The Measurement of Permeability and Other Ground Fluid Parameters

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Abstract

Different branches of engineering tend to adhere to historic practices that are used by their discipline alone, and tend to ignore developments from other groups.

In the case of permeability measurement, civil and mining engineers tend to stick to packer testing and the determination of an index called a Lugeon value. This bears little relationship to a real value of permeability. In soils, there is a tendency to use falling head tests. These also have problems associated with their analysis, which generally renders them invalid.

The hydrogeologist wants large scale well tests that are frequently of long duration and suitable for productive aquifers. The analysis of these is usually based on drawdown.

The petroleum reservoir engineer wants a quick test down a deep hole. However, because of the dollars involved in these tests, a lot of thought has been put into their analysis. This enables the separation of the real permeability of the ground from damage to the well bore area brought about by drilling. The key to this success is in ending the test with a zero-flow period where the test zone is closed in.

Sigra has operated in all of these disciplines, and has developed equipment and techniques that are as simple as a packer test to conduct, but yield all the advantages of tests conducted by the petroleum industry. These are a true assessment of formation permeability, a measurement of well bore damage, the ground fluid pressure and an indication of the mean effective radius of the investigation.

What single borehole testing cannot do is provide information on the storage characteristics or the anisotropic nature of permeability. To achieve this, other pressure sensing points (piezometers) must be installed. This brings the testing process full circle, to one where a full pumping test might be used with at least three correctly placed piezometers to enable the determination of anisotropy in permeability, and the storage behaviour. The problem with this approach is that it is not possible to differentiate between anisotropy and inhomogeneity.

There is an alternative that enables the measurement of both inhomogeneity, anisotropy and storage parameters. This is the pulsed DST approach. It involves sequentially testing individual boreholes and placing piezometers in these as each borehole test is finished. The next borehole to be tested sends a pressure transient to those boreholes drilled before and fitted with piezometers. The most convenient way to test each well is by conducting a DST in each of the test zones. Hence the name “pulsed DST”.

This method enables multiple measurements of mean permeability and directional permeability,

so that both inhomogeneity and anisotropy may be assessed. This provides comprehensive information on the groundwater/fluid regime that is generally ignored by mining and civil engineers.

A lot of poor quality measurements with intrinsic flaws do not make up for a few good ones!

The Reasons for Measuring Permeability and Storage Parameters

The reasons for measuring groundwater parameters include:

- Slope groundwater behaviour – for stability
- Dewatering needs:
  - quantity of fluid
  - magnitude and extent of drawdown
- Settlement due to dewatering
- Containment and removal of contaminants
- Water supply

The prime reason for measuring parameters in the world of petroleum fluids is to delineate a reserve and deduce a production scheme.

The Need to Understand the Geology

No matter what technique is being applied to measure ground fluid behaviour, an understanding of the geology of the area is essential so as to be able to interpret the results. Having a measurement in unidentified strata means little, and certainly precludes the extrapolation of this measurement elsewhere. Preferably all data available should be used to identify the geology. This might include core logs, geophysical logs, geochemistry and seismic survey information. It may also include well test data itself, as this can be used to identify the rock type and such features as reflections from barrier boundaries or the recharge zones.

Testing Practice

Each engineering discipline has developed its own way of measuring permeability and storage behaviour, and we do feel that these practices have often proved inadequate, specifically in reference to civil and mining projects. These could be improved with some understanding of the process and the use of suitable technology.

Let us examine these practices.

The Hydrogeologist

The hydrogeologist who requires groundwater will choose to drill a well or wells into a suitable aquifer, and will pump from this to determine the production rate versus pressure (head) depletion in the well. If economics permit, they have observation wells and will then observe pressure (head) changes in these so that the storage behaviour of the aquifer may be deduced, but without them

this is not possible.
Long term pumping tests of wells and the response in adjacent wells is a very good way to determine aquifer characteristics. Hydrogeologists will interpret their measurements in terms of hydraulic conductivity, which is a combination of absolute permeability of the ground and the viscosity of water.

They will describe the storage behaviour in terms of yield of fluid per unit area per unit fluid head change. The storage term used for a confined aquifer is storativity, and for the unconfined case, specific yield.

The Petroleum Reservoir Engineer

The petroleum engineer will drill a well which is usually deep and expensive. They wish to test the formation (ground) as quickly as possible because drill rig time is real money. They seldom use pressure measurements in adjacent wells to determine storage parameters, due to the prohibitive costs of such wells for pressure sensing.

Because of the variation in fluids with location and time, the petroleum engineer focuses on absolute permeability and in determining the fluid parameters, such as viscosity and density, separately. The determination of storage behaviour is as much as possible determined by laboratory studies of core. The key words regarding storage are porosity and compressibility (change in porosity) of the rock, and the compressibility of the fluids. They are a function of fluid pressure.

The hydrogeologist and the petroleum reservoir engineer both want to know permeability and storage. In addition, the hydrogeologist will probably want to know something about the recharge mechanism of groundwater. Any field testing undertaken by either of these disciplines will focus on examining transient behaviour.

The hydrogeologist will usually want to pump at a constant rate until the transient behaviour of the well can be defined, while the petroleum engineer will frequently use a drill stem test (DST) to produce fluid for a short period, then shut in the production zone and wait until the transient recovery behaviour is well established.

Both disciplines will want to obtain information on their reservoir or aquifer away from the test well. This is accomplished by the use of pressure measurement in surrounding wells, or by suitably designed test methods and analysis.

The Civil and Mining Engineer

The civil engineer, and to some degree the mining engineer, want to know whether water will be a problem for whatever structure they are designing and building. Their concern then is likely to be water make into an excavation, tunnel or mine, or water loss from a dam or through an embankment.

Very frequently they wish to know what the pressure distribution is within the ground, as it directly affects the effective stress, and therefore the potential for failure.

Sometimes the civil or mining engineer will employ a full pumping test with associated pressure observation by piezometers. These cases are however unusual. Time and cost pressures have tended to lead to a series of short term tests that have been historically used. In soils, these are typically falling head or slug tests, in which a hole is filled with water and the rate of change of head and hence volume change within the hole, is monitored for a period.

In rock, the test method is typically the packer test, in which a section of hole is sealed, and water is pumped in at a fixed pressure of one atmosphere as measured at surface, and the rate of inflow is monitored. The final supposedly steady state (10 minute) flow rate is measured in Lugeons (litres/metre/minute), a value that was developed originally to simply determine whether the ground would take cement grout. Neither of these tests can be analysed to produce real values of permeability, and by definition single hole tests cannot provide any information on the storage behaviour of the ground.

Problems with a Falling Head Test

The falling head test produces a varying rate inflow. This causes a problem in separating pressure loss around the well bore, usually associated with drilling, from the response of the soil outside the zone of influence of the well. This problem is made much worse because the process of injection almost invariably carries soil particles into the zone around the well bore, thus changing the near well bore behaviour. This means that it is not generally possible to separate near-well bore pressure (head) loss from the transient response in the ground.

The results of such tests are therefore misleading—if the test is left for long enough to come to stabilisation it can yield information on the groundwater fluid level, and very little else.

Problems with a Packer Test

The civil engineering industry has used packer tests for many years. The basic technique was put forward by Maurice Lugeon (1933). In this, a section of borehole is straddled by packers and water is injected with 1 atmosphere pressure at surface. The hydraulic conductivity is expressed in terms of the Lugeon value, which is empirically defined as the conditions required to achieve a flow rate of 1 litre per minute per metre of test interval under a reference water pressure equal to 1 MPa. If the flow rate is higher the Lugeon value is proportionately higher. The inflow period is normally 10 minutes. This sort of test takes no account of the initial fluid potential (level) in the hole. It also assumes that the flow rapidly becomes steady state and it takes no account of near-well bore effects. These three assumptions mean that the test results are not interpretable in terms of real values of permeability. The method has some use in empirically defining the degree of fracturing in the rock mass being tested, but should not be interpreted beyond this.

The methodology of the packer test is that it should reach a steady state of fluid injection. If in fact it does so, it is an indication that the pressure drop between the rock and the fluid pressure within the hole are dominated by near well bore losses, typically by the size of the joint openings to and adjacent to the borehole. The real information from such tests on the rock mass being tested is lost, because no attempt is made to determine the transient response of the ground. Neither does the test provide information on the fluid pressure (head) within the ground, nor take this into account in how it affects the inflow rate.

Literature abounds on how to interpret such tests, and spurious correlations are published between the value of Lugeons and units of hydraulic conductivity, and by consequence, permeability.

We therefore have two tests that are widely used by the civil engineering industry which cannot provide the information that is required. Indeed, the results obtained are misleading, and their adoption could lead to serious errors in design. What can be done to remedy this?

The short answer is to change test methods.

Improvements to Current Practice

The most effective way to improve matters is to adopt the analogue of the oilfield DST for civil and mining applications. Sigra has used these extensively for the coal seam gas and coal mining clients. We developed equipment and analysis to suit these applications.

The test needs a period of flow followed by zero flow from the test zone, during which pressure stabilisation is achieved. This is followed by an inflow period and then a period of no flow from the test zone, during which the pressure buildup is monitored. This buildup time must be long enough to get a meaningful answer. By focusing measuring on a period without flow, it is possible to remove the effects of pressure drop through a damaged near-well bore area.

Low permeability ground tends to take a lot of time for the pressure recovery to deliver results with a useful measure of permeability. If there is no need to measure permeability down to low levels, then the test may be terminated early without providing a precise value.

While flow from the test zone is the best choice, as it avoids contamination of the well bore with foreign fluids and clay particles, it is sometimes more practical to inject for a period at a constant rate, or by falling head, in the drill string. Changing the flow direction does not change the basis of analysis though changing flow due to particle blockage on the well bore may complicate or invalidate the test.

This test approach may be used in rock or soil.

DST In Rock

The test equipment for conducting a DST test in rock may take several forms. One used by Sigra is its system which enables it to test though an HQ core system. The operation of this is shown in Figure 1, with sequencing described below.

A. The wireline DST tool is lowered through the HQ drill string.
B. The DST tool is shown landed and locked into the core barrel.
    a. A head seal is placed at the top of the drill pipe.
    b. Compressed air is used to push down the water level in the drill string.
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 so inflow can take place.
E. The valve is closed so that a head build up can take place.
F. The packers are deflated and the tool can be pulled out of the hole.

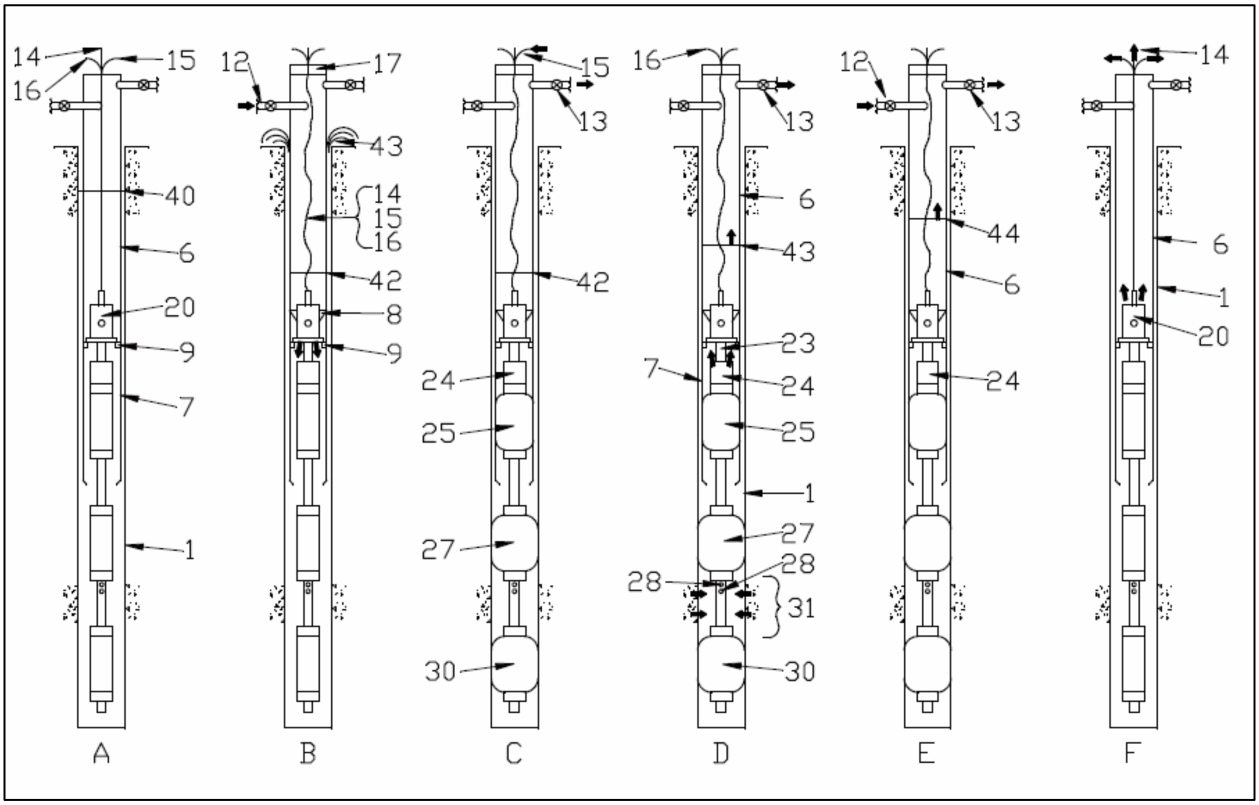

Figure 1. Operation of Sigra's through the string DST tool

Figure 2 shows an example of the inflows and pressures during a DST test. This is a test in a particularly low permeability coal seam. As a consequence there is very little inflow in either of the two inflow periods, and the recovery times after shut in are very long. However, this permitted the detection of very low permeability. What is also apparent is the very rapid rise in pressure in the test zone after the closure of the valve, indicating a very high well bore damage (skin).

Figure 3 shows the derivative of pressure with respect to Agarwal time in this test. The flat area indicates stabilised conditions, when the build up may be used for permeability analysis. This period is the straight portion of the Horner build up plot shown in Figure 4.

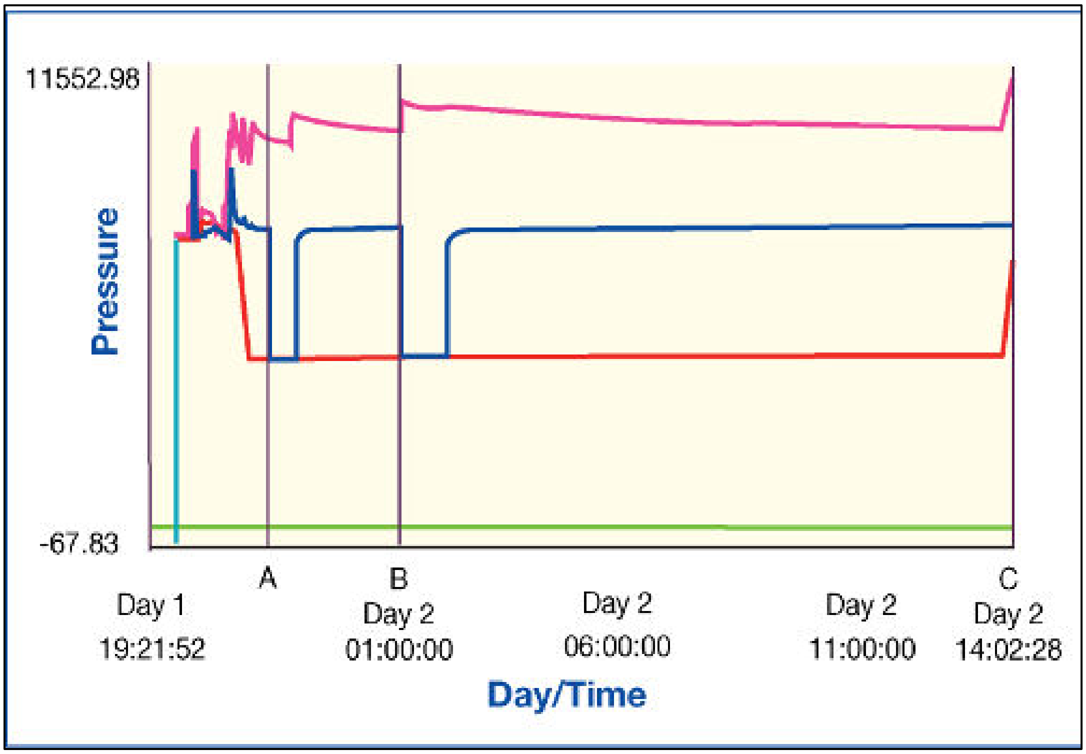

Figure 2. Pressure-time trace for a very long time interval drill stem test. The red trace shows the drill pipe pressure; the blue trace shows the test zone pressure while the pink trace shows the packer pressure. Depending on permeability and storage characteristics of the ground most tests take a few hours.

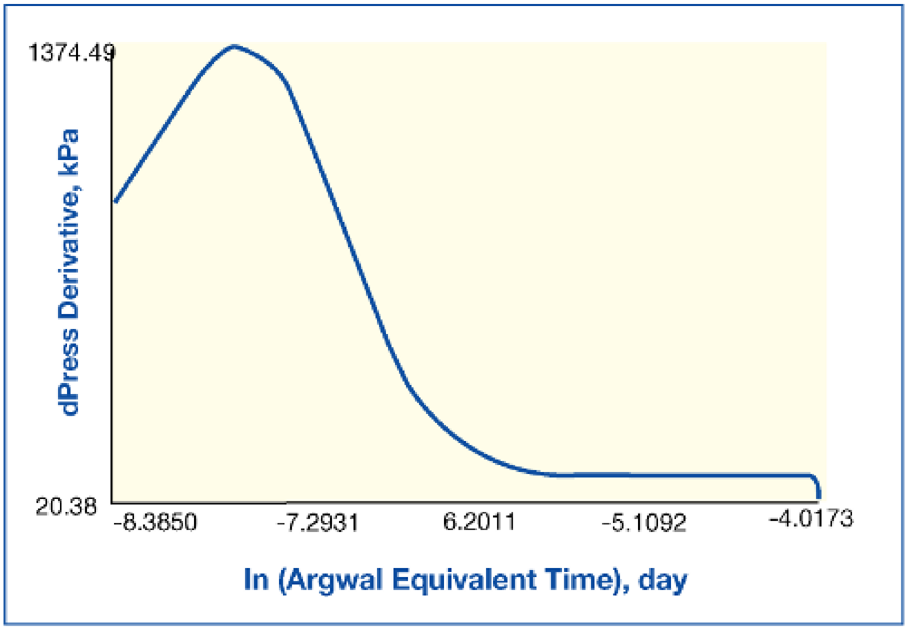

Figure 3. The derivative of pressure with respect to Agarwal time.

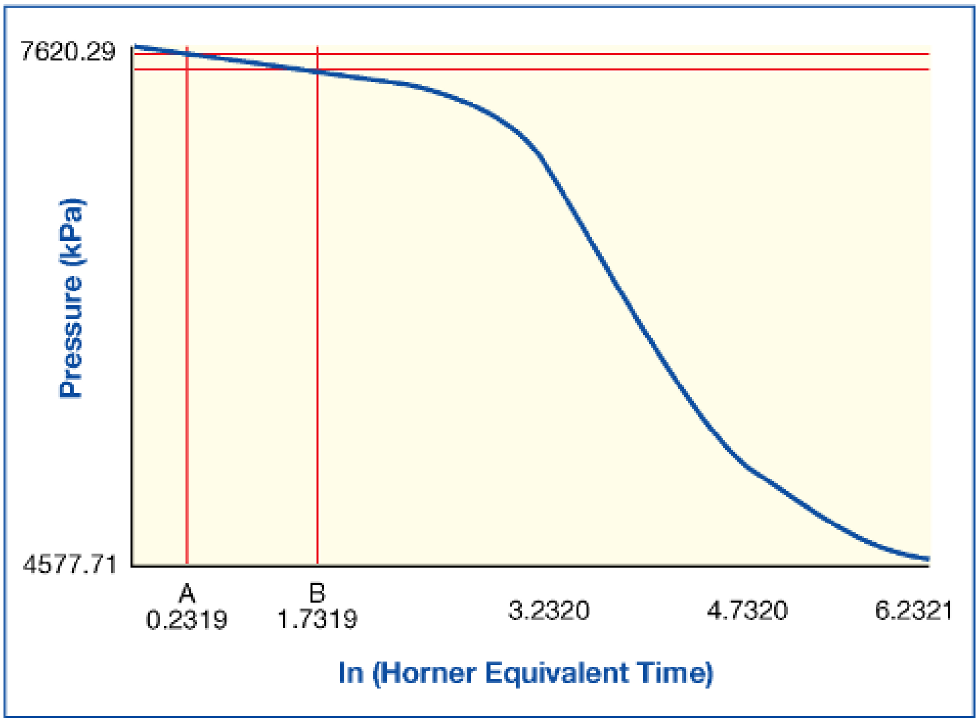

Figure 4. The Horner plot of build up. The analysable straight line section is shown in red. The left hand side of the plot represents the longest time from shut in.

Equation 1 describes the Horner build up plot which has a slope m.

$$p \quad versus \quad \ln(\frac{T+\Delta t}{\Delta t}) \tag{1}$$

Where T is the flowing time
Δt is the time after shut in

Equation 2 is used to derive permeability from the Horner Plot.

$$k = 9.21 \cdot 10^{-10} \frac{q\mu}{mD} \tag{2}$$

Where: k is the permeability in m^2
q is the flow in m^3/day
m is the slope of the Horner plot in kPa per natural log cycle
D is the thickness of the unit being tested
μ is the viscosity ($N \cdot s/m^2$).

In addition to permeability, the reservoir pressure can be determined from the Horner plot. It is obtained from the extrapolation of the pressure to the zero value of $\ln(\frac{T+\Delta t}{\Delta t})$ at the left hand side of the plot in Figure 3. It is also possible to derive a value of the extent of the test. Sigra uses the term *mean effective radius of investigation*. It is important, because too small a zone of investigation may mean that the value of permeability obtained has little relevance. This is particularly the case where the permeability is very low and the well bore damage high. The well bore damage describes the degree to which the near well bore permeability deviates from the general reservoir permeability. The term ‘skin’ is used to define well bore damage. It is given in Equation 3. It may be related to an effective well bore radius through equation 4.

$$P_{loss} = \frac{\mu q S_k}{2\pi k D} \tag{3}$$

Where	P_{loss}	is the wellbore pressure loss
	S_k	is the skin term
	q	is the flow rate
	u	is the fluid viscosity
	k	is the permeability in consistent units
	D	is the test zone thickness

$$r_{we} = r_w e^{-Sk} \tag{4}$$

Where	r_{we}	is the effective well bore radius
	r_w	is the nominal well bore radius

The value of *Sk* can be calculated by examining the difference in well pressure at the end of the flow period from the calculated reservoir pressure. Using the well equation linearised by a log approximation, this takes the form of Equation (5).

$$S_k = \frac{1}{2}\left(\frac{P_{diff}}{m} + 1.722 - \ln\left(\frac{Q}{r_w{}^2 D\varphi c m}\right)\right) \tag{5}$$

Where:	P_{diff}	is the pressure difference between the flowing well and the reservoir pressure
	m	is the slope of the Horner plot in units of pressure per natural log cycle
	Q	is the cumulative flow over the flow period (assuming uniform flow rate)
	$\varphi \cdot c$	is the product of porosity and total compressibility
	r_w	is the wellbore radius
	D	is the test zone thickness

In solving equation 5 an assumption must be made as to the value of the compressibility porosity product, as this cannot be determined from a single test alone.

In addition to determining the value of permeability alone, it is sometimes possible to detect the presence of sealing faults or zones of recharge, by deviations from the normal buildup behaviour.

DST in Soil

It is possible to use a form of DST test in soils also. This is designed to replace the slug test. It involves setting a standpipe and filter in a test formation. The preference here is to have a developed test zone over an entire soil type interval rather than at a point. This forces radial flow. The procedure involves the use of a packer fitted with a pressure transducer and a data logger.

The procedure is then to:

1) Set a packer in the standpipe below the water level
2) Wait for pressure stabilisation
3) Fill the standpipe above the packer
4) Deflate the packer and monitor the water outflow
5) If necessary add water to the standpipe at a known rate to maintain flow
6) Inflate the packer and monitor pressure stabilisation.

In the event of a high groundwater level, water must be pumped. This can be achieved by air lifting through the packer, bailing or using a pump. At the end of production the packer must be sealed within the standpipe to enable recovery.

The use of the packer acts as a valve in the standpipe, removing problems with well bore storage as the water level changes in it. This is a very important feature of the process. The analysis is similar to those described for rock.

DST Test Results - Summary

A drill stem test can be used to provide information on:

- Permeability
- Groundwater head
- A radius of investigation for the test – how much ground is tested.
- Well bore loss behaviour, which may be expressed in terms of an effective well bore diameter – to determine to what extent the test has been dominated by well bore issues.
- An indication of the features of the tested rock, such as boundaries and fractures.

What it cannot do is provide information on the storage characteristics or the anisotropic nature of permeability.

Pumping Tests

Pumping tests involve pumping for a period from a well. Most analysis is undertaken on the basis of constant flow, and deviations from this practice cause complications in the determination of reservoir versus well bore loss behaviour. The exception is a test in which the rate is deliberately increased in steps. The purpose of such a test is to determine the non-linear well bore loss characteristic of the well.

While some pumping tests are conducted in a single well without monitoring piezometers, information may be gained on storage terms (porosity.compressibility product or storativity and specific yield in hydrogeological terminology) by placing piezometers around the pumping well. This constitutes an interference test.

If information is sought on the anisotropy of the ground then three piezometers are the minimum that may be used. These piezometers should not be placed diametrically opposite each other.

The problem with this approach is that it is not possible to differentiate between anisotropy and inhomogeneity. The characteristic of the test is dominated by the single pumping well, and it is always possible to determine a precise solution for anisotropic permeability from the three piezometers. In fact the apparent anisotropy may simply be an artefact of inadequate sampling points in an inhomogeneous formation.

Pulsed DST Testing

By increasing the number of locations from which fluid is withdrawn, it is possible to get more information on the mean permeability. If each of these wells is then fitted with a piezometer, it is then possible to obtain a directional permeability from the subsequent test well to the piezometer. This approach has the advantage that the test programme may be developed as each test is undertaken. This overcomes the normal problem with an interference test, of trying to determine what spacing to place piezometers from the pumping well before the testing has been undertaken. The use of a DST test for fluid withdrawal is convenient, because it may be conducted in slim core holes without the complications of setting up a pumping well.

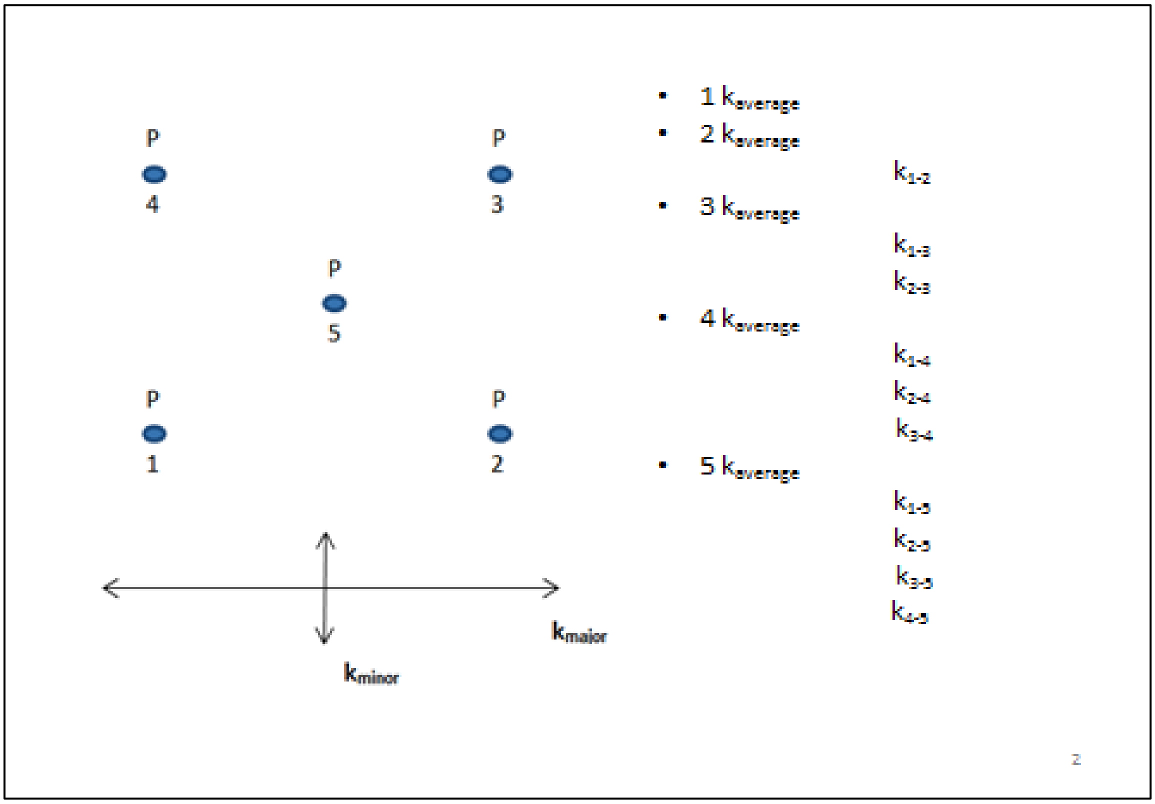

Figure 5. Hypothetical well layout for pulsed DST testing.

A hypothetical well layout is shown in Figure 5. This shows five test wells drilled and tested sequentially, and then each fitted with a piezometer. These produce five measurements of mean permeability and ten measurements of directional permeability. The five wells do not necessarily need to be drilled and tested. The process could be terminated sooner or extended, depending on how much information is required. The spacing of wells is dependent on permeability and storage parameters and is determined as the testing progresses. Figure 6 shows a characteristic DST test in one of the wells while Figure 7 shows the pulse received in an adjacent piezometer. This also shows the best fitted curve between well theory and the experimental data. The fit is very good and provides directional permeability and storage information.

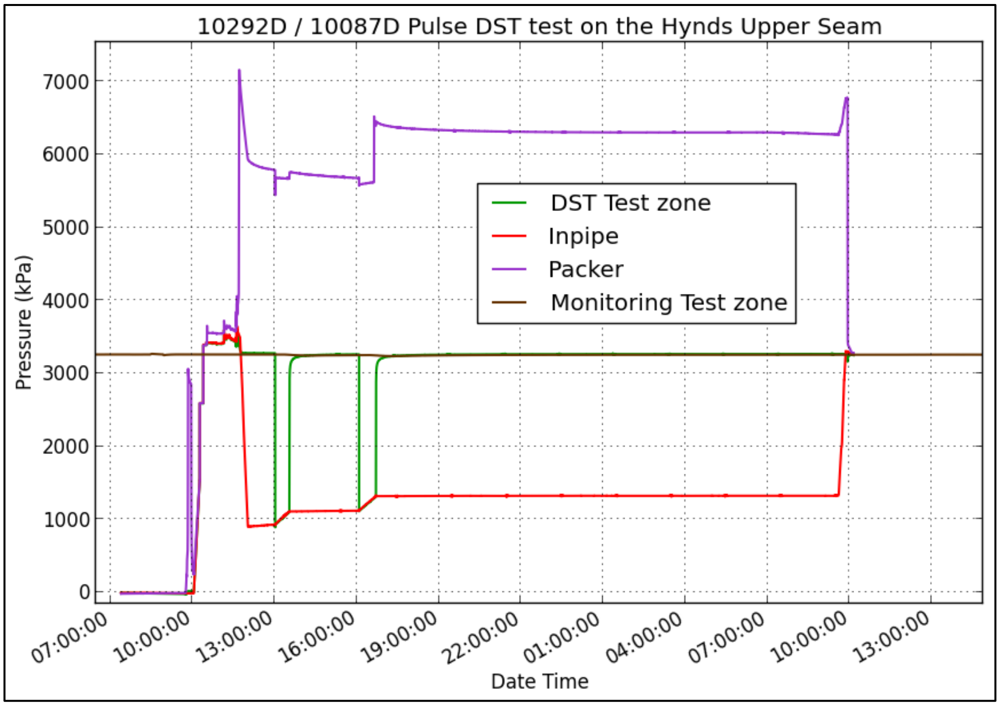

Figure 6. A DST test used as part of pulse testing.

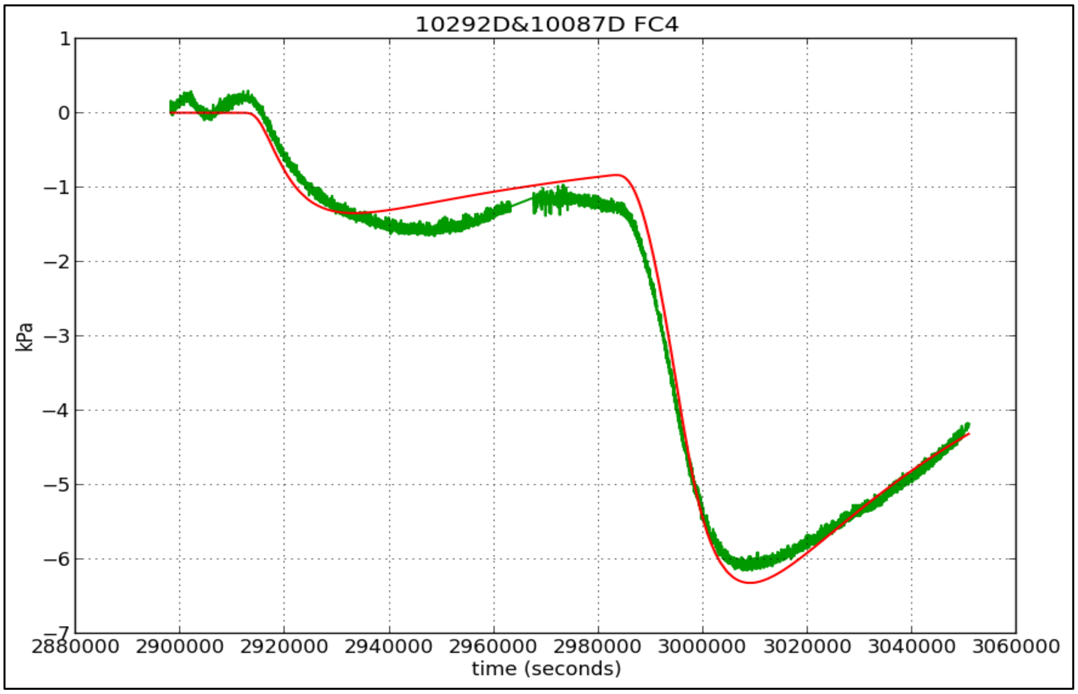

Figure 7. A pressure trace from a piezometer caused by a two inflow DST test.

Pulsed DST testing provides information on:

- Permeability
- Storage, compressibility-porosity product, storativity or specific yield
- Anisotropy
- Inhomogeneity
- Well characteristics, namely well bore loss, effective well bore diameter
- Boundaries to the system, such as recharge or barriers
- Fractures

Piezometers

There is a need to measure fluid pressure in a formation either for testing purposes or simply for long term monitoring. This is more complex than it may first appear, and there are many traps in achieving a good outcome. The keys to good pressure sensing are certainty of what is being measured, and reliability. Certainty can only be achieved if the system can be tested. Reliability comes from good equipment and good installation practice.

The options to install pressure sensors include removable systems and those that are permanently installed. The removable systems are usually packer based and used for installation inside casing that has been perforated to connect it with the formation. While it may be considered that the removable systems are superior because they can be serviced, the cost of doing so is considerable as it requires removing the packer and transducer system from a live well that needs to be kept under control. The cost of this may easily exceed that of the initial installation.

The permanent transducer installations usually involve cementing transducers into the well. As such they rely on communication between the pressure sensing diaphragm of the pressure transducer and the formation to be monitored. To establish this communication the cement used must have some permeability and yet not enough permeability to enable pressure connection between the various formations intersected by the well. These are conflicting requirements.

The process of cementing transducers into a well is further complicated by the filtration of the cement grout mixture into the formation under hydrostatic pressure within the well. This leaves a very dense impermeable mixture next to the formation to be monitored. The consequence of this is that the transducer response may be slowed by some months (Neels and Gray, 2014).

The solution to these problems was the development of cement grouted installations with the displacement of cement from around the filter of the transducer and the borehole wall. It enables the use of low permeability cement grouts that avoid problems with intra-well connection between transducers and permits the transducers to operate in an installation that is independent from the cement grout-formation interaction. It also provides a means by which intra-well connection can be tested and where communication with the formation to be monitored may also be tested.

This type of installation involves the placement of permanent pressure transducers in a borehole. In this application, a cement grout pipe is fitted with pressure transducers, cables and cement displacement lines and then lowered into the borehole. By preference, this is undertaken inside a casing or wireline drill pipe (in this case Boart Longyear HQ pipe of 89 mm OD and 78 mm ID).

This drill pipe is then withdrawn over the grout pipe assembly. The assembly is picked up from what will be a helically buckled form in the hole and hung from the hole collar so as to locate the sensors at the pre-determined positions. This is the situation shown schematically in Figure 8. Here a single transducer is shown hanging in the well with a cable attached. The transducer is connected to a fitting to which a filter is attached. The filter separates the transducer diaphragm from borehole. A pressure pressure relief valve is also attached to the fitting. This pressure relief valve is designed to support the water column above it contained in an injection tube. This injection tube is either nylon or stainless steel depending on the depth and application.

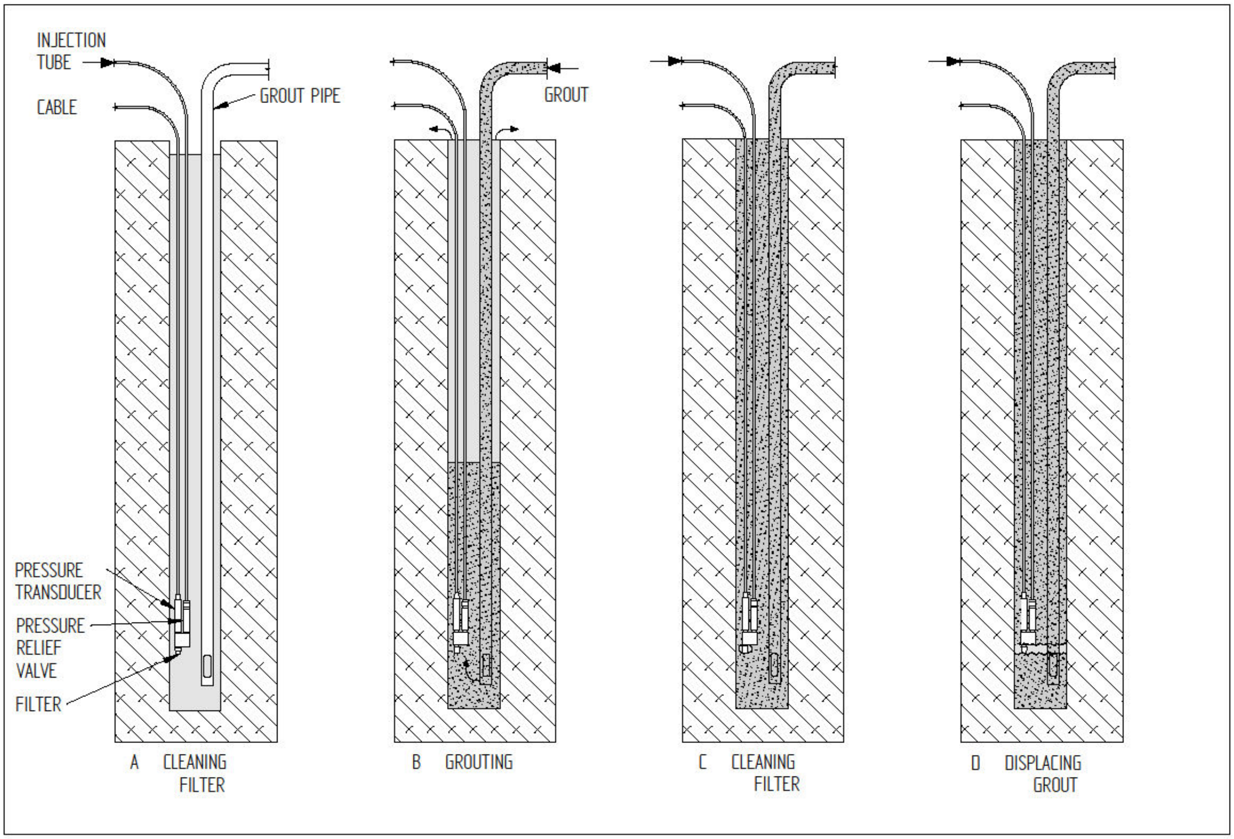

Figure 8. The installation sequence of a pressure transducer by cement displacement.

- Figure 8A shows the operation of pumping water through the injection tubing to clear the filter.
- Figure 8B shows the hole being cement grouted.
- Figure 8C shows the filter being cleaned with a small quantity of water.
- Figure 8D shows the cement grout being displaced by water injection when it has reached a plastic state.

The actual installation process involves installing transducers on tubing containing pockets to protect them. This tubing is of steel, or where mining may take place, it has been replaced by fibreglass. In shallow holes it may be plastic. The transducers are connected by cable to the surface. Each transducer diaphragm is connected to a common chamber with a filter and a pressure relief valve. The that is in turn connected to the surface by the injection tubing.

Case Study of Piezometer Installation

The case study involved a coal seam bearing sub basin in Queensland. A density log of this is shown in Figure 9 for borehole 1 of the group of holes drilled. It shows an upper coal seam (1) at 292 to 297 m and then a group of seams from 356 to 378 m depth. The latter group comprises a main seam (2) from 356 m to 361 m which is separated from seam 3 by a tuff band and then a sequence of interbedded seams and shales. In the latter, seams (4) and (5) are identified. Pressure transducers were installed in seams 1 to 5 by the method described above. Their locations are marked in Figure 9.

Five transducers were installed in the hole as closely as two metres apart. Injection testing through the capillary tubing following the setting of the cement grout, showed no interconnection within the borehole. Decay of pressure took place, indicating connection to the coal seams being monitored. Figure 10 shows the results of pressurisation and pressure decay during this test period. The large pressure spikes and their subsequent decay are caused by pumping into each filter zone. The small responses in adjacent sensors are due to the expansion of the nylon injection tubing in the adjacent filter zone.

The transducers used were vibrating wire devices that are generally used in civil and mining applications. They are extremely stable over very long periods and produce a frequency output that can be read to 1/1000 th of a Hertz in a signal lying between 2000 and 3000 Hz bandwidth. The theoretical sensitivity is therefore 1 in 10^6. Practically the sensitivity achieved was within a bandwidth of 0.04 kPa (0.006psi) in a 10000 kPa transducer, corresponding to 1 in 250000. The accuracy of these devices is really dependent on the quality of calibration. With careful calibration this can reasonably be within 0.05 % of full scale. As they are a fraction of the cost of quartz sensors and provide a digital (frequency) signal, they are a good, cost effective transducer for reservoir monitoring.

This case was for an installation between 290 to 380 m depth. Others have been completed without complications to 600 m and no major problems are foreseen in using the system to greater depths. In deeper installations the nylon can be replaced by stainless steel capillary tubing. The system is subject to patent applications.

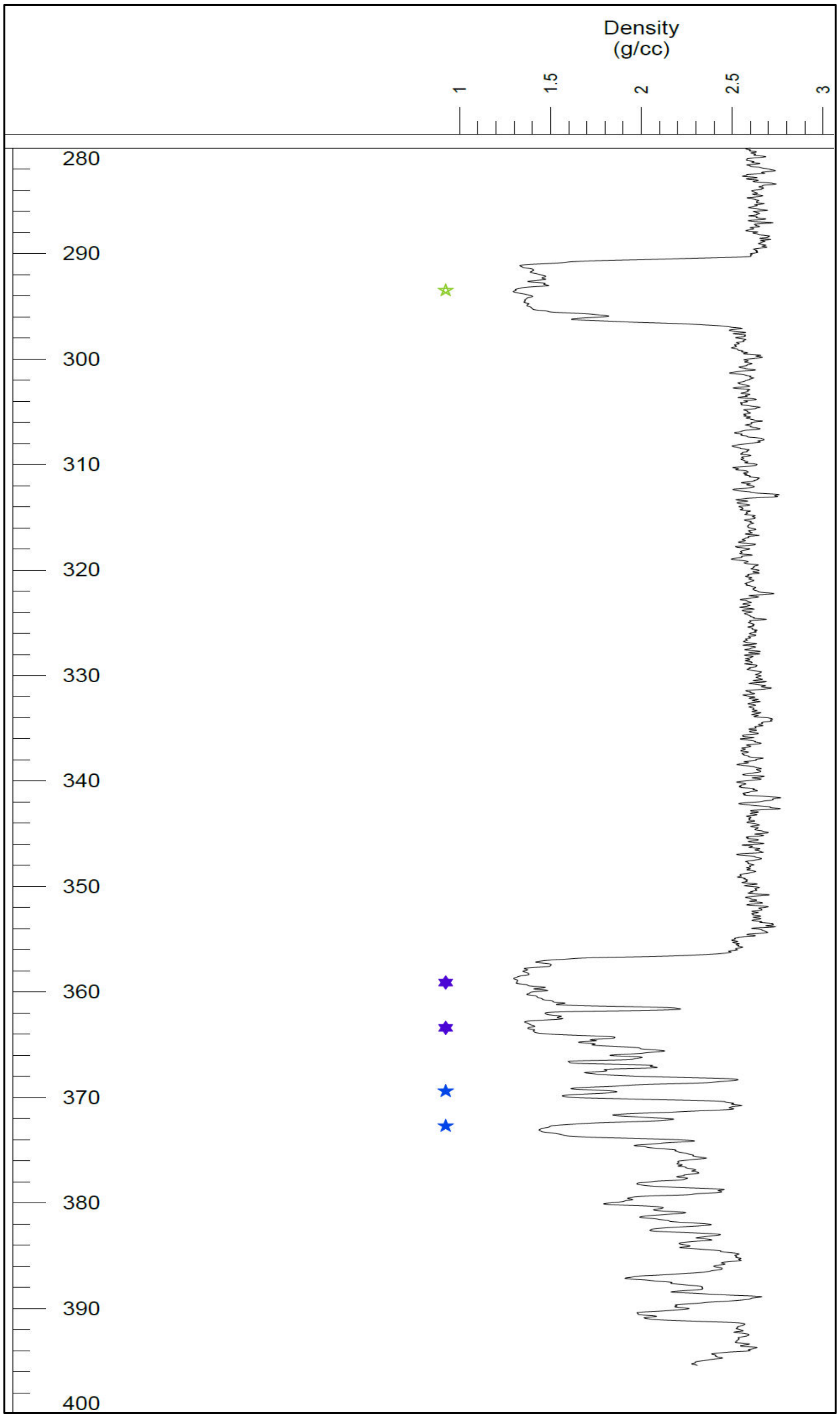

Figure 9. Location of piezometers in coal seams in Borehole 1.

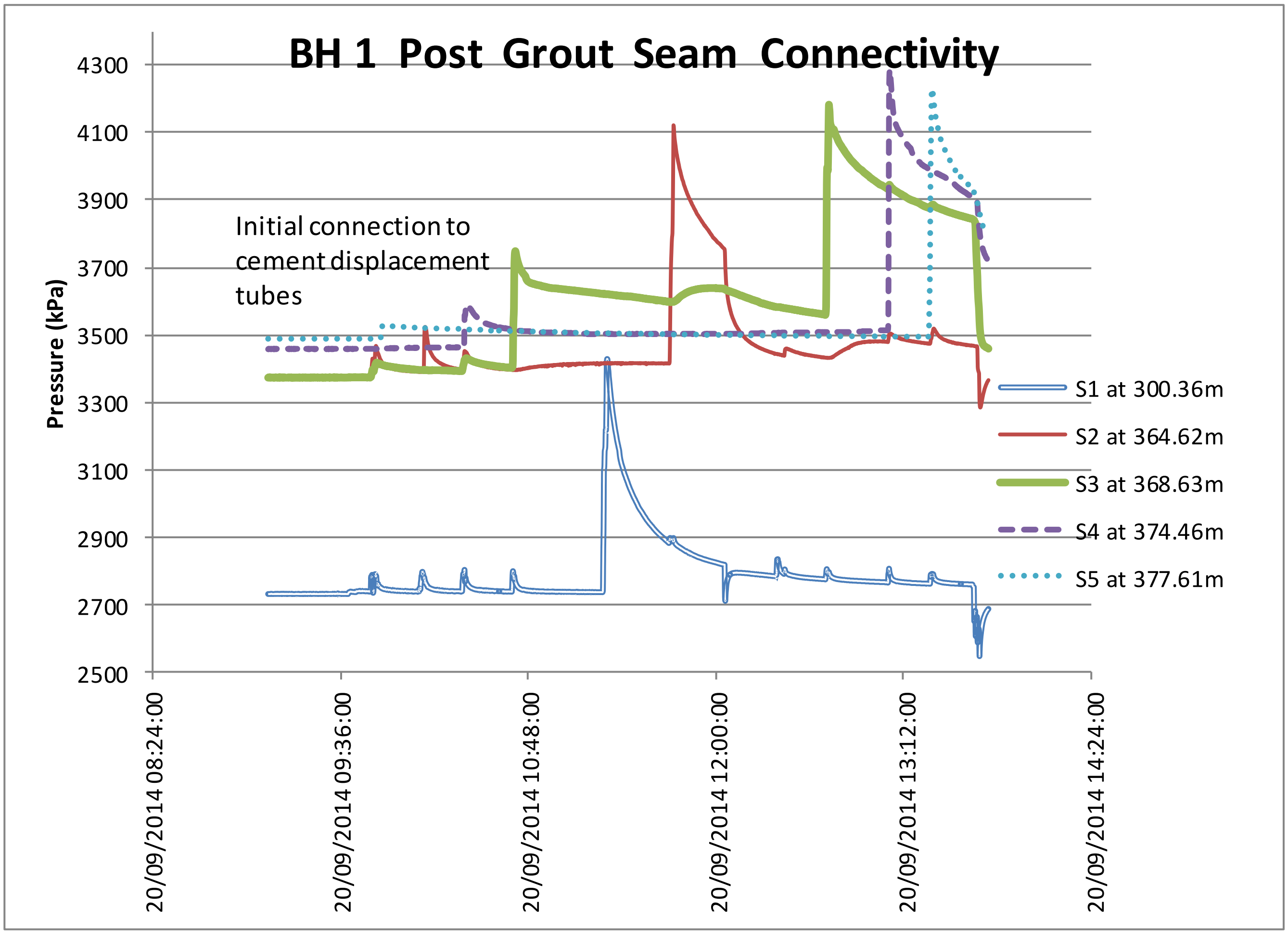

Figure 10. This shows water injection into each seam level and the associated pressure spike and decay.

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Conclusions

This paper examines typical practice to determine groundwater parameters in the civil engineering and mining environment. It compares this with hydrogeological and petroleum engineering practice. The packer tests, falling head or slug tests used in the civil and mining industries are found to deliver incorrect information about permeability due to the test processes and their analysis. The principal problem with these is that they do not deal with well bore damage nor do they properly analyse the transient pressure response from which permeability information may be derived.

The use of a modified petroleum industry Drill Stem Test (DST) is shown to overcome most of the problems associated with these tests, without undue extra complexity. The results are tests which provide a real permeability as opposed to some uncertain measure of near well bore damage brought about by drilling.

The modified DST test provides information on:

- Permeability
- Well bore loss
- Mean effective radius of investigation
- Possible boundaries

However, as a single hole test it does not provide information on:

- Storage terms
- Anisotropy

While the traditional pumping test with surrounding piezometers (interference test) provides information on:

- Storage terms
- Anisotropy

However it does not enable the precise separation between anisotropy and inhomogeneity. Furthermore the risk of an incorrect choice of pump well size and pump type and piezometer locations means that there is a potential for the test to be designed incorrectly.

The pulsed DST test approach suggested in this paper enables information to be gained progressively and economically, while maximizing the information gained and reducing the potential for disasters.

A new method is presented to install piezometers. This overcomes the storage issues associated with standpipes that will delay response to piezometric change. It also overcomes problems associated with pressure transducers that are grouted into a hole and have poor connectivity to the ground or too much intra-hole connectivity. This new installation method is testable by pumping water into the test zone and observing the pressure decay without intra-hole pressure variations.

It should be appreciated by the reader that this paper merely scratches the surface of the subject of well testing and analysis. The object of writing it is not to replace a full study of the subject but rather to overcome current bad practice, and replace it with systems that are not dissimilar in implementation but yield reliable results.

References

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