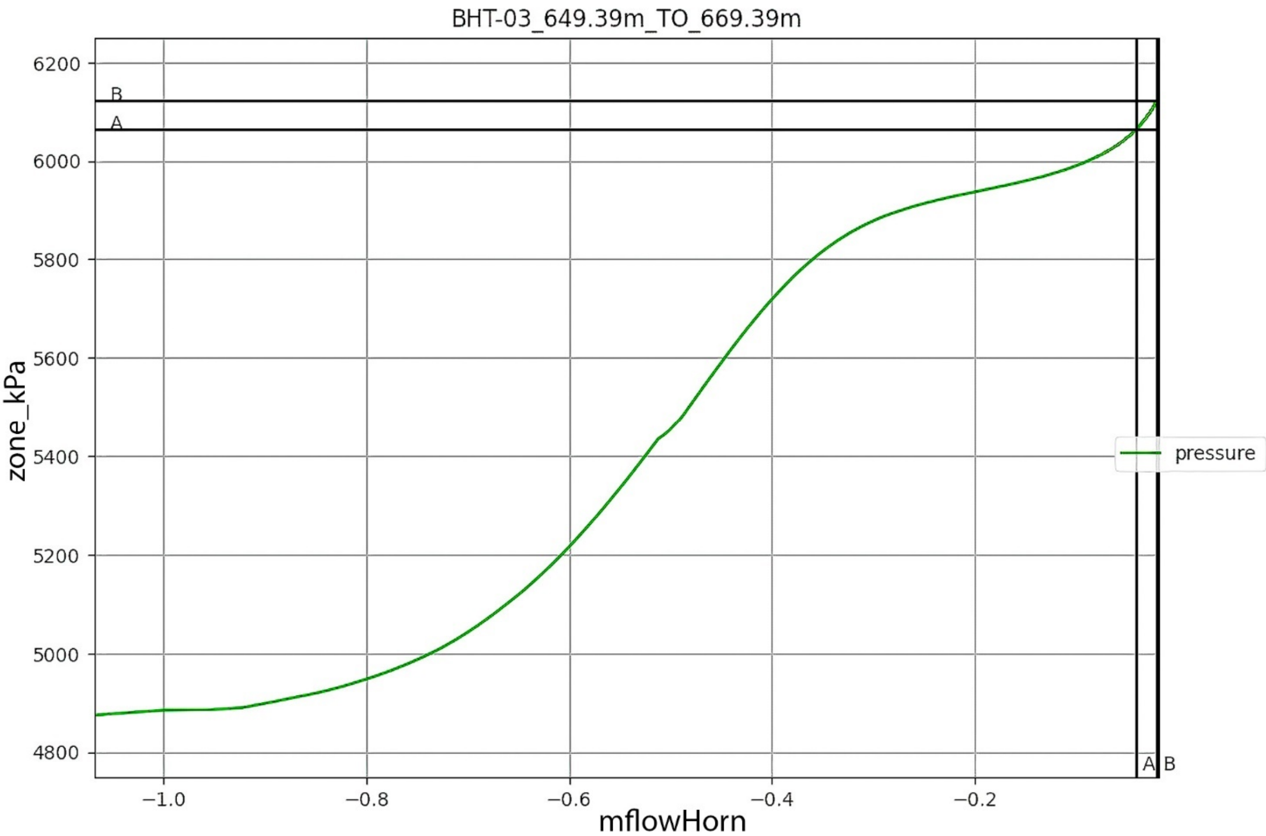

Figure 6 Multi-flow rate build-up analysis plot. X axis shows m^3/day

The result of such analyses is to produce a value of permeability. While this has a direct meaning in terms of a reasonably homogeneous porous rock mass it might be interpreted differently in terms of a fractured crystalline rock mass. In this case the questions are: what is the number of fractures and what is their effective width? The number of fractures may be learned by examining core and acoustic or optical televiewer images. The apparent fracture width may then be determined. Snow (1968) showed the relation between fracture spacing and permeability in Equation 4. This is based on parallel fractures.

$$k = \frac{a^3}{12A} \tag{4}$$

where:

a = the fracture width (m).

A = the fracture spacing (m).

k = the permeability (m^2).

3.1.4 Injection tests

The tool described in Figure 2 may also be used for injection or, more commonly, a falling head test with shut-in at the end of the flow period. The latter test is essentially the mirror of the DST, with the difference being that outflow from the drill string takes place when the valve is opened and the recovery is by pressure decline in the test zone after the valve is closed. It is otherwise similar from an analytical viewpoint. Injection tests are typically used where there is no differential pressure to cause inflow from the test zone. This may be because the test equipment is not suitable or because there is inadequate fluid pressure in the rock mass.

3.1.5 Diagnostic fracture injection testing and hydrojacking

Because the petroleum industry was trying to access reserves in lower permeability reservoirs, particularly unconventional reservoirs in the form of shales and coals, new approaches were sought to measure the properties of these. Due to the very low-permeability nature of these, new production systems were sought; notably hydrofracturing, directional drilling and, frequently now, a combination of the two.

The diagnostic fracture injection testing (DFIT) process involves conducting a combination of the hydrofracturing and permeability measurements. The process is to seal off a section of borehole and to hydrofracture it with high-pressure fluid. This is followed by a period of continued injection, then by shutting in the test zone. The process of leak-off and fracture closure then occurs and would normally be identified by the G function, square root time or log-log plots showing the pressure after shut-in with functions of time, and their first and second derivatives. These analytical processes are admirably described by Barree et al. (2007).

The pressure at which fracture closure occurs will, in ideal circumstances, correspond to the minimum stress. If the borehole from which hydraulic fracturing is taking place is not in the plane of the minimum stress the fracture will rotate to that orientation, leading to a complex multi-stage closure. Similarly, if the fracture is captured by planes of weakness (joints) then the closure of multiple joints may be sequentially detected. These events serve to complicate analysis but do not invalidate it. They just require interpretation.

Opening joint sets is called hydrojacking in rock mechanics parlance and it is deliberately undertaken to try to find the opening, and more particularly the closure, stress on existing joints. Knowing the stress on joints is particularly valuable if the opening in the rock mass is going to be subject to fluid pressure such as in a headrace tunnel or pressurised storage cavern. In the ideal situation the closure stress across multiple joints can be obtained independently and a stress tensor determined from these. This is generally not possible because either inadequate joint sets exist, or multiple joint sets are opened in a single hydrojacking operation.

The DFIT does not end with fracture closure. Pressure monitoring takes place for some considerable time afterwards. The purpose of this is to provide information for after-closure analysis to determine the permeability of the formation. The analysis is based on the volume of fluid pumped into the test zone over the period from the start of pumping to fracture closure as this is the injection period. The recovery behaviour is initially governed by linear flow towards the fracture(s) but in late time becomes more radial, allowing the determination of the permeability and fluid pressure. The danger associated with after-closure analysis in a fractured rock mass is that the fractures will have been fundamentally altered by the hydrofracturing process. This applies particularly to the case where the permeability is controlled by fractures within a crystalline rock mass.

Overall, the process of DFIT facilitates the measurement of hydraulic fracture parameters while enabling an adequate volume of fluid to be injected into a tight formation to produce a measurable pressure effect for transient permeability analysis. To make full use of the technique for stress measurement it is necessary to undertake a fracture reopening step after the transient component has subsided. This is seldom completed because of time constraints.

Hydrojacking combined with after-closure analysis can do the same for excavations in the ground, whether for mining, cavern storage or tunnelling. The purpose in this case is to find the minimum stress on fracture groups and to measure their permeability. In the case of pressurised storage, the pressures that will lead to hydrojacking are of vital importance as this indicates the pressure at which catastrophic leakage will take place. The measurement of permeability provides a basis for leakage estimation to or from the openings.

3.2 Multiple hole tests

The measurement of pressure (head) change at points surrounding a well that is being used for production or injection enables the interpretation of the test to provide information on storage behaviour and directional permeability in conventional hydrogeology. This involves extracting water from a production well in an aquifer, with surrounding piezometers installed in the same aquifer or in adjacent formations to determine connectivity.

Such tests are ideal for establishing the behaviour of a production well. They are not necessarily the best to determine the characteristics of an inhomogeneous rock mass. The reason for this is that the test is dominated by the characteristic of the formation surrounding the production well. It is also possible to mistake inhomogeneity within the rock mass as being anisotropy. An alternative approach (Gray 2015) is to test in one hole and then leave a piezometer in it while moving and testing in an adjacent hole. This approach enables the determination of inhomogeneity and its separation from anisotropy; something that cannot be determined from a single production or injection well. Both anisotropy and inhomogeneity are likely to be of major importance in a fractured rock mass.

In a complex geological situation the ideal process is to have multiple injection or production holes and to have multiple piezometers so that testing can be conducted in 3D. This includes injection or production at different zones within the holes to suit the variable lithological units and fracture systems. This may well be justified if the problems with groundwater are likely to be sufficiently great. Unless they are mined out the piezometers will continue to provide information as mining proceeds.

3.3 Testing in the underground environment

Testing in underground environments is crucial for assessing the hydrogeological conditions and ensuring safe and effective mining operations. It requires holes to be drilled from underground workings with test processes that are safe to conduct. Drilling into a rock mass and hitting a major open fault zone pressurised to 15 MPa is a dangerous and potentially disastrous scenario. Under such conditions it is possible to have a velocity of discharge of more than 200 m/s and a flow rate exceeding 1 m^3/s from a 100 mm diameter borehole. The options are to let the water drain out and the flow decline, which it may not, or to endeavour to cement the hole. The latter process is almost impossible unless some form of well control system has been incorporated. Endeavouring to put packers up holes discharging at a high rate is almost impossible and certainly dangerous.

Well control means the ability to control flow from the borehole and especially to be able to close it in while implementing some form of permanent solution to the inflow. For a well control system to work it requires a cemented-in standpipe, or well head in petroleum jargon. Reliably cementing these into rock that is producing water is basically impossible and it is necessary to seal seepage first so that the standpipe can be set properly. This may require various quick set chemical grouts to be used. It is far better to set a standpipe in solid rock where grouting can be completed properly and to drill from this safe ground into the unknown. The standpipe needs to be fitted with a rotary seal, a blow-out preventer and possibly a fully managed pressure drilling system. The latter enables the borehole to be pressurised to prevent uncontrolled discharge.

The drilling system to be used in exploration drilling from underground needs to be considered from the viewpoint of risk. The commonly used process of wireline coring is fundamentally not safe if high inflows and pressures are expected. The problem with this is that when the inner barrel is pulled it may be propelled by water. While this can be readily controlled using a stuffing box attached to the end of the drill string, this must be removed at some time to get the inner barrel out. When the stuffing box is removed there is an uncontrolled outflow. This outflow is limited by the length and diameter of the drill pipe and the pressure of the water encountered in the hole. The only effective control on inflow is by jamming the bit against the face of the hole, thus restricting fluid entry. In the case of the drill bit entering a void this option does not exist.

If the drill rods are fitted with a non-return valve this outflow is prevented, but so is the use of wireline coring. The incorporation of a non-return valve requires drilling by either the open hole method, without core recovery, or with a conventional core barrel which requires the drill string to be pulled to recover the core. The use of down-the-hole hammers is possible but the system at the collar of the hole must then incorporate some means to safely separate a large amount of pressurised air and water in a confined space. This can be done but it requires forethought and proper design.

Assuming a hole can be drilled the next requirement is to monitor what fluid is being pumped into it and what fluid is coming out, and to calculate the net fluid loss or return. This provides information on the water-conducting nature of the rock mass. If a standpipe is used this is not difficult and it provides instantly available information on what is happening. The borehole can also be shut in and the approximate pressure of the fluid being encountered can be estimated. Some caution is required in this pressure measurement as it will be affected by inflow and leakage, with both occurring along the length of the hole.

These inflow and leakage problems affect testing over the length of a hole and may invalidate the use of the analytical techniques to determine real parameters as it is uncertain what is happening in which section of the borehole. Under these circumstances it is necessary to deploy a tool that is the underground analogue of the DST tool described earlier. This tool has a single or straddle packer assembly fixed to the end of the drill string. Such a system, developed for the coal industry, is shown schematically in Figure 7. In this figure it is fitted with a single packer for testing at the end of the hole though it may also be used in straddle form.

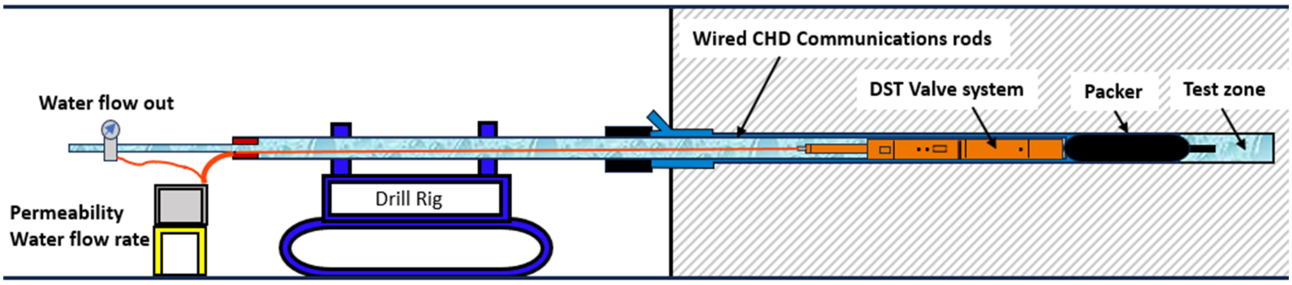

Figure 7 Example of a system for pressure and permeability testing

The system in Figure can be inflated by pressurising the drill rods to inflate the packer(s). The valve can be shut to seal the test section or opened to allow flow. The typical DST process of shut-in, flow and shut-in can therefore be used with all its inherent advantages so real values of permeability and fluid pressure can be determined. At the end of the test the packers are deflated by pulling the drill string to open a dump valve. The system shown in Figure 7 has been built to enable the testing along a hole so that the spacing for subsequent drainage holes may be determined. There is no reason why its use should be confined to coal mining; indeed, it is about to be used in a cavern project for compressed air storage.

Once exploration is completed the hole may be left open for drainage or it may be grouted, grouted with the inclusion of pressure transducers (Gray 1987b) or used for grouting to seal the rock mass, depending on mining requirements.

4 Controlling inflow

The geological variability that may be encountered when mining is vast and so therefore is the nature of groundwater. The problems may extend from a nuisance inflow to rapid mine flooding in the case of pump failure. It may also involve dealing with saline or toxic water. The danger of broaching pressurised fault zones, which may deliver high quantities of water and cannot be readily sealed, needs to be considered. If water is a problem something needs to be done about it. The options are to put up with it and drain the mine, drain it first or prevent it from entering the mine. None of the options are easy.

4.1 Drainage options

Drainage before mining means drilling adequate dewatering holes, which may be directionally drilled, and pumping them for long enough that the water within the mine area is removed. For this to be effective the ingress of water from the surface or surrounding ground needs to be prevented. This may be achieved by using cut-off wells surrounding the mine area. Theoretically it may be done by creating a grout curtain, but this would, in most instances, be very difficult to achieve.

The most widely applied pre-drainage method is that of specific water-bearing strata. It is applied in particular to coal mining, where both water and gas are involved. To achieve this a number of directional surface-to-in-seam holes are drilled. The flanking holes act as cut-offs to prevent gas and water to recharge the area, while those within act to drain the block to be mined. The directional holes may typically be 2 km in length within the seam. Typically the directional holes are drilled to intersect another vertical well which houses the pump to lift water. This well usually permits the flow of gas around the tubular (pipe) which bears water. This approach is described by Corpuz et al. (2015). This approach has been extensively used outside of mining as part of commercial coal seam gas extraction where water drainage is fundamental to getting the adsorbed gas out of the coal. Directional drilling is particularly successful in dealing with fluid-bearing strata that shows high directional permeability as the directional boreholes may be designed to cross the direction of major permeability.

Drainage may be accomplished by underground drilling to a similar pattern using cut-off wells and drainage of the block in between. This is particularly suitable for use in tabular aquifers or deposits.

The keys to the use of long holes are the ability to drill them and their carrying capacity. It may be noted from Table 1 that many of the wet mines are in carbonates. These are quite readily drilled using downhole motor or rotary steering systems as used in the petroleum and coal mining industries. However, the diameter of such holes needs to be adequate to accommodate the water flow they are required to take.

The type of drainage that is used is dependent on what is required. If it is to lower fluid pressure in a relatively low-permeability rock mass the water flow will be low and the emphasis on adequate drain hole spacing to lower the water pressure. If it is to deal with a high permeability rock mass how can this be isolated from recharge and drained? If the water is in isolated faults the problem becomes one of dealing with these. In the latter case, sealing (rather than drainage) may be the prime option.

In the case of a high permeability rock mass the first question to be asked is whether cut-off drains will work. The second is whether the block in between them will drain. Both answers are tied to the permeability of the rock mass. If the permeability is high it is likely that a lot of cut-off holes will be required simply to have the flow capacity to drain what is required of them. Depending on the nature of the rock mass these holes should be placed to best intersect any directional permeability such as is induced by jointing or controlled by impervious boundaries. Drainage holes may be drilled vertically or directionally from the surface. They may also be drilled from underground. Long directional holes can be very effective in intersecting joints but the limit on their drainage efficiency is likely to be their length. Keeping the hole open may then be the limiting factor. One case of this type was that of a rotary steering directional drilling system which was used to drill behind the slope of an open cut mine in Russia to effect drainage (personal communication).

If blocks can be protected from recharge, and if they contain a lot of water, the main consideration is how to drain them. If homogeneously permeable they may simply drain into holes drilled at their base. If the intra connection of voids within the block is less consistent, connections may need to be generated. The shale gas option of drilling parallel holes and hydrofracturing between them should be considered. Such a layout is shown in Figure 8.

The zone created by the horizontal borehole and the hydrofractures is referred to as the stimulated reservoir volume. The boreholes may be 2 km in length. Such hydrofracture operations are undertaken sequentially, stage by stage, using very high power frac pump spreads. These may contain 12 × 1,500 kW pumps which are pumping a mixture of sand or artificial proppant mixed with a frac fluid. The latter may have a wide range of properties, from quite viscous to viscosities that are less than water, to suit the conditions.

While arranging such a pumping system underground would be difficult it is quite possible to reticulate frac fluid from a surface pump facility to underground. A circular reticulation system is required so that any proppant is not allowed to settle in the frac lines.

The scheme described would certainly lead to the capture of fluid from natural fractures. The downside is that an entire hydrofracture stage may be captured by a fault or joint swarm. This may be good or bad. The good aspect is that it will help drain the fault while the bad aspect is that the fracture fluid will not act to open the fracture beyond this zone.

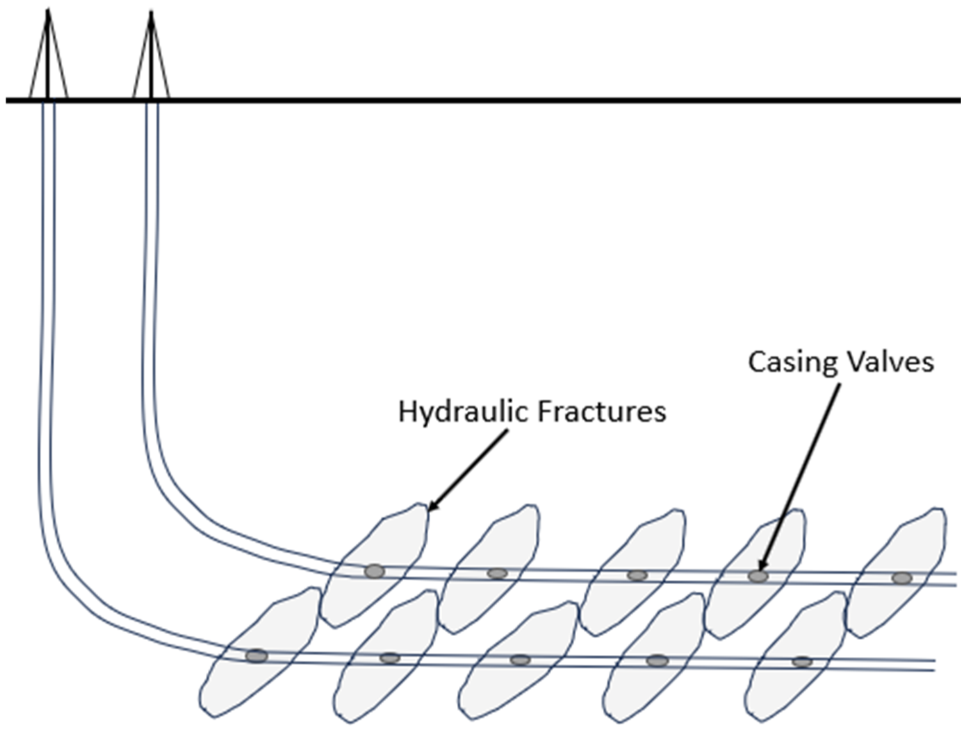

Figure 8 Oblique view of adjacent near horizontal wells drilled from the surface, with staged hydrofracturing from each well

One of the problems encountered when drilling into ground which is already partially drained is differential sticking. Differential sticking occurs because fluid flow is from the hole into the ground. Most drilling muds are designed to build up a filter cake on the hole wall to reduce this loss. The consequence is, however, that they form a seal between the drill pipe and the hole wall. Therefore a large differential pressure can build up between that existing in the borehole and that in the rock mass. This pressure forces the drill pipe into the hole wall and the resulting friction frequently stops the drill string from turning. The result is a stuck drill pipe and frequently the loss of the hole. To avoid this it is better to drill all surface drainage holes before pumping or mining takes place so that there is no depletion of pressure in the area.

Drilling from underground does not suffer from differential sticking problems because flow is generally from the rock into the hole. If the pressure difference is too great, however, it is possible to induce borehole failure in some rock types. While managed pressure drilling systems can be used to maintain pressure in the hole and avoid hole wall failure, at some stage the drill pipe will need to be removed and either an open hole left or a screen inserted. In the case of an open hole in weaker rock it may be best to lower the pressure within it gradually to reduce the possibility of hole failure.

Where drainage is implemented there will be a need to deal with the produced water. While in a few circumstances it may be possible to discharge the produced water into a watercourse this is generally not the case. Some injection system may be devised to dispose of the water back into the ground from where it came, albeit further away from the mine. This serves the purposes of disposal, recharging groundwater and, in many cases, preventing the subsidence of soils nearer the surface. Reinjection wells require as much design as those used for drainage. Alternatively, such systems as reverse osmosis must be used to treat the water before its discharge.

4.2 Grouting options

Hauge & Germishuys (2003) discuss the conventional approach to grouting, which is to drill a pilot hole from the face to isolate permeable zones. Once this is done closely spaced holes of 30 to 40 m in length are drilled from the face and grouted with microfine cements. Microfine cements are less likely to block in the narrower fractures than normal ones. Apart from the hazards associated with drilling pilot holes into unknown territory this is a slow process of drill, grout, test, regrout and test until the system works. It also only covers a small volume which requires the process to be repeated each time the conditions occur. Traditionally cordon-type grout curtains have been remarkably ineffective in reducing seepage below dams. To make the process work, multiple stages of grouting and testing need to be undertaken.

The sort of approach used in civil tunnelling is shown Figure 9. It shows holes that are drilled progressively from the face and outwards in a fan. Each of these is grouted in a first stage (1) and then redrilled, the next stage is grouted (2), and this is followed by the third stage (3). This is a very slow and expensive process, and is not generally justified for use in mining except where bad local conditions may be encountered.

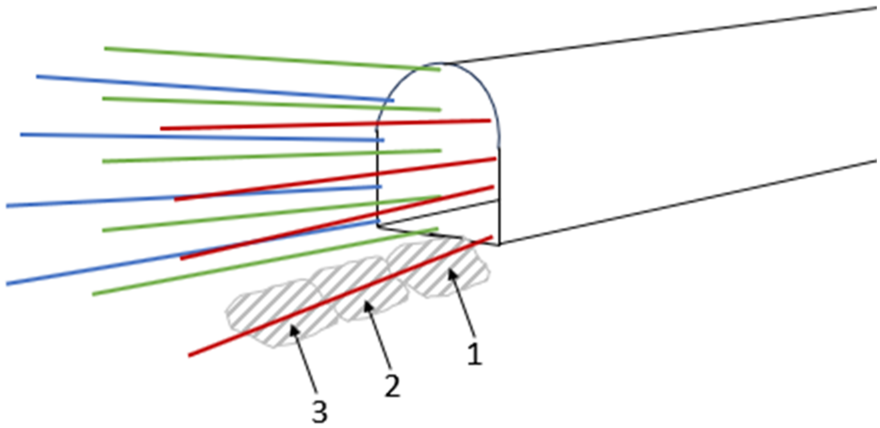

Figure 9 Multi-hole and stage grouting for tunnelling

The use of ground freezing is sometimes a possibility. However, it is expensive and if there is significant groundwater movement it becomes difficult to adequately cool the ground to freeze it.

Having described the process of hydrofracturing and the concept of the stimulated reservoir volume it is time to introduce the concept of blocked volume. While the same sort of pressures and volumes are used to hydrofracture the ground, the difference is that grout is used as the fluid. The intention is to fill every natural fracture that can be reached. This process could be undertaken from the surface or underground. In the latter case the circulating fluid would be grout. The cost of such an operation would be considerable but no more than an oilfield frac operation. The difference is the comparatively short duration of the operation, and the much lower overall energy and implementation costs than the repeated process of local grouting and drainage. The sort of drilling and grouting pattern that might be used is similar to that shown in Figure 8. In some geologies it may be more effective to grout from vertical holes. Here casing would be cemented in place; something that is not necessarily simple. It would then be perforated using a perforating gun. Grout injection with hydrofracture could take place from that level. The casing would then be filled with sand to above this level and the perforate/hydrofracture/grout sequence repeated. This can be repeated multiple times up the casing.

5 Conclusion

The key to understanding the groundwater situation is a sound comprehension of the lithological and structural geology of the site. Without this there is no hope of being able to understand whether there is a groundwater problem, let alone devising a methodology to deal with it.

Several facets of technology from the petroleum industry can be used to contribute to solutions for controlling groundwater problems in mines.

The first of these technologies is an adaptation of the numerous test techniques used to determine permeability: in particular, the use of single hole testing in the form of DSTs or injection fall-off tests. These are efficient test processes that focus on pressure recovery after a flow period, thereby avoiding many errors that occur in much of the testing currently in use; especially the failure to adequately deal with near wellbore (borehole) losses. Many of the current test techniques produce valueless information because they fail to deal with such losses. The worst of these is the packer test producing almost meaningless Lugeon values. However, other tests in which pressure analysis is conducted in the flow period, as opposed to after flow has been stopped, also produce erroneous results because of changing near wellbore losses during the test. Correct testing techniques should be conducted at each change of lithology and structure within a borehole.

These methods may be extended to multiple hole tests. Such a process has a better probability of detecting inhomogeneity as well as anisotropy than a single big well test. In these, a hole is tested and piezometers are left in place. Another nearby hole is then drilled and tested, and any pressure transient induced by it can be measured in the piezometers. The single well test usually involves producing from several horizons and then trying to sort out what is going on using surrounding piezometers. The results are, however, very much dominated by local conditions around the production or injection well.

A development that is needed is in the analysis techniques for fractured rock masses. The oilfield practices currently used are focused on homogeneous radial flow.

The second most important aspect of petroleum technology is in the use of hydrofracture. This may be to enhance drainage by creating drainage pathways. It may also be used to inject mass grout to block pores, fractures and faults. This latter use has the potential to totally change the way in which mining may be conducted in wet rock. It requires the adoption of oilfield technology in the form of hydrofracture systems. However, the potential gain from dealing with water on a large scale rather than in a bitwise manner is considerable.

The third gain from the petroleum industry is in drilling technology. Directional drilling has changed the way in which reservoirs are developed and produced, and its use in mining is considerable. This has already been realised in the coal mining industry and its benefit can be gained in other minerals. The limitations are: firstly the hardness of the rock, which may preclude the use of polycrystalline diamond cutter drill bits, thus slowing drilling; and secondly the carrying capacity of long holes, which may not be adequate in very permeable rock masses, thus leading to back pressure issues.

A fourth adaption of petroleum technology is in the control of flow from underground boreholes. It is not safe to drill into potentially wet ground that may flow at high rates without some form of well control system. This must be attached to a soundly cemented standpipe (well head) that enables the flow to be shut off and for control measures such as grouting to be implemented. The establishment of such a standpipe requires that the ground in which it is set is sound and impervious. This may require the rock near the opening to be treated with quick setting chemical resins first. The use of managed pressure drilling where some controlled back pressure is maintained in the borehole may also help prevent hole failure.

This use of standpipes enables net flows from the hole to be monitored. These are a good indicator of problems that may lie ahead. If a very high flow zone is encountered it is possible to grout through the standpipe at high pressures to seal up the problem. It is much better to deal with a problem that is 200 m away than one that has been encountered at or near the face.

The use of wireline coring in underground drilling in wet permeable ground is potentially hazardous because it is impossible to implement full well control techniques with an open wireline coring rod string. The main control is limited to pushing the bit against the face to form a seal and control water ingress.

The operation of mine drainage systems must be monitored by pressure monitoring using piezometers. These can be installed from the surface and underground at any angle of hole. The use of flow monitoring alone is inadequate to ensure that a drainage system is operating satisfactorily.

The control of water in mines should not be considered as just a drainage matter. The use of sealing by stage grouting has been in use for many years, particularly in tunnelling. It is, however, slow and expensive. The concept of mass grouting to fill all voids and remove permeability is an important concept. It has the added benefit of stabilising broken, faulted ground.

Mass grouting in the form of seals may be used in combination with drainage. Alternatively, the use of cut-off drains which prevent water ingress to an area that is being drained may be more cost-effective. The problem with drainage remains in that something must be done with the water. This often poses significant environmental challenges. Therefore the use of sealing methods has distinct advantages.

The concept of hydraulic fracturing is presented both to enhance drainage and to seal up a substantial volume with grout. Most of this technology can be imported from the oil and gas environment and used with relatively minor modification. The key to this technology is the pressure that exceeds the minimum stress in the ground and creates fractures which link up with the natural fractures. In the case of grouting, the object is to fill every fracture with grout in a significant volume and thus block flow paths. It has the added benefit of stabilising a fractured rock mass.

No doubt the author's preference for oilfield pressure rather than head units and compressibility-porosity products rather than storativity will bring protest from hydrogeologists but they do present a more consistent approach to analysis of 3D rock masses, especially when they are couched in SI units; something the oilfield has failed to adopt.

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