Comparison of Borehole Testing Techniques and Their Suitability in the Hydrogeological Investigation of Mine Sites

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ABSTRACT

Analytical and numerical groundwater flow models are usually used to estimate groundwater inflows into mines and assess the need for dewatering and/or depressurisation of the rock formations around the mine. These models require various input parameters that have a defining control on the model results and the subsequent design of dewatering and/depressurisation systems. Therefore to increase confidence in model predictions and the efficiency of the mine water management design, it is essential to achieve accurate estimation of the hydraulic parameters.

Hydraulic parameters of geological formations are usually estimated from data obtained from borehole testing. There are five main hydraulic testing techniques commonly used in the hydrogeological investigation of mine sites: (1) Slug tests, (2) Airlift tests, (3) Flow logging (also called spinner tests), (4) Packer tests, and (5) Pumping tests.

In this paper the degree of suitability of the above borehole testing techniques is investigated, taking into consideration the data collection objectives, the expected water management challenges, and project stage. The paper also highlights the advantages and disadvantages of each of these tests, and compares ballpark cost and logistic requirements.

Keywords: Hydrogeology, borehole, hydraulic testing, techniques, mining.

INTRODUCTION

The type of hydraulic testing carried out in mine sites depends on the hydrogeological setting and geotechnical characteristics of the rock formations, and the mine project stage. At an earlier stage of a mine project (often called Scoping Study or Preliminary Economic Assessment), limited hydrogeological data collected from exploration boreholes or from an existing mine can provide enough information for the hydrogeological assessment of the project. However, as the project progresses toward advanced level (Preliminary Feasibility Study, Feasibility Study and Detailed Design Study) site specific data collected from specialist hydrogeological boreholes are necessary. This is particularly more relevant if the results of the initial study suggest significant challenges in the mine groundwater management. The degree of challenge and complexity of the water management aspect of a mine project usually depends on the project location and the hydrogeological and geotechnical setting of the mine, which may entail the followings:

- The proximity of the mine to surface and groundwater reservoirs and the hydraulic properties of the geological formations around the mine will have a significant control on the amount of groundwater inflows into the mine and dewatering requirements;
- The geotechnical and hydraulic parameters of non-aquifer saturated formations around the mine may have direct implication on mine stability and depressurization requirement;
- In cases where groundwater is the only potential water supply source for the project, investigations and borehole testing, possibly for a longer period of time, are required.

To assess the water management risk and challenges that a mine project may face, the hydraulic properties of the geological formations around the mine should be sufficiently investigated. This is usually achieved with the use of well positioned boreholes and testing techniques appropriate for obtaining the vertical and lateral variations of the parameters. The hydraulic parameters often obtained from borehole testing are: hydraulic conductivity (K), transmissivity (T), storativity and specific yield (S and Sy), conductance (C) and leakage coefficient, hydraulic boundaries, and anisotropy of aquifer response.

In this paper we compare five different types of borehole testing, namely: slug tests, airlift tests, flow logging, packer tests; and pumping tests. Other types of test, such as tracer test, exist but these are not widely used in the industry and usually carried out for specific purposes such as the delineation of contaminants and estimation of travel time. Laboratory testing of drill cores and grain size distribution of bulk samples are also sometimes used to estimate hydraulic conductivity when field tests are not possible. Therefore these are not considered in this paper.

Hydraulic test techniques are sometimes combined in one form or another depending on site characteristics and available equipment. For example packer tests can be combined with falling or rising head tests in a way that the target test zone is isolated with the packer and the borehole standpipe is either filled with water or pumped, and water level in the borehole measured subsequently for a certain time to obtain a drawdown-time curve that can be used to estimate the hydraulic parameters of the test zone. Water level in the borehole standpipe can also be kept constant in such configuration and the injection flow measured over time.

DISCUSSION

Slug tests

A slug test consists of displacing a known column of water instantly in a borehole and monitoring the subsequent water level recovery to the initial static state. Since water level recovery can be very fast in permeable formations, the use of a pressure transducer (or water level logger), is more suitable to achieve accurate and frequent measurements of water-level.

An appropriately sized slug should be selected that can produce enough displacement to provide a measureable change in water level. A water level change of 1 to 2m is adequate (Cunningham & Schalk, 2011). In high permeability formations a larger displacement is desirable due to the rapid recovery of water level towards equilibrium conditions.

In open coreholes falling head tests are not suitable because of interference with the unsaturated zone, contrary to rising head tests that can provide reliable results in such case.

Airlift Tests

Airlift testing can be conducted in exploration holes in order to provide an early estimate of permeability. Airlift tests can easily be implemented as part of early resource drilling programmes and are useful for projects where expensive hydrogeology programmes cannot be justified.

The most effective method for completing an airlift test in the early stage of a project is through the use of a drill rig that is equipped with a compressor (usually reverse circulation [RC] or rotary air blast [RAB]). In airlift tests using a drill rig, the drill bit can be removed and a bespoke airlift attachment threaded to the end of the rods. Subsequently air is injected down the drill rods into the hole and the air bubbles rise in the column of water, entraining and lifting water up the rods and out of the discharge hose (Howell, 2012). Careful consideration must be given to compressor capacity and dynamic submergence of the airline. The attachment diverts injected air and incorporates a chamber for a data logger at the base. The water level logger allows accurate measurements of drawdown and the recovery of water level during the test. More dedicated airlift testing outside a drilling programme involves the use of a drop pipe and air injection pipe, a compressor, and water discharge hose. The air flow is usually directed upward and the drop pipe ensures that water is flushed out of the hole with a smooth variation of water level and pressure, which can be measured using water level logger installed outside the drop pipe.

Airlift testing may also be conducted during drilling at pre-determined intervals in order to assess cumulative vertical permeability variations. If there are open holes located nearby then it is possible to monitor water level in these as in observation wells for a conventional pumping test (Beale & Read, 2013).

Spinner tests

Spinner flow logging is a well-documented technique used to determine vertical variation in hydraulic properties of geological formations (Molz et al 1989, Hill 1990, Paillet 1998). A rotating impellor is lowered at a constant low speed down the hole using a geophysical logging winch from which the impeller rotational velocity is measured and converted into a vertical flow profile. The analysis of spinner test data should preferably be completed in combination with caliper logging data (borehole diameter), acoustic televiewer (ATV) survey, and/or geotechnical core logging in order to improve the level of structurally-related interpretation (Pedder & El Idrysy, 2013).

The success of spinner testing is highly dependent on the condition of the hole that is being tested. Newly drilled diamond holes are suitable and commonly used for spinner testing since geotechnical core logging and ATV survey results, if available, yield useful validation data. However, it is imperative that the borehole design and drilling practices and procedures during planning stages take into account the subsequent use of the hole for flowmeter logging. This includes pre-collaring of any unstable overburden, drilling mud management and borehole cleaning/development techniques.

Flowmeter logging can either be conducted under ambient condition (i.e. water level is static; without pumping), or with a simultaneous pumping at a constant debit. The former is referred to in this paper as a static spinner test, and the later as a dynamic spinner test.

Typically, if vertical differences in hydraulic head exist between the geological formations in a borehole, groundwater inflow into the hole will not be uniform under ambient conditions and the flow will preferentially enter at permeable horizons (West & Odling, 2007). Ambient flow can be measured using static spinner tests. Non-detectable ambient flow during the test would suggest uniform hydraulic head or negligible hydraulic gradient. Detectable ambient flow would suggest vertical head differences.

Pumping of the borehole is necessary in order to sufficiently reduce the hydraulic head and induce flow from all permeable horizons. Assuming that the well is pumped with reasonable drawdown, the resulting hydraulic gradients should promote flow from all permeable horizons, with differing contributions based on permeability (Lloyd & Jeffery, 1983). This is an important consideration to ensure that the test result is representative of all permeable horizons. An open borehole with vertical head differences will exhibit a composite groundwater level and the level of drawdown during pumped spinner testing becomes of greater importance in order to draw water from all permeable horizons. The depth of the pump intake should not have a controlling effect on borehole inflows, providing that drawdown is sufficient. Instead of pumping, water injection (constant head/debit) can be used in some circumstances but the application of this method has more disadvantages and limitations.

Since pumping of an open borehole will initially draw water from borehole storage, it is important to achieve an appropriate flow regime prior to running the spinner test. Various authors (West & Odling, 2007; Paillet, 1998; and Molz et al, 1989) have cited that pumping should achieve a pseudo-steady state. This is achieved when all boundaries have been reached and pressure drop becomes proportional to time (Lu & Tiab, 2010, Bourdet, 2002 and Kruseman & De Ridder, 1994). Pseudo-steady state may take a long time to reach, particularly in unconfined aquifers and where multiple boundaries exist. This may be uneconomical when conducting spinner testing in line with other programmes (such as geotechnical drilling).

The outcome of dynamic spinner tests is a vertical profile showing cumulative reductions in inflow contribution. The relative reductions can be proportioned and analysed using established methods to calculate discrete fracture permeability. In numerical groundwater models for mine projects, fractured layers are often represented as “Equivalent Porous Mediums”. Consequently the availability of individual fracture estimates are of limited use. Instead, the test results will feed into a conceptual hydrogeological model to define the numerical model geometry and set-up. Also equivalent hydraulic conductivity for each model layer can be derived by incorporating fractured and non-fractured horizons into the analysis of spinner test results.

Packer Tests

Packer testing involves the use of an inflatable rubber packer to isolate an interval of a borehole for hydraulic testing. To conduct such a test, the packer is lowered down the hole and inflated using water (or compressible gas) that is injected and controlled from the ground surface. The packer tool channels the pumped water flow through a central pipe (the mandrel), which is blocked at one end by a blow-out plug, retained by a shear pin. When inflation pressure exceeds the shear pin rating, the blow out plug is ejected and the flow is directed into the test zone (rock formation), thus shutting down water flow into the packer element. Water is subsequently either injected or withdrawn from the test interval while flow rates and pressures are recorded. Once the injection/withdrawal of water and monitoring is complete the packer is deflated and removed. This process is repeated until the entire borehole is tested in a series of discrete or cumulative tests.

Packer tests can make use of either single or double (straddle) packers. The packer element can be inflated using either water or compressible gas. The former presents the advantage of being capable of testing borehole of much greater depths, and the approach is considered safer. In this paper the discussion relates mainly to water-inflated packer, specifically the Standard Wireline Packer System (SWiPS ®) manufactured by Inflatable Packers International.

Packer tests can be carried out during borehole drilling, whereby once drilling reaches the desired test depth, the drill string is pulled out to a certain level where the packer element needs to be set for the test. Once the test is completed drilling continues until it reaches the next packer designed depth. The next test is normally carried out covering the interval from the depth of the previous test to the current one. The advantage of such techniques is that it provides more accurate data compared to cumulative testing or straddle packer tests because it involves less risk of leakage, and all intervals are tested separately without the risk of masking that may happen if the hydraulic conductivity of the tested formations is low and anisotropic. The disadvantage of this, however, is that it causes delay of the drilling operation and additional cost, which may not be acceptable in some resource drilling programmes.

The alternative to testing while drilling is to test the borehole once the drilling is completed. This type of test requires either the use of double packers to isolate the test intervals or alternatively cumulative testing of the entire depth of the hole. The former presents the advantage of isolating and testing shorter intervals, however this may be time consuming and presents higher risk of leakage from around the double packer seals which translates into errors in the test results. Errors in packer test results related to leakage are especially more significant if the hydraulic conductivity of the tested formations is very low. Another risk involved in the use of double packer is the loss of the equipment due to borehole collapse because the length of the double packer configuration is very long, far beyond the protection of the drill string.

When packer testing is carried out using injection under several pressure steps, the procedure is called Lugeon test (Lugeon, 1933). The pressures used during an injection or Lugeon test must be high enough to force flow into the formation, but low enough to avoid artificially increasing the formation permeability. Lugeon test is the most widely used approach to packer testing, compared to water withdrawal or falling head tests. Lugeon tests have the advantage of being fast; 3-step pressure tests are usually carried out quickly compared to groundwater level recovery time if a withdrawal or falling head test is used. Attention should however be paid to pressure level and rock condition to avoid artificial fracturing, especially in shallow formations.

Pumping Tests

Pumping tests are an important and widely used method for characterising bulk-scale groundwater flow behaviour. Pumping tests usually involve the use of a submersible pump to pump water from a large diameter central well while monitoring groundwater level in the pumped well and nearby observation holes. Observation wells can be located up to hundreds of meters from the test well and should either be drilled or sought from existing exploration holes located nearby. Pumping tests are probably the most widely used hydraulic tests used in hydrogeological investigations and are therefore well known to all hydrogeologists. A full description of procedures is beyond the scope of this paper, so the reader is instead pointed towards literature such as Kruseman & De Ridder (1994) and Brassington (2006). The most commonly varieties of pumping tests are the calibration, step-drawdown test and the constant-rate discharge test.

The aim of the calibration test is to assess what the maximum short-term pumping rate might be, and to define the discharge control valve positions for the step test. Once the calibration test is complete and water levels have recovered, a formal step-test can be carried out.

The step-drawdown test is important to determine an appropriate pumping rate for the subsequent constant-rate test. It is equally important in order to account for head losses, the latter consisting of aquifer, linear and non-linear head losses (Rorabaugh, 1953, Jacob, 1947). Linear well losses are the most preventable and can be caused by the development of a well skin. A positive well skin may consist of drilling mud invading the formation that results in a low K skin. Conversely, negative skin can consist of a high K zone around the borehole, essentially caused by inadvertent hydraulic "fracking" due to poor drilling practices. If head losses are not properly accounted for, analysing the pumping test data may result in serious overestimation of S and underestimation of T (Agarwal et al, 1970; Jargon, 1976). The implications for mining projects might mean underestimated mine inflow estimates, which would lead to an under-designed dewatering system. It is therefore essential to design the constant-rate pumping test in conjunction with the step-test analysis. Once head losses have been calculated, the well performance can be expressed as a well efficiency percentage (Kruseman & De Ridder, 1994).

The constant-rate test should be carried out at the maximum sustainable pumping rate defined from the step-test results. The purpose of the constant-rate test is to obtain information on the hydraulic characteristics within the radius of influence of the pumping well (Beale and Read, 2013).

Criteria for Selecting a Hydraulic Technique

A guideline transmissivity range for selecting a hydraulic technique is proposed in Figure 1. These are based on the authors' test results and experience and input from various literature as shown in the list of references. The transmissivity is the criterion used in this paper since this parameter is more directly relatable to the overall capacity of a well, whereas the hydraulic conductivity alone is not enough.

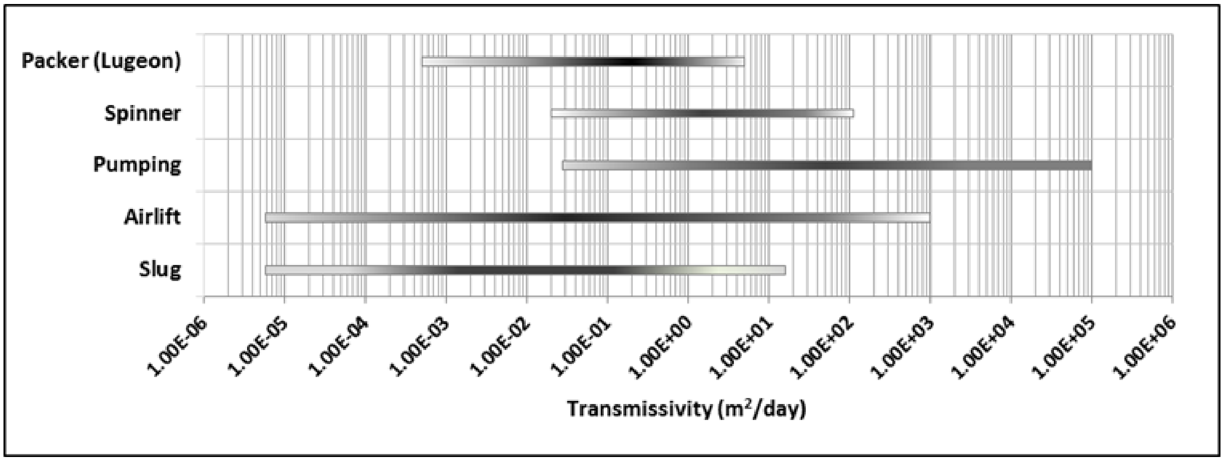

Figure 1: Approximate transmissivity range for the 5 hydraulic testing techniques

Hydrogeological investigations, and especially borehole testing, should be designed taking into consideration two criteria:

- The hydrogeological setting of the project and available logistics and resources;
- The level of confidence required in the mining study (PFS, FS, etc.). Usually each stage of mine development requires a certain level of design and justifies a commensurate investment.

Slug tests can be applied in a wide range of transmissivities, including very low permeability formations. Slug testing is limited to holes that are not highly transmissive due to rapid return of displacement towards original water level. This test becomes more reliable with decreasing permeability, however practical considerations (such as test time, seasonal impacts, etc.) may become relevant where measurement of displacement takes weeks or maybe months.

Airlift can be effective for a wide range of permeability conditions making this a very flexible test. Studies have shown (Howell, 2013) that conventional pumping test analysis of airlift tests that have produced less than approximately 0.1-0.2 L/s may result in unreliable estimation of permeability. Where airlift tests produce such yields they should be stopped early and the recovery data analysed as a rising-head test (e.g. Hvorslev, 1951).

Packer testing is applicable in a smaller range of transmissivity, from low to moderate. Previous packer testing programmes carried out by SRK in HQ boreholes suggest an upper limit of 3 m^2/d of transmissivity for packer testing results to be reliable. The results also suggest that packer testing can detect inflows for a transmissivity as low as 0.0005 m^2/d if the packer seal is placed within a non-fractured fresh rock section of the hole where the packer seal is effective to prevent leakage. It is less reliable at very low permeability because the accuracy of the data can be compromised by minor packer leaks, flow measurement, residual drill muds. The upper-limit is typically constrained by the maximum capacity of the packer equipment (pumps, compressor, etc.) and/or bore diameter.

Spinner tests can however be carried out in slightly larger range spreading especially toward the relatively higher transmissivities. The minimum start-up velocity of the spinner (velocity of water required) will vary depending on manufacturer and should be considered carefully. From the authors' experience, spinner testing has yielded inconclusive results where the transmissivity of a tested formation is less than approximately 0.02m²/d.

Pumping tests can be used to test highly transmissive mediums, and the upper limit would depend only on the size of the submersible pump available and borehole diameters which is controlled by the available drill rigs capacity.

At the early stages of a mine project, hydrogeological investigations should attempt to utilise boreholes from resources drilling programmes and any existing historical drill holes. Rising head tests in such old boreholes may provide a coarse assessment of the hydraulic conductivity around the boreholes, although the results may be questionable. In newly drilled and cleaned boreholes with appropriate bentonite seal for the test zone, slug tests can provide useful data. Airlift testing may also be implemented very early in a project to test existing drill holes where the range in permeability is poorly understood. As part of exploration programmes, drill rigs often have the capacity to carry out airlift tests.

If it is necessary to characterise fracture flow or vertical variances in primary porosity, spinner tests may be considered. However, spinner tests are often not necessary at the early stages of the project, but rather at PFS or FS levels. Packer tests may be integrated into existing drilling programmes in consolidated and fractured rock. It is also important to consider the condition of the drill hole (packer seating) and experience of the driller.

Pumping tests provide the most reliable estimates of aquifer properties where groundwater management represents a high-risk to the project, and the required accuracy of the hydrogeological investigations has the potential to significantly affect the project engineering feasibility or economics. Given the associated high costs and required amount of resources, the justification for pumping tests should be based on existing data derived from integrated and retrospective programmes. Pumping tests are carried out in most of mining projects at PFS or FS stages, regardless of the level of risk of groundwater management. In fractured rock, when the control of groundwater is required, spinner or packer tests should be specified instead to define the vertical variation of rock mass and assess the dewatering requirement.

Cost and Logistical Comparison

The shipping of testing equipment into a project country requires consideration of cost, customs documentation (both departure and destination country) and insurance. Comparisons of these considerations are shown in Table 1. For simple hydrogeological tests (slug testing) there is no major cost or logistical issues. However, shipping equipment that is made up of numerous components (e.g. spinner, packer and pumping) increases the complexity of the process and can add significant time and cost. Therefore, the requirement for these tests needs to be considered carefully within the context of the investigation objectives in order to provide adequate justification for its use. Alternatively, good quality contractors should first be sought in-country where possible.

Table 1: Estimated Cost and Logistical Comparison of Common Tests

Test Equipment	Equipment Capital Cost (GBP)	Annual Maintenance Cost (GBP)	Shipping Cost (GBP)	Shipping Preparation Time
Slug	50 - 200	n/a	50-150	1 hour

Spinner	10,000 – 15,000	250 – 1,000	1,000 – 4,000	1-3 days
Packer	20,000 – 50,000		1000 – 8,000	
Pumping	8,000 – 20,000		1,000 – 6,000	

Advantages and disadvantages

Table 2: Advantages and disadvantages of various hydrogeological tests

Method	Advantages	Disadvantages
Slug Tests	-Quick and inexpensive. -Good for early-stage projects. -Good where permeability is low to moderate. -Can be used in polluted water wells because abstraction is not necessary -Very simple logistics and low cost -Maybe the only test suitable underneath a flowing-river bed to estimate conductance. -The stability of the borehole is not a problem.	-Less reliable where permeability is very high. -Less reliable than all other tests. -Only tests immediate area around the hole. -Sensitive to near-well conditions (low K skin, gravel pack, etc.) -No storage estimate. -Falling head test is not suitable for testing unconfined aquifers in open hole. The unsaturated zone requires bentonite seal.
Airlift Testing	-Cost-effective, if no significant rig standby time. -Good for early-stage projects and exploration hole testing. -Easily incorporated into existing drill programmes. -Covers wide permeability range. -Can use observation wells to estimate S and increase radius of characterisation.	-Less reliable than other tests. -Not good in polluted water due to abstraction -Becomes time-consuming at very low permeability where rig time is at a premium. -May cause erosion of borehole walls and cavitation in some circumstances. -The debit may not be stable enough to assume steady state condition for data analysis.
Spinner Tests	-Good for hydrogeological characterisation of bedrock fractures. -Provides vertical variation of hydraulic properties and accurate depth of flowing fractures (±10cm). -Can be easily compared with geotechnical, structural and geophysical data. -Static test can reveal natural flow between aquifers due to vertical hydraulic gradient. -Can be completed without a drill rig. -Can be easily combined with other downhole tools such as salinity, temperature or other surveys.	-Requires a clean, open hole at the test interval. -May require significant drawdown if large vertical head differences exist. -Risk of equipment loss due to hole collapse. -Not suitable for very low permeability formations. -Requires specialised equipment that may not exist in all countries. -To quantify the hydraulic conductivity in the tested borehole, spinner test results are not sufficient; a small scale pumping test is required in parallel with the spinner tests.

Method	Advantages	Disadvantages
Packer Tests	-Can easily be incorporated into existing drill programmes. -Can provide hydraulic input parameters readily incorporable into groundwater models. -Provides approximate location of groundwater flow zones, especially in fractured rock formations. -Can be carried out in vertical or inclined boreholes even in angles as low as 50 degree. -The test can be carried out in various small diameter holes (PQ, HQ or even NQ sizes). The packer equipment comes in various sizes to fit into specific borehole sizes.	-Experience is critical. -Unreliable in non-diamond holes (RC, rotary, etc.) due to potential poor packer seating risk. -Typically requires a wireline drill rig. -Not suitable in very high or very low permeability formations. -Require specialised equipment that may not exist in all countries. -Leakage around the packer can cause false interpretation of the test results. -Requires a relatively clean borehole. -In shallow, soft formations packer tests may induce hydrofracturing or hydro-jacking.
Pumping Tests	-Provide accurate and reliable estimations of more hydraulic parameters. -Wider aerial characterisation. -Many hydraulic parameters can be estimated (e.g. T,S, Sy, Kz/Kr, etc...). -Diagnose borehole efficiency. -Suitable to identify boundaries and flow regimes. -Comprehensive literature. -Tests can locally mimic dewatering operation. -Test wells can be used for dewatering and monitoring water level and quality.	-Time consuming and can be expensive. -Typically involves drilling of large diameter pumping wells and observation holes. -May not be suitable in polluted groundwater due to potential discharge permit. -Require more human resources and logistics than all other tests. -Not suitable in low permeability media, as low rate pumps may not be available. -Pumping tests are not suitable in fully open or steeply inclined boreholes.

CONCLUSIONS

Five hydraulic testing methods of boreholes for mine studies have been discussed in the present paper. A brief definition of each type of test has been presented, and their limitation and suitability discussed. Also the advantages and disadvantages of each of the tests have been highlighted. The material presented in this paper is mainly based on existing literature and the authors' work carried out using such techniques in various types of environments and hydrogeological settings.

At early stages of a mine study, slug tests and airlift tests are widely used; because these are simple and cheap and yet provide preliminary assessment of the hydraulic parameters of the rock formations around the mine. Further specialised testing is usually designed based on the results of these early stage testings and groundwater monitoring. At advanced feasibility studies pumping tests are usually carried out. Although such tests may be the most expensive option, they are usually carried out in most mine projects because they provide more representative values of the hydraulic parameters. Pumping tests usually require the use of contractors, but the availability of pumps and pipes in almost every country, however, justifies their use.

In projects where the vertical variation of the hydraulic parameters is predominant and the risk of groundwater inflow management is high, characterisation of the vertical profile of the hydraulic parameters is required. Pumping tests cannot provide such results, unless a very expensive investigation programme involving drilling many boreholes in various geological horizons is carried out. The alternative methods to pumping tests in this environment are the use of packer testing or flowmeter logging. The former can provide readily usable parameters for groundwater models if the tests are designed for such purpose. Spinner tests provide continuous profile of the hydraulic parameters thus accurately depicting the depths of open fractures and flow zones. The results of spinner tests however can be quantified for use in groundwater model only if a pumping test is carried out in the tested hole. Spinner tests and especially packer tests can be carried out in inclined and/or very deep boreholes. However, hole collapse and loss of equipment remain a major risk in packer testing and flowmeter logging. Also borehole cleaning is required prior to these tests to obtain more meaningful results.

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