Looking Deeper: Key Considerations for Planning Mining Hydrogeology Investigations using Deep Boreholes

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Abstract

Hydrogeological investigations of the deep subsurface are becoming an integral part of mine design and development alongside the geological, geophysical, and geotechnical investigation programmes. Data obtained from these site and depth specific investigations improve hydrogeological characterisation, resulting in reduced project risk and uncertainty.

Deep hydrogeological investigations using deep boreholes (>500 m depth) require specialised planning, services and equipment, and testing procedures. This paper aims to present key considerations when planning and executing deep borehole-based hydrogeology investigations, drawing on experience across three different continents, to aid practitioners planning for similar programmes on mining projects.

Keywords: Deep Mining, Hydrogeology Testing, Packer Testing

Introduction

The majority of underground mining developments are positioned below the water table and require hydrogeological characterisation to support studies of feasibility, mine design planning and assess impacts of the mine development on the environment. In most cases, the hydrogeological characterisation below 500 m depth will be aided by investigations using small diameter drillholes. Given the cost of drilling, hydrogeological investigations are often conducted in multi-purpose boreholes which are drilled for the primary purpose of collecting geological and geotechnical data. The borehole depth, diameter, and selected testing method poses challenges that require specialised resources. This paper highlights some of the key considerations in relation to hydrogeological investigations in deep boreholes.

Transmissivity and Beyond

The primary aim of most deep mining hydrogeological investigation is characterisation of hydraulic properties of the hydrostratigraphic units present in the area of the mine development. Improving the quality of the available data allows better understanding of potential mine inflows and hydraulic gradients and reduces the risk and uncertainty associated with the basis of mine design. Information on the nature of the flow regime and groundwater chemistry also provides support to the construction design including grouting, stability of the underground workings, and trade-off studies.

The data collected as part of these investigations are also required for costing studies, baseline definitions and environmental assessments, and water disposal and water treatment studies. Improving the data quality in mining hydrogeology investigations in deep boreholes should allow improved confidence and a wider application to studies in support of the mining development.

Perils of the Deep –Downhole Environment and Equipment Selection

Challenges of deep borehole testing are generally similar to those that can occur with shallower testing, but the risks are magnified by the depth. Common challenges are related to the potential variability of conditions along the depth of the borehole so an array of test stages should be considered.

Technical challenges stem from the selection of the suitable equipment to allow collection of defensible data from the deep intervals. At deeper depths, hydraulic testing equipment becomes more feasible (and safer) to use over pneumatic equipment because it does not have to overcome the hydrostatic pressure at depth prior to inflation. This approach however means that the methods to apply and deliver the inflation pressure and to create a pressure differential for testing are often shared and requires more complicated equipment that employs a series of mechanical and or pressure actuated valves to allow and maintain packer inflation. Equipment for deep hydrogeological testing can therefore be quite different in their design and operation compared to typical gas operated borehole testing systems generally used for shallow hydrogeological testing with which operators may be more familiar.

For most mine hydrogeology investigations real-time data monitoring from the test interval is not feasible, and autonomous pressure data collection is utilised instead. Inability to directly observe the pressure response during the test introduces risks around the test progression (e.g., the test may not be progressed long enough to observe static conditions), as well as potential for loss of data in the event of logger failure. To mitigate these risks, real-time data are often collected, simultaneously with the downhole memory gauge, from the upper part of the water column inside the test tubing (above the test interval), however the utility of this approach is limited by the equipment and testing methodology used. This secondary shallower real-time data monitoring cannot be easily implemented within a sealed or pressurised system and will not reflect the formation response if the test interval is isolated using a down hole shut-in valve. Testing using a downhole shut-in valve that isolates the test interval from the test tubing is of particular value in low permeability formations which are commonly encountered in deep investigations.

Planning - the Key Stage of Investigation

Detailed planning of the hydrogeological investigation can and should occur during all stages of the ground investigation programme. Input to planning prior to the programme commencing is of key importance. The planning stage should include input from specialists to ensure that proper testing methodology and equipment is selected. This will avoid informal design based on existing familiarity with a general technique or type of equipment used previously which may not be fully appropriate for the current planned investigation.

The application of generic testing designs can be inappropriate for all types of investigations, however deep investigations in hard rock mining developments tend to be viewed generically as low flow, with a low risk of fracture flow/ enhanced zones of permeability and therefore planning activities may not consider potential variability in downhole conditions.

Investigations for mine development in deep sedimentary environments like coal and salt or in “high flow” environments like karst, fault zones or zones of enhanced permeability inherently have water placed higher in the risk view of project stakeholders. These projects may engage larger drilling rigs, and well control and mud engineers, with an expectation to demonstrate and quantify higher flow conditions and challenges may arise with constraints around fluids and stability. The stakeholders on these projects generally have background that reflects experience based on hydrocarbon exploration, not groundwater. These experiences can be very helpful and knowledge exchange between the disciplines

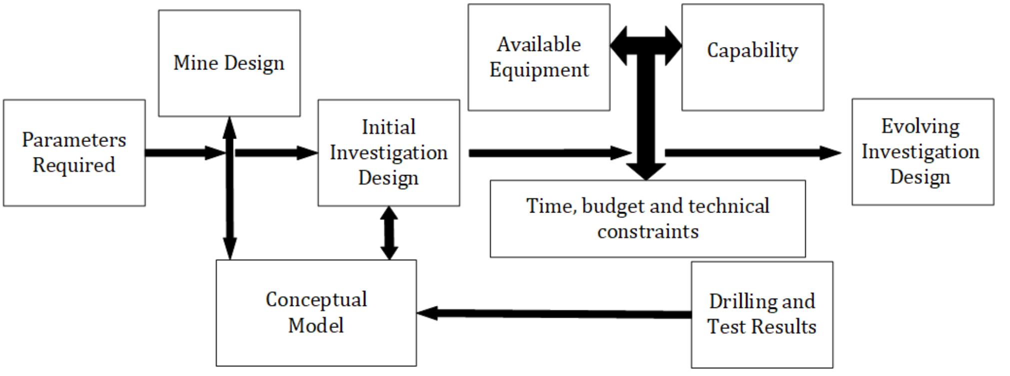

***Figure 1** Considerations at planning stage.*

should be encouraged, however there are some unique considerations related to test work in deep multi-purpose mining boreholes and oil and gas investigations. It should be noted that although some equipment manufacturers supply both sectors there is less crossover within professional practitioners. Some mining practitioners have experience in the nuclear repository sector; these experiences are also very valuable.

The considerations at the first phase of planning are inter-related and can be summarised in a flow chart (fig. 1).

Designing and Planning Deep Hydrogeologic Investigations with Constraints

The design of ground investigations will naturally consider the hydrogeological conceptual model, known ground conditions, the proposed mine design, and the design parameters that the investigation is required to obtain. It is rare for a mining hydrogeological investigation to be considered the primary aim of a deep drilling programme. Hydrogeological investigations will be in most cases viewed as an add-on to the geological and geotechnical investigations. Time required for hydrogeological tests during drilling is seen as drilling downtime because the borehole is not being advanced during these periods so hydrogeological testing activities are often constrained by the need to minimise drill rig down time and to avoid borehole destabilisation or collapse during testing activities.

Testing challenges can be considered in two broad categories: budgetary and time related; and technical and capability related.

An example of budgetary constraints may be a limit to the amount of time the exploration program can set aside for hydrogeological data collection or similarly the amount of time that is available to meet a project milestone. An example of a technical constraint may be the permitted volume of water that can be discharged or a limit to the local workforce capability. Hydrogeological investigations in deep boreholes uses complex equipment and should be supervised by an experienced testing engineer and supported by a drilling crew to convey the tool and support the testing. Complex programmes may require simplification, supervision and training. Ultimately the majority of ways to address issues related to technical or capability constraints have budgetary and time implications. A summary of key testing considerations are listed here:

Budgetary or time related considerations:

1. Equipment outlay and level of expense afforded to specialised testing and monitoring equipment including narrow diameter equipment suitable for use at the pressures expected in the deep subsurface and automated data collection equipment. The nature of deep drilling and conveying specialised equipment to depth also increases the risk of tool loss which can add cost to the programme.
2. The cost of drill rig down time needed to conduct the hydrogeological testing

may be constrained. Drilling contracts often included charges related to testing time and time for testing also means the advancement will be delayed. There are often set associated costs related to length of drilling programmes, e.g., personnel fees, camp charges, fuel.

3. Hydrogeological testing adds time to a geological/geotechnical drilling programme. Extension of the drilling programme to accommodate hydrogeological testing activities may have to be balanced with the effect on project milestones.
4. Scheduled time for hydrogeological tests may be constrained by factors such as the need to circulate fluid to stabilise the unsupported borehole (or control gas in the case of deep coal deposits). When estimating the duration of the individual tests, it is important to consider all of the following: time to flush the drilling fluids from the borehole prior to testing; time to pull rods and convey the equipment to position in the borehole (time increases with depth); time required to observe the test response (this may be long in low permeability formations or may have to include an allowance if real time instrumentation is not available); time for proper test preparation and potential repeat stages or extensions. Inadequate borehole preparation and tests being terminated too early due to time pressures are factors that can have a direct effect on test reliability and data quality.

Technical or capability related:

1. Consideration of drilling fluids: Drilling fluids containing muds, other additives, or brine may be required during drilling to maintain borehole stability, control gasses or to avoid dissolution of the formation around the borehole (in the case of salts/evaporites). These fluids can have an effect on observed hydraulic response of the formation if they clog the pores and features in the vicinity of the borehole. Dense fluids can also have an effect on interpretation of the test results if the analysis is done assuming the pressure responses were those of pure water. Ideally drilling fluids should be flushed from the borehole prior to testing activities however this may not be practical.
2. Drilling grease and rod vibration: Large amounts of drilling grease are often used to reduce drill rod vibration in areas where there is a deep water table. This should be noted during drilling activities as it can have an effect on hydrogeologic testing.
3. Test design: If it is suspected that drilling fluids or drilling grease have locally lowered the permeability around the borehole or clogged the borehole wall, a testing methodology that allows fluid to move into the borehole from the formation (i.e., rising head or constant rate pumping test versus falling head or injection testing) should be selected. Fluid moving from the formation into the borehole could be expected to be less influenced by these effects. This type of testing is challenging in narrow diameter drillholes and where groundwater levels are deep and specialised equipment (and capacity to operate it) may be required. Additionally, there may be practical or permitted limits on the volume of fluids that can be abstracted or discharged.
4. Need for high pressure equipment: Some inflatable packer systems for deep well testing require higher pressures to be delivered to the system to operate it and an associated higher degree of control and measurement. These systems require high pressure pumps, gauges, and controls and therefore additional training in the use of this equipment. There may be a desire for wireline deployed (versus tubing conveyed) investigation equipment to speed up the testing time; but this can limit the equipment selection and maximum depth of deployment.
5. Low permeability conditions: Testing in low permeability conditions can be complicated as formation responses take longer to observe. The use of a down hole shut-in valve is recommended when testing in lower permeability formations to accelerate the observed response. Downhole valves can be difficult to operate successfully, and leakage of equipment valves can be misinterpreted as formation response.

6. Support and direction of inexperienced mine site staff and contractors: Most hydrogeological investigations involve the use of drilling contractors and inexperienced site staff to support the investigation therefore direction, supervision, and training will be required. Most contractors will have previous experience, sometimes this experience will be based on a standard method and/or operation guided by the manufacturer. Whilst this is useful, adherence to the investigation design will need to be checked as it is common for a habit to be developed of going through the motions of a test without paying attention to the test data being collected resulting in poor investigation outcomes.

Additional Challenges and Considerations

The above discussion confirms that collecting hydrogeological data from deep boreholes is challenging. The challenges vary with each specific investigation but there are some common aspects to most deep investigations; these include the following: borehole preparation requirements; advantages of planning testing activities over day shift; focusing on local/relevant variations to hydrogeologic condition over longer borehole lengths; test stages and optimisation; and test analysis.

Borehole Preparation

Borehole preparation prior to hydrogeologic testing is key to the success of the testing activities. Flushing of the borehole to reduce the influence of drilling muds, fluids and additives is required. This must be done in conjunction and discussed in advance with the drilling contractor, mud engineer and client representative. In some cases, there may be a trade-off between borehole cleaning and borehole stability. Also, the flushing is often inadequate, being shortened to save time and may unduly influence the test results. The risk can be managed by good record keeping and monitoring of volumes, density and viscosity of drilling and testing fluids. In a similar manner, static water levels corresponding to each test interval are required, but the period of time required to obtain the static levels is neglected.

The Day Shift Advantage

Most drilling investigations will make use of day and night shift work. The quality of work is often best during the day shift. As such there are benefits to timing the more active stages of the hydrogeological test to be carried out during the day shift and using night shift for less active parts of the test sequence like recovery stages.

Focus on Local/Relevant Hydrogeologic Variations

Many underground mine developments can involve boreholes of more than 1,000 m and some of these will intercept long sections of formation that would appear to be homogenous. As such there can be tendency to use test intervals at the scale of hundreds of metres, but this approach can overlook and mask local variations in hydraulic properties.

Test Stages and Optimisations

Testing should be progressed through several individual test stages to be flexible and adaptable to conditions encountered and to optimise data collection. An example of adaptation is to observe the response to initial test stages and extend the recovery time so that equilibrium or pressure recovery is achieved and recorded during testing. As described earlier, the hydrogeological investigation is often planned to be “piggybacking” on the main drilling investigation resulting in a pressure to reduce the testing time. However, it is important to run each test to completion as the ability to repeat test work is often limited. Each test stage should be considered carefully to inform the next stage and justify the approach and time spent on the test. For instance, a response from an initial falling head test (FHT) indicative of a low permeability would suggest that a further stage of injection or production to/from the formation is unlikely to be sustainable and would not produce an analysable pressure response. In this case, re-apportioning testing time to allow full recovery of the FHT to determine static levels and/or a test repeat to confirm the response may be more valuable use of testing time.

Test progression decisions should assess each test stage response prior to progression to the next stage. Whilst following a rulebook

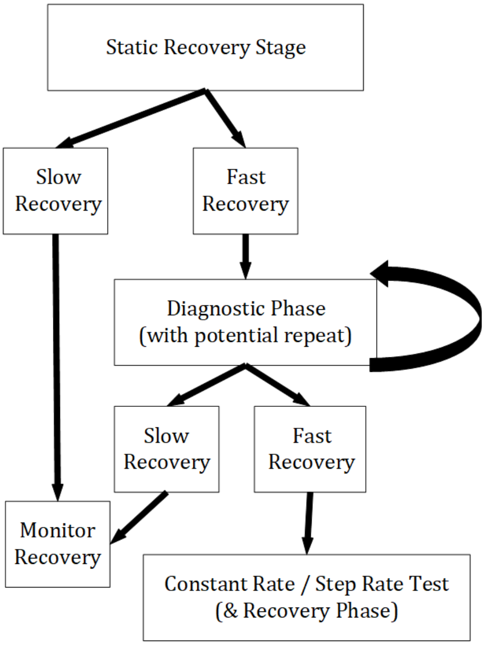

Figure 2 *Example of Flow Sheet Guidance for Test Stages.*

can be counter-productive, the use of decision flow sheets (a simplified example is shown in fig. 2) can provide a useful basis of support as well as a communication tool between designers, practitioners, and operators.

Test Analysis

The use of specialised software for hydrogeological test analyses in hydrogeology investigations that have been well designed and correctly executed can provide more information than just transmissivity and pore pressures. Additional information on the nature of flow and boundary effects can also be obtained. Diagnosis of the flow condition is based on diagnostic curves (Gringarten, 2008), similar to pumping test diagnostic curves (Kruseman & de Ridder. 2000). Diagnostic tools can use "skins" (Pickens *et al.*, 1987), the deconvolution of pressure data and the pressure derivative to interpret all types of test which can be considered individually or as multiples via superposition. An example of a software for hydrogeological data analysis is Golder's proprietary curve fitting Hydrobench software that allows comparison of results from different test stages.

Conclusions

Hydrogeological investigations using deep boreholes involve substantial challenges. These are primarily the result of complexities that occur due to the unique borehole drilling methods, presence of low permeability formations, and the specialised testing equipment that is required for testing at depth. The challenges can be overcome using specialist resource to support test planning and supervision, provide training and guidance, and carry out data analysis. This paper has discussed some of the key factors for consideration by mining hydrogeology practitioners when designing hydrogeologic investigations in deep, multi-purpose mining boreholes.

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