Advances in Hydrogeologic Testing of Mineral Exploration Boreholes

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Abstract

Mining companies integrate geotechnical investigations with mineral exploration coring programs to minimize cost and to streamline mine design and permitting. The classic Lugeon method of testing is a widely accepted method for rock permeability estimates. Recent advances in testing equipment, such as down-hole shut-in capability, enable implementation of improved testing and analysis methods that provide a more detailed picture of hydrogeologic conditions, without significantly increasing characterisation costs. Improved knowledge of pore pressure and hydrogeologic flow regimes elevates the confidence in and accuracy of pre-mine modeling efforts.

Key words: IMWA 2012, Lugeon, wire-line packer system, numerical borehole simulator, constant-pressure test

Introduction

Hydrogeologic testing with wireline packer systems is a common component of geotechnical testing programs. The Lugeon method of testing has long been a standard in civil and geotechnical engineering for producing rock permeability estimates. The Lugeon test was developed for grouting design and has proved adequate over the years for that purpose. It remains a popular method for conducting field tests due to the short testing time, simplicity of equipment required, and straight-forward analysis using simple spreadsheets, all which results in a relative low cost of testing. However, the Lugeon method has inherent limitations in terms of producing the type and quality of hydrogeologic parameters that are often required for generating computer models for mine and de-watering design, and environmental permitting.

Applications such as nuclear waste site characterization, water resource evaluation, and environmental remediation have developed a more detailed level of hydrogeologic testing and analysis due to industry standards and a rigorous oversight process driven by legal implications. The costs of testing and analysis in those industries tend to be significantly higher due to longer test periods (days instead of hours), greater infrastructure requirements (multiple well tests), and more detailed analysis. The purpose of this paper is to demonstrate that integrating key components of more detailed hydrogeologic testing and analysis from other industries can significantly increase the quality and robustness of data collected in single borehole tests for mining projects without significantly increasing the cost of the investigation.

Lugeon Method

The Lugeon method (Lugeon 1933) was developed in the era of dam and tunnel construction, and has been improved over the years to provide a dependable approach for rock permeability assessment for grouting design. A typical Lugeon test is conducted by installing an inflatable packer in a single borehole and conducting a series of short (10 minute) constant-pressure injection steps, noting the ending injection flow rate. Analysis is performed by plotting injection pressure versus flow rate. Rudimentary diagnostic analysis has been developed for quality control purposes (Quiñones-Roza 2010), to determine whether the test was conducted under laminar flow conditions, which are an underlying assumption of the analysis method. Details on conducting Lugeon tests are widely available in the literature and are not presented here.

The Lugeon method has proved effective for grouting design as it largely mimics the conditions under which grouting occurs. However, mine-site evaluations require hydrogeologic parameters for much larger scale applications such as mine planning and ground water modeling. Predicting groundwater flow on a local or regional scale requires knowledge of parameters including static formation pressure, transmissivity, storativity, and flow geometry. While effective determination of storativity requires multi-well testing, the other three parameters can be characterized using single-well tests that evaluate transient flow and pressure responses during testing. Recent improvements in testing and analysis tools make it feasible to perform higher-level hydrogeologic testing at remote sites.

Equipment Advances

Single-borehole test data can be significantly improved by incorporating the following technical improvements into the test system:

1) Down-hole shut-in capacity
2) Down-hole pressure measurement
3) Electronic surface flow-rate data acquisition

The above items have long been accepted as standard equipment in other applications. Down-hole shut-in greatly reduces the amount of time required to reach or approach static formation pressure because it effectively reduces the wellbore storage. Combined with a down-hole data-logging pressure transducer, a down-hole shut-in valve (DHSIV) allows simple incorporation of a pressure recovery period prior to and/or after injection testing. Electronic flow rate acquisition provides transient flow data that can be analyzed in a variety of manners and allows for analysis of a constant-pressure test even when the pressure is variable, as often happens. As demonstrated in the analysis section below, pressure recovery periods, transient analysis, and down-hole pressure measurement significantly increase the scope and robustness and of hydrogeologic test results.

Test equipment for mineral coring boreholes has been improved in recent years to incorporate the above aspects of more rigorous hydrogeologic testing programs, while maintaining flexibility and the small footprint of traditional wireline packer systems (Figures 1&2). Hydraulically inflated packer systems that use drill rods to inflate the packer rather than nitrogen or compressed air on a separate control line have increased the depth limits of field testing, making detailed hydrogeologic testing significantly more attainable at remote sites. Some systems are equipped with drill-rod activated down-hole shut-in valves that isolate the test interval for rapid determination of static formation pressure and facilitate performance of a pressure recovery test following the injection period.

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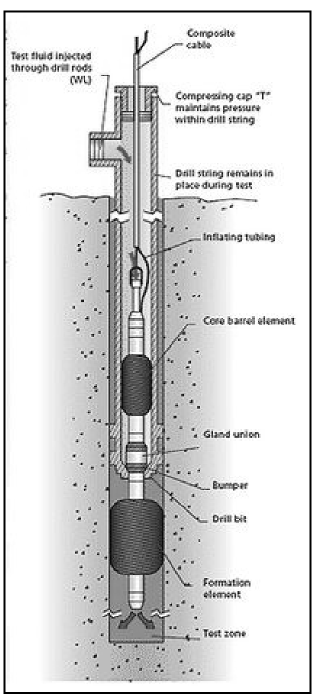

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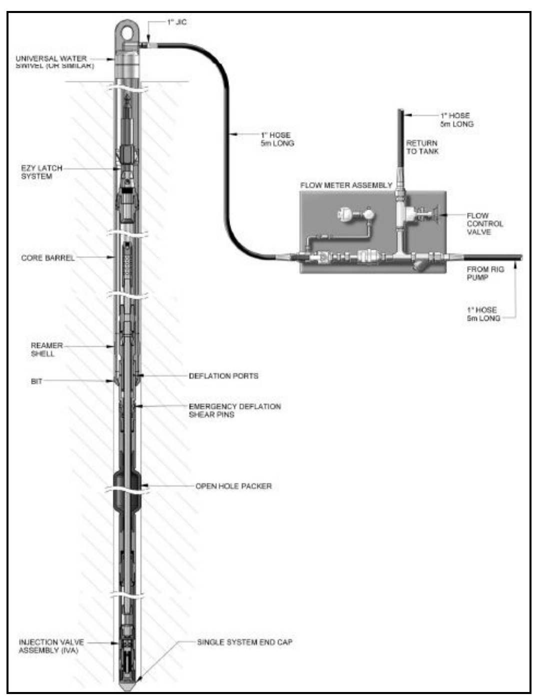

Figure 1 *Schematics of a) nitrogen-inflated and b) hydraulically-inflated wire-line packer systems*

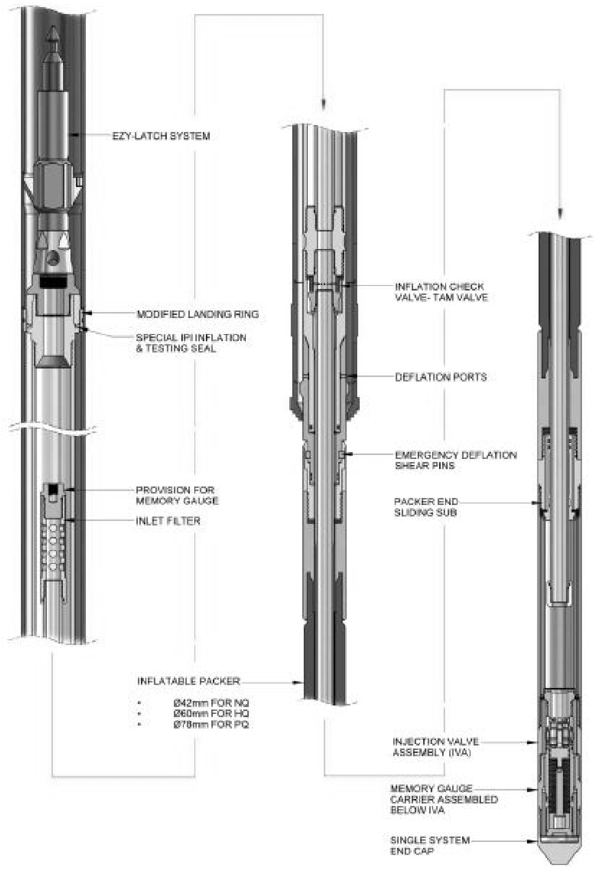

Figure 2 *Detailed components of a hydraulically inflated, through-the-bit inflatable packer system*

Real-time data aqcuision of downhole pressure is a costly and procedurally complex luxury at remote sites. However, the incorporation of data-logging pressure transducers into the downhole system is a cost-effective method to increase quality control and analysis quality without running data cables to depth.

Testing Methods

Hydrogeologic testing in any environment poses significant challenges to produce test data that can be evaluated using analytical methods. Mineral exploration boreholes provide an exceptional degree of difficulty due to remote locations, limited infrastructure availability, extreme weather conditions, and the fact that hydrogeological investigations are often secondary to the purpose of the drilling program. These factors tend to discourage consulting companies from advocating for rigorous testing programs, and explain the pervasiveness of Lugeon testing methods in mineral exploration holes.

Improved wireline packer systems, as described above, enable a testing approach that includes multiple events that can be analyzed independently, thus providing a higher degree of confidence in results. A single constant-pressure period followed by a shut-in pressure recovery period (Figure 3) can be conducted in similar timeframe as a traditional Lugeon test, yet provides the opportunity to perform a much higher level of analysis, including diagnostic evaluation of flow geometry.

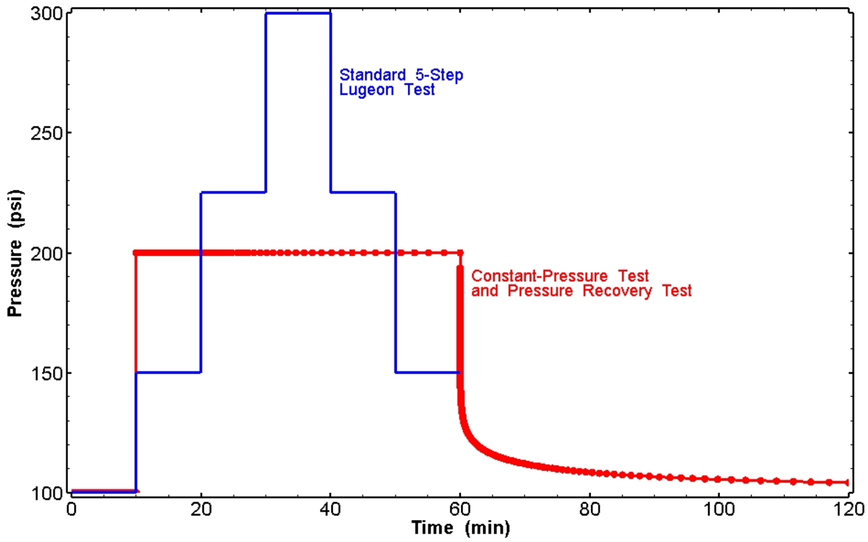

Figure 3 *Comparison of pressure versus time for a Lugeon test and a constant-pressure test and pressure recovery test.*

Analysis Approach

Hydrogeologic analysis of single borehole tests has evolved greatly in industries such as nuclear waste site characterization and energy exploration. Multiple test events can be analyzed by borehole simulation software packages that apply superposition methods to account for transient effects. Most analysis packages rely on analytical approaches that assume a given flow dimension and require quite constant flow or pressure periods to be effective. Mineral exploration projects are conducted in fractured rock, which often exhibits fractional dimensions, rather than a fixed 2-D or 3-D flow dimension. In addition, the reality of field testing under extreme conditions with limited infrastructure is that test data are often less than ideal (Figure 4), yielding data that are difficult, if not impossible, to evaluate using analytical-solution-based software. Application of a numerical wellbore simulator allows multiple test events to be matched simultaneously, thereby reducing the uncertainty in the fitting-parameter estimates.

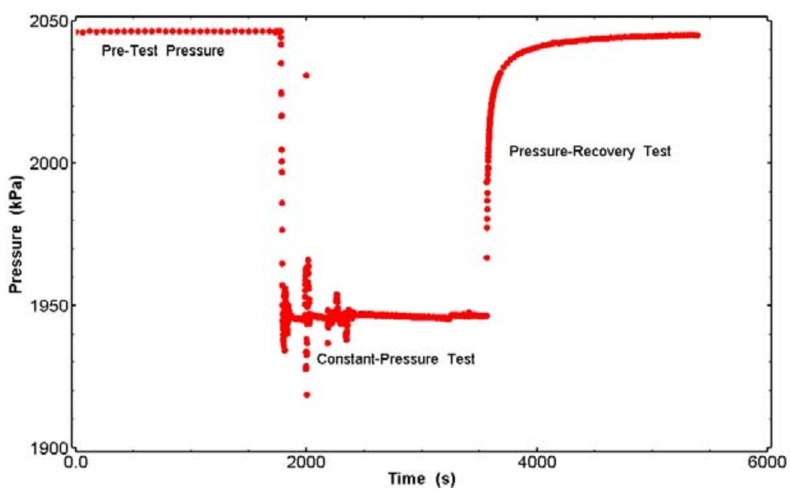

Figure 4 *Example of field-test data from a constant-pressure test followed by a pressure recovery test.*

Well-test analysis is the process by which hydraulic parameters of interest such as hydraulic conductivity (K) and specific storage (S_s) are estimated from measured pressure and flow-rate data. This problem of inferring K, S_s, etc. from a measured response is generally known as an inverse problem. An inherent quality of inverse problems is that the parameters estimated via this process have some degree of uncertainty associated with their values. For a given conceptual model, uncertainty can result from correlation among fitting parameters, noise in the data, and correlation among fitting and non-fitting parameters. Given that uncertainty in the estimates of the fitting parameters is an inherent part of the well-test analysis process, there are several things that an analyst can do to address this uncertainty. The most straightforward response to the uncertainty is to quantify it. It is also possible to use one's knowledge of the sources of the uncertainty to minimize it.

Analysis can be conducted using wellbore simulation software such as nSIGHTS, (Nuclear Waste Management Program 2006), which is a numerical well-test analysis code developed to analyze data from well tests that are performed in complex hydrogeologic systems under non-ideal conditions, i.e., data that are not amenable to analysis using conventional analytic methods (Figure 5). The code has a full suite of statistical routines that allow the analyst to quantify the uncertainty in the estimates of the fitting parameters of interest.

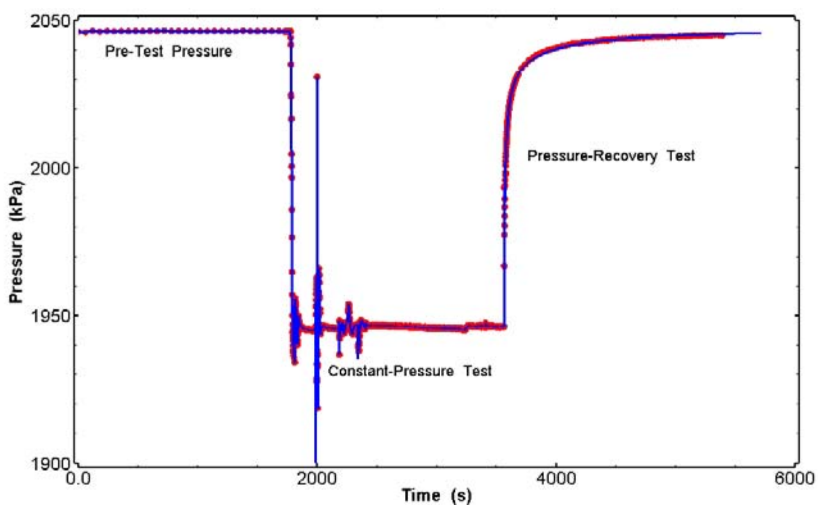

Figure 5 *Example of field-test data and simulation results using nSIGHTS software.*

The nSIGHTS code uses non-linear regression to optimize the values of the fitting parameters and thereby obtain the best match to the measured pressure and/or flow rates. The type of test(s) performed and the chosen conceptual model determine the type and number of fitting parameters. In practice, the analyst must assign reasonable initial estimates of the fitting parameters prior to beginning an optimization. The results of a single optimization include values for the fitting parameters that produce an acceptable fit to the measured data. A process referred to as *perturbation analysis* is then used to determine the amount of uncertainty in the fitting-parameter estimates. Perturbation analysis begins by assigning a plus/minus range corresponding to the parameter space one wishes to investigate to each of the initial (baseline) fitting-parameter values. Starting at the baseline value, the fitting parameters are then randomly perturbed a specified number of times (hundreds to thousands) to fall somewhere within their assigned ranges and are then optimized from these random starting points.

The objective of perturbation analysis is to adequately sample the parameter space and locate all of the minima within the parameter space. It advantageous to match constraints from two different types of tests, i.e., constant-pressure tests and pressure recovery tests. If we require that both constraints be satisfied simultaneously, then the solution for the combined constraints becomes the intersection of the individual solution sets, and the overall uncertainty in the values is reduced.

Figure 6 shows the solution sets obtained from perturbation analysis when matching the flow-rate data, the pressure data, and the combined flow-rate/pressure data. The solution set obtained when matching the combined constraints is simply the intersection of the individual solution sets. As a result, the nSIGHTS software yields a set of parameter estimates and provides the analyst a quantifiable uncertainty evaluation in addition.

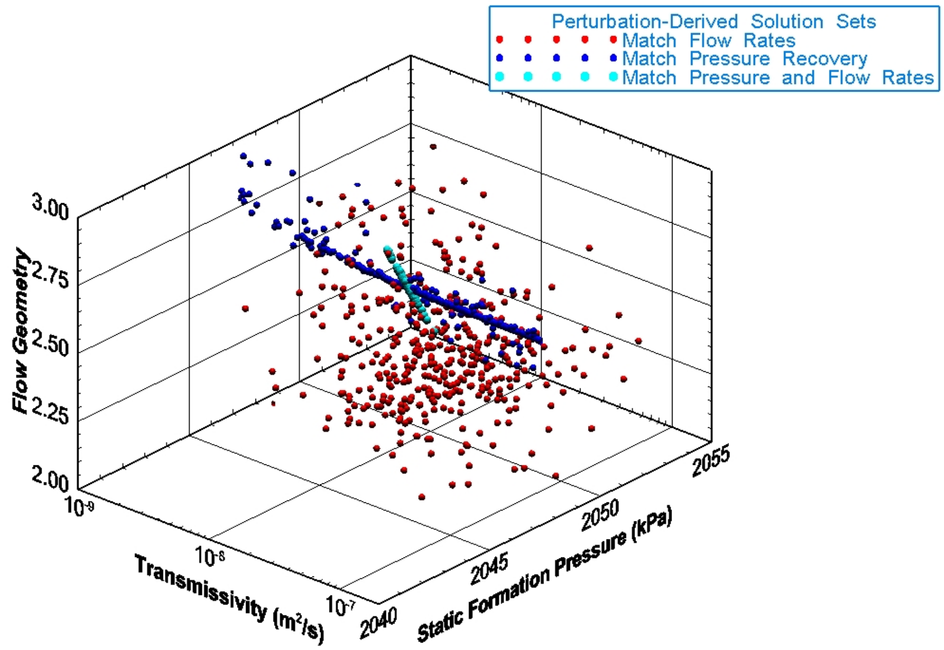

Figure 6 *Example of perturbation-derived solution sets from a constant-pressure test followed by pressure-recovery test.*

Conclusions

1) Mineral exploration boreholes drilled primarily for mineral resource evaluation provide a unique opportunity for obtaining hydrogeologic and geotechnical data, the quality of which can be significantly enhanced by applying methods and tools reserved for more detailed evaluations.
2) Recent advances in wire-line packer systems include hydraulically-inflated packers, drill rod-activated down-hole shut-in valves, and down-hole pressure data acquisition using data-logging pressure transducers.
3) Replacing the traditional Lugeon tests with constant pressure tests coupled with pressure recovery tests yields more detailed hydrogeologic information, including static pressure and flow geometry information.
4) Numerical wellbore simulation can characterise complex flow geometry and provide a tangible evaluation of uncertainty associated with analysis results.

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