High Resolution Packer Testing in Fractured Sedimentary Rock

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Patrick Quinn

Abstract: Packer tests in boreholes in fractured rock involving injection or withdrawal of water in borehole segments have been standard practice in bedrock hydraulic investigations pertaining to geotechnical and water resource projects since the 1950's. However in contaminant hydrogeology, the tests are conducted to assess groundwater velocity and contaminant fluxes and therefore, much improved resolution and measurement accuracy is needed. For this thesis study packer testing equipment was designed specifically for studies of contaminant behavior in fractured rock with the ability to conduct four types of hydraulic tests: constant head/flow injection step tests, slug tests, pumping tests and recovery tests, all in the same borehole test interval without removing the equipment from the hole while acquiring high precision data for calculation of transmissivity (T) and fracture hydraulic apertures (2b). This equipment records pressure above, within, and below the test interval to gain insights regarding open borehole flow patterns, and to identify short circuiting to the open borehole above or below the test interval. The equipment measures flow rates as low as 6 ml/min up to 20 L/min, and the temperature in the test interval and at the ground surface is measured to account for density and viscosity variations. Each type of test is conducted repeatedly over a wide range of imposed applied pressures and flow rates and the equipment was applied to assess performance of this new methodology for packer testing and gain new insights concerning fractured rock hydrology in 6 boreholes in the fractured dolostone aquifer underlying the City of Guelph, Ontario.

In the first stage of the equipment application in the fractured dolostone aquifer, over 150 high precision straddle packer tests using constant rate injection (Q) were conducted to identify the conditions of change from Darcian (linear) to non-Darcian (non-linear) flow based on the Q vs dP relationship where dP is the applied pressure above ambient. In the Darcian regime, the

linear Q vs dP relationship passes through the origin (0,0) where the ambient pressure represents static conditions (i.e. Q=0 and dP=0). After the onset of non-Darcian flow, proportionally less Q per unit dP occurs so that the interval transmissivity (T) calculated from the test results using Darcy's Law based models is underestimated by as much as an order of magnitude. The Darcy-Missbach equation was found to be a robust conceptual model for representation of step constant Q tests in which the linear proportionality constant relates Q^n vs dP. It was found that quantifying non-linear flow allows for a more accurate determination of the linear data to obtain better estimates of T and hence the hydraulic apertures derived from the T using the Cubic Law.

In order to obtain hydraulic apertures from the packer test T values, the number of hydraulically active fractures in the test interval is needed. The only data collected regarding individual fractures was the core log created during the coring process and the acoustic televiewer log, both of which identify the location of fractures, but neither could tell if the fractures identified were hydraulically active. A sensitivity analysis concerning the effects of non-linear flow and the number of hydraulically active fractures on the calculated hydraulic aperture shows that the number of fractures selected as hydraulically active has the greatest effect on the aperture values. A new approach is proposed for determining apertures from hydraulic tests in fractured rock utilizing the onset of non-linear flow to aid in the choice of the number of active fractures present in the test interval.

In the second stage of the equipment application, the four types of hydraulic tests (constant head, pumping, recovery, and rising/falling head slug tests) conducted in the same test interval at gradually increasing flow rates showed that non-linear flow can be most easily identified and quantified using constant head tests providing a higher degree of certainty that the data used to calculate T are from the Darcian flow regime. Slug tests are conducted most rapidly, but formation non-linear behavior is commonly exaggerated by non-linearity within the test equipment at large initial displacements. However, the equipment non-linearity can be accounted for using a Reynolds number (Re) analysis allowing identification of the non-linear flow in the formation. In addition, non-linear flow can interfere with evidence of fracture dilation. The pumping and recovery tests are the most time consuming because of the relatively long time required to reach steady state. However, these tests offer the most potential to give insight into the influences of the peripheral fracture network and rock matrix permeability on test results

In addition to the actual transmissivity of the test interval T values obtained from packer tests can be influenced by several factors including non-linear flow in the formation and in the test equipment, aperture dilation or closure, hydraulic short circuiting or leakage from the test interval to the open borehole and dual permeability properties of the system (fractures and matrix). The equipment and procedures developed in this thesis provide an improved framework for identifying these influences and in some cases avoiding them so that the aperture values calculated from T measurements are more accurate than those obtained through conventional approaches. In the conventional procedures for packer testing in fractured rock as recommended in manuals and guidance documents, the applied head and flow rate can be expected, based on the results of this thesis, to produce transmissivity values biased low because of non-linear (non-Darcian) flow.

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Designing and building the packer equipment was a daunting task made much easier with the expertise of Paul Johnson (UW) and Bob Ingleton, (UW). Bob designed and built the original packer trailer based on the Environment of Canada model that previous students used to collect the initial transmissivity data from the Guelph Tool site. He was an invaluable resource for the equipment modification. Jay Sitts of Hydrite Chemical Company, Cottage Grove, WI also helped in the development of the packer testing equipment with his ingenuity and experience when I conducted packer tests at the Wisconsin site.

Many other individuals provided expertise throughout this study. I would like to thank the tireless effort to perfect the art of core logging focusing on the fracture locations and angle of intersection with the borehole by Jonathan Kennel, University of Guelph (UG), and the wealth of information derived from the various borehole geophysical logs collected and interpreted by Pete Pehme, (UW) and Ryan Kroeker (UG). Rob McLaren graciously offered invaluable assistance with all things computer related, including of course the HydroGeoSphere code, and any other programs I needed from data processing to determining safe packer pressures from a virtual caliper log. I would also like to thank Drs. Bob Gillham, Andre Unger, Kevin Lamb, and Marek Stastna for their time helping me understand the physics and mathematics involved in radial parallel plate flow.

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Chapter 1 Thesis Introduction

1.1 PROBLEM STATEMENT

The widely accepted approach for delination of well head protection areas for municipal wells involves identification of the capture areas and then specification of travel time domains within the capture area based on groundwater velocity estimates for this aquifer volume. The calculation of average groundwater velocity in fractured geologic media is commonly done in the same manner as for porous media whereby the Darcy flux is divided by a value assigned to represent the rock porosity, however, this assigned value is commonly considered an arbitrary fitting parameter deemed to include the effects of rock matrix diffusion, sorption, and other processes (e.g. Cherry et al., 2006). Commonly in bedrock, the rock matrix permeability is much less than the fracture permeability. Therefore, calculating the bulk "advection" porosity for the velocity calculation requires only determination of the fracture aperture values, which in combination with fracture spacing and fracture geometry characteristics, yields the bulk fracture porosity. However, although advective (fracture) porosity values are critical to wellhead protection analyses, the literature pertaining to these analyses in porous media focused without any guidance concerning methods and uncertainties associated with the acquisition of the porosity values. The size of each travel time domain is always directly proportional to the velocity which is inversely proportional to the bulk fracture porosity and therefore identification and estimation of error in the porosity is an important issue.

In the literature concerning the modeling of contaminant transport in fractured rock there is substantial agreement that discrete fracture network (DFN) approaches rather than equivalent porous media (EPM) approaches are most appropriate (Gale, 1982; Berkowitz, 2002; La Pointe et al., 2002). There are many mathematical models available for simulating contaminant transport in the DFN context including analytical parallel plate models for single fractures and sets of parallel fractures (e.g. Tang et al., 1981; Sudicky & Frind, 1982) and numerical models capable of simulating groundwater flow and solute transport in networks of interconnected fractures (Sudicky & McLaren, 1992; Smith & Schwartz, 1993; Therrin et al., 2006). These mathematical models have been used for simulations of hypothetical cases with emphasis on sensitivity analysis. However, the DFN models have only rarely been used for simulating contaminant transport for actual contaminated sites because of the difficulties and challenges associated with the acquisition of the field data needed for specification of input parameter values and boundary conditions.

An important parameter that must be specified in the inputs to these models is fracture aperture. The only practical method available for obtaining aperture values involves the use of the Cubic Law (Snow, 1965) whereby the groundwater flow in each fracture is proportional to the aperture cubed and groundwater flow is governed by Darcy's Law based on the assumption of a linear relationship between the driving force (Δh) and the flow (Q) described by the empirical constant known as the hydraulic conductivity (K). Apertures obtained in this fashion are known as hydraulic apertures to distinguish them from apertures obtained in other ways (e.g. the solute aperture from tracer tests, visual and acoustic apertures from borehole geophysics). Aperture values can also be obtained through tracer tests, but these tests are very time consuming and to conduct such tests at numerous locations at a contaminated site is generally not feasible. The Cubic Law approach applied at fractured bedrock sites involves measurements of transmissivity (T) at many depth intervals in boreholes by means of straddle packer tests and the apertures are calculated from these measured T values for each test interval.

Although there is an abundance of literature concerning the use of straddle packer tests to obtain T values, there are only a few publications wherein aperture values have been derived from the T values (Snow, 1979; Gale, 1982; Novakowski, 1988; Rutqvist et al., 1992; Cappa et al., 2005). The rarity of hydraulic aperture values in the literature is likely due to the fact that the goal of many contaminated site investigations has been to use packer testing results to produce T values for use in groundwater flow analysis based on an EPM approach.

Although the literature includes several papers reporting hydraulic apertures obtained in the general context of contaminant transport studies, none addresses issues concerning reproducibility, accuracy, precision or uncertainty associated with the reported T values measured in the field or the subsequent calculated aperture values. This is an important issue because the groundwater velocity in fractures (i.e. contaminant advection) is proportional to the aperture squared. The determination of hydraulic aperture values is fraught with difficulties and uncertainties beyond those associated with the T measurements because the use of the Cubic Law in the straddle packer test context requires judgment concerning the number of hydraulically active fractures that are intersected by the borehole in each test interval. Therefore, when straddle packer tests are conducted for the purpose of obtaining aperture values, information should also be obtained concerning the type and number of fractures intersected by the borehole. Although fractures intersecting boreholes are commonly identified by examination of cores and borehole televiewing (e.g. acoustic, optical, electrical), these fractures are not necessarily hydraulically active. Therefore, possibilities for gaining insights from the packer test data concerning the existence of a single fracture or multiple fractures in the test interval need to be examined.

1.2 LITERATURE REVIEW

In analysis of packer test data, the T values are commonly derived using mathematical models based on the assumption of Darcian flow in the fractures (Braester and Thunvik, 1984; Bliss & Rushton, 1984; Barker, 1981; Witherspoon et al., 1980; Novakowski, 1997). In Darcian flow, the relation between the injection flow rate (Q) and the induced pressure change (dP) is linear and therefore the Darcian condition is commonly referred to as linear flow. However, the literature reports very few field studies showing actual evidence of Darcian flow during packer testing. Elsworth and Doe (1986) used mathematical modeling of packer tests in fractured rock to show that calculation of T using non-Darcian data can lead to underestimation errors as much as an order of magnitude. However, in the literature providing guidance concerning equipment and testing procedures for constant P or Q tests in fractured rock (e.g. U.S. Bureau of Reclamation, 1974 & 1977; Sara, 2005; Nielson, 2006), minimal advice is provided for discerning whether the flow regime is Darcian or non-Darcian, although use of multiple test stages is recommended. There is abundant literature concerning Darcy-based mathematical models for analysis of packer testing data to obtain values of T or K, however, lacking knowledge of whether or not the test data are from the Darcian range imposes errors irrespective of the model used.

Academic research in fractured rock in the discrete fracture network context began with PhD theses by Snow (1965) and Louis (1970). Snow's research was driven by the need to estimate grout volumes required to seal fractured rock at dam sites. Snow's thesis was mainly theoretical in which the Cubic Law was derived for a variety of different situations, but he also addressed related topics such as fracture frequency and aperture distributions. He used data compiled from previously conducted packer tests by himself and others at dam sites, to test the theory and he determined fracture frequencies and aperture sizes based on the geologic and hydraulic data collected. A standardized test was developed (25 foot test interval in a 3 inch hole with 100 psi applied pressure) to enable the use of all of the field data. Louis was involved in comparing laboratory studies on single fracture flow vs parallel plate flow theory. He identified non-linear flow and created empirical relationships to account for deviations from linear flow and the Cubic Law. Fracture apertures and asperities (relative roughness) were the additional parameters he used to describe flow through fractures. He found that deviation from linearity was similar to pipe flow as long as the relative roughness was <0.033. As the relative roughness increases, the deviation from linear flow begins at lower flow rates. He used the Darcy equation to describe linear flow and the Missbach equation to describe non-linear flow.

Other theses at this time included a combination of laboratory tests of flow through fractures and field studies using packer testing. Sharp (1970) conducted laboratory experiments in a single granite fracture. He observed non-linearity in the test results and reported that the degree of non-linearity increased with increasing aperture. He developed relationships covering the linear, transitional and turbulent flow regimes. He also used modeling to determine the significance of various processes on field test results and developed a triple packer system for packer testing. Maini (1971) concentrated on improving packer testing equipment and methods, but also conducted laboratory studies on fracture network flow using brick models. He also used the Missbach equation for quantifying non-linear flow. Gale (1975) conducted both field packer tests and radial laboratory tests on a single fracture in a 38 inch granite core. He observed fracture deformation in the laboratory tests and reported that there may be a size effect of laboratory test cores on the results indicating that the REV of a fracture is related to the fracture volume tested. All of the above field studies involved constant head step tests and apertures were determined from the measured T values.

The petroleum industry became interested in fractured rock transmissivity in the 1950s and Horner (1951) used the Cooper-Jacob (1946) approximate solution to develop a method to analyze recovery data from a shut in test, in which the pump is running for an unspecified period of time and then the test hole is 'shut in', effectively instantaneously turning off the pump and the pressure recovery data is monitored. The pressure build up data (recovery) are much less influenced by non-ideal effects than the pumping data. He derived solutions for an infinite homogeneous reservoir, an infinite reservoir with a single fault, and for a well in the center of a spherical reservoir. Pollard (1959) developed a method for evaluating acid treatments in fractured limestone oil fields using a semi log plot of time vs log dP that had three exponential terms, representing flow from the system into the larger fractures, flow from the larger fractures to the well, and a skin effect between the large fractures and the well. The late time slope is the system supplying water to the coarse fractures after the skin effect and the recovery of the coarse fractures become negligible. The difference between the early time data and the late time slope creates a difference curve representing the skin effect and the coarse fractures. Pirson (1961) extended this analysis to include the rock matrix volume and the radius of influence of the test but Warrren and Root (1962) points out that in the case of no fractures present in the test interval the Pollard analysis would be in error and recommends that this type of analysis be used with extreme caution. Other double permeability models and transient analysis techniques began to be developed and reported mainly in petroleum journals throughout the 1970s (Gringarten & Witherspoon, 1972). These studies all used pumping tests usually conducted on entire boreholes aimed at obtaining values for the permeability of an entire reservoir.

The nuclear industry became interested in underground disposal options in the 1970s creating another need for understanding the hydraulic characterization of fractured rock. Unlike the petroleum industry, the nuclear industry was interested in igneous rock with extremely low matrix permeability wherein all flow is essentially through the fractures. The US Bureau of Reclamation published their first guidance document, Earth Manual in 1974 describing packer testing and procedures for conducting constant head tests in open boreholes. A subsequent publication (U.S. Bureau of Reclamation, 1977) addressed anomalous data and included trouble shooting tips as experience was gained in packer testing. The US Army Corps of Engineers also published a comprehensive document regarding the measurement of transmissivity in fractured rock environments using constant head step tests (Ziegler, 1976).

In the 1980s and 90’s interest in contaminant migration through fractured rock was also developing due to concerns for drinking water supplies and the USGS researchers began publishing papers on hydraulic tests in fractured rock (Hsieh et al., 1983; Shapiro & Hsieh, 1998) culminating in the design of improved packer testing sampling and testing equipment (Shapiro, 2001). This equipment measures the pressure above and below the test interval and can conduct injection or withdrawal hydraulic tests. The papers by the USGS researchers included results of slug tests and constant head injection tests, however, no aperture values were reported. Contaminated fractured rock sites caused interest in packer testing in the 1980's for the purpose of aperture determination using both hydraulic and tracer tests. In a number of cases there were discrepancies between the hydraulic and tracer apertures (Novakowski, 1988; Silliman, 1989). Silliman argued that this behavior is a result of the averaging involved in the use of the Cubic Law and proposed that for flow in isotropic aperture fields and flow parallel to aperture channeling the tracer aperture will be greater, while flow perpendicular to aperture channeling results in a larger hydraulic aperture.

These early packer test studies always assumed linear flow for T calculations, but the existence of Darcian flow was rarely shown to exist in the test results. In addition, all publications were within specific discipline boundaries such as hydrology, petroleum engineering, and civil engineering with minimal cross referencing.

1.3 THESIS HYPOTHESIS, GOALS, OBJECTIVES AND SCOPE

This thesis began by use of a packer testing system which was first introduced conceptually by Gale (1982) and a working version was obtained from Environment Canada which was described by Lapcevic (1988) and Novakowski (1993). Data collected as part of the first field season for this research indicated that the majority of the tests were conducted in the non-linear flow regime based on the Q vs dP relationship. Most of the modifications to the system involved the measurement and control of flow rates, especially low flow rates, in order to obtain data within the Darcian flow regime. In addition, modifications were made to allow for the conduction of all four hydraulic tests while improving resolution as experience was gained at field sites.

The city of Guelph, Ontario was selected as this study site because several open boreholes were available in two very different parts of the same dolostone aquifer. Four boreholes were in the industrial section of the city and three were located in rural areas just outside the city. Laboratory tests conducted on rock core from a local contaminated site had shown that the matrix K in this part of the aquifer was low making this site appropriate for the study of non-linear flow in fractures while avoiding the dual permeability effects. At this site the rock is predominantly fractured Silurian dolostone overlain by Quaternary deposits and underlain by a massive shale formation. The rock units identified at the Guelph site extend over a large area and are part of an important dolostone aquifer regionally (Singer et al., 2003; Dekeyser et al., 2006; Brunton 2008). Top of rock was typically encountered at 3-5 meters below ground surface (mbgs) and well casings were keyed into the rock.

All cores were examined on site to identify geologic and physical features and fractures were identified as open (core separates at the fracture), closed (core does not separate at the fracture), broken zones and signs of flow (weathering, mineralization) were recorded. Samples were also collected from the cores for analysis of contamination and rock physical properties. Various geophysical logs were also collected in the boreholes before packer testing. The number of active fractures present in the test interval is an important factor that must be determined when using the Cubic Law to calculate apertures from packer test data (Maini, 1971). There are two main sources of data regarding fracture locations; geophysical tools (acoustic and optical televiewer logs), and the core log.

The City of Guelph was conducting a water resource evaluation in this same aquifer further from the town, in which reef mounds had been identified in the three cored boreholes based on core examination (Brunton, 2008). Hydraulic tests conducted in these boreholes indicated much higher matrix permeability, completing the data set required to create a double permeability conceptual model for use in analyzing pumping/recovery tests (allowing a comparison of high and low matrix permeability responses).

Thesis Hypothesis

Packer tests in fractured rock aquifers have been conducted without use of rigorous procedures aimed at acquiring test data suitable for assessment of non-ideal conditions such as non-linear flow, short circuiting or leakage, and fracture dilation that can cause the T values calculated from the test data to be substantially different from the actual T of the formation. Rigorous packer testing whereby all four types of tests are done in each test interval under a broad range of imposed conditions will provide T values with minimal influences of these non-ideal effects.

Thesis Goals

This thesis has two main goals. One of the goals is to develop a packer testing system involving improved equipment and procedures, capable of efficiently conducting four different types of hydraulic tests in rock boreholes: constant head step tests (steady state), instantaneous pulse (slug tests), constant flow pumping tests to near steady state conditions and the subsequent recovery (recovery test). These four types of tests were established many decades ago for determining T by hydraulic tests in piezometers or wells in unconsolidated deposits (i.e. porous media). The most basic mathematical models used to calculate the T values from the field data for all four methods assume homogeneous permeable media with radial horizontal Darcian flow occurring during each test. For these ideal conditions in the test interval, these tests would produce the same value of T. However in fractured rock there are several common possibilities for one or more of these assumed idealities to be invalid, so that the T values calculated using the models for the ideal cases would deviate from the reality.

The second goal of this thesis is to apply the system in fractured rock boreholes to develop improved understanding of the effects influencing packer test results from the four methods and thereby provide new insights concerning the differences and similarities and relative advantages and disadvantages of the methods. The pursuit of this goal required extensive packer testing, involving all four tests in the same interval in fractured rock boreholes without moving or deflating the packers. This thesis also encompasses the following specific objectives each of which is addressed in a separate chapter in this thesis:

1.) Develop and assess packer testing equipment capable of efficiently conducting all four types of hydraulic tests in the same test interval at different levels of applied stress.

2.) Use constant head step tests to determine when Darcy's Law applies because all conventional methods of packer test data analysis assume without proving that Darcian flow exists.

3.) Apply a sensitivity analysis to determine the influence of non-linear flow and the uncertainty in the number of active fractures used on the determination of hydraulic aperture and average fracture velocity and develop a system utilizing all data from core logs, geophysical logs and hydraulic tests to determine fracture apertures for input into a discrete fracture network model.

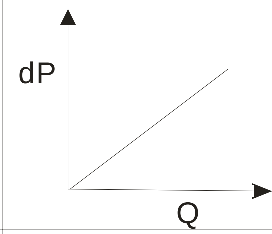
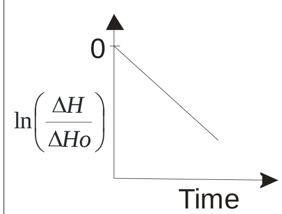
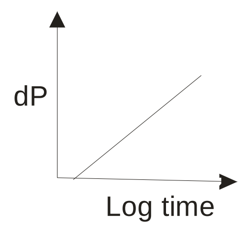
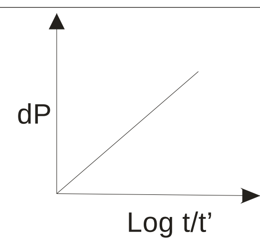
4.) Determine the effect of initial displacement on the results of slug tests in fractured rock and identify the key physical processes that cause deviation from ideal responses.

5.) Examine pumping and recovery tests as a means for identifying dual permeability effects (fracture flow and matrix flow).

1.4 THESIS ORGANIZATION

This thesis contains five chapters (Chapters 2-6) written in manuscript format and the thesis is bounded on the front by an introduction chapter (Chapter 1) and at the back by conclusions (Chapter 7) because each of the core chapters was written as a stand-alone document intended for submission to a peer-reviewed journal. This resulted in some repetition from chapter to chapter of introductory material, background information, and methodology. The first step was the development of the necessary test equipment and procedures for conducting numerous field tests which is described in Chapter 2. Non-linear flow encountered during constant head packer tests is described in Chapter 3 and a method for determining the degree of deviation from linear flow during a packer test is presented. Flow was not fully turbulent in any of the packer tests and the Darcy-Missbach relation developed accounts for the non-linearity observed and can be used for predictions outside the collected data range. In Chapter 4 a sensitivity analysis is conducted to determine the influence of non-linear flow and the uncertainty in the number of active fractures used on the determination of hydraulic aperture and average fracture velocity and develop a system utilizing all data from core logs, geophysical logs and hydraulic tests to determine fracture apertures for input into a discrete fracture network model. Chapter 5 describes a method for conducting slug tests at increasing initial displacements to determine the effect of initial stress on T determinations and identify the key physical processes that interfere with the test results. Chapter 6 describes a new conceptual model that describes the results of pumping/recovery tests using a double porosity interpretation. Finally, Chapter 7 summarizes the main conclusions presented in earlier chapters along with recommendations for future work.

Tables

Test Type	Typical Analysis Method	Typical Analysis Graph	Head and Flow
Constant Head Step Test	Thiem $T = \frac{Q}{2\pi\Delta H}\ln\left(\frac{r_o}{r_w}\right)$		Head = Constant Flow = Constant
Slug Test	Hvorslev Radial Flow $T = \frac{slope}{2\pi}\ln\left(\frac{r_{\blacksquare}}{r_{\blacksquare}}\right)$ Spherical Flow $T = \frac{slope}{2\pi}$		Head and Flow Variable
Constant Rate Pumping Test	Cooper-Jacob Straight Line Method $T = \frac{2.3Q}{4\pi\Delta s}$		Flow = Constant Head Variable
Recovery Test	Theis Recovery Method $T = \frac{2.3Q}{4\pi\Delta s'}$		Head and Flow Variable

T = Transmissivity
Q = flow rate
rw = well radius
ro = radius of influence
s = drawdown

Assumptions :
- Homogeneous, isotropic confined aquifer
- Radial flow or spherical flow
- Theis assumptions

Table 1-1 Types of Straddle Packer Hydraulic Tests

Chapter 2 Performance testing of a versatile high resolution packer system for hydraulic tests in fractured rock boreholes

2.1 INTRODUCTION

Hydraulic tests in boreholes are commonly conducted using inflatable packers to isolate intervals in the borehole where water is injected or withdrawn for measurement of the transmissivity (T) of the rock in the test interval (e.g. NRC, 1996; Sara, 2005). Such T measurements are used in many types of investigations including waste isolation, mine site water control, groundwater resource assessments, and contaminated site characterization. Four very different categories of hydraulic tests are reported in the fractured rock literature: constant head tests (steady state), pumping tests carried out to near steady state, the subsequent recovery test, and slug tests. Most commonly, two packers are used (straddle packers) to isolate and test the interval between the packers. In nearly all applications of straddle packer tests reported in the literature, the investigators have opted to conduct only one type of hydraulic test. However, because of the complexities inherent in fractured rock and the large differences between the four categories regarding the hydraulic conditions imposed on the formation, new possibilities for acquiring useful additional insights appear when more than one category of tests are conducted in selected test intervals. In one study using two categories of tests, Schweisinger et al. (2009), conducted rising and falling head slug tests and constant rate injection recovery tests in the same test interval and report that the falling head slug test give a larger value for T than the rising head tests and the recovery tests give an even smaller value for T. They postulate that the T values determined from these tests were sensitive to the changes of effective stress in the fracture causing fracture dilation and contraction.

This paper describes straddle packer hydraulic test equipment developed to conduct conveniently all four types of tests with high precision in each test interval using a wide range of head differentials and flow rates into and out of the formation. An impetus for the development of this equipment is the desire to use the T values to calculate hydraulic apertures using the Cubic Law. Results from simulations of contaminant or heat transport in discrete fracture network models (DFN) are strongly sensitive to aperture values (Sudicky, 1992; Molson et al., 2007). Therefore, it is necessary to conduct assessments concerning biases or uncertainties in the T values used to calculate hydraulic apertures.

In the conventional packer tests for T, only one test is conducted in each interval, or in some cases two tests, but this is generally too limited for assessments of the flow regime in the context of Darcian versus non-Darcian flow. This study is based on the premise that this can best be achieved by conducting all four types of hydraulic tests at gradually increasing driving force in each test interval. Therefore, the equipment was designed to conduct tests beginning with minimal driving force where Darcian flow is most likely, and then gradually increasing the driving forces causing non-Darcian flow to examine the influence of the test conditions on the T values obtained. This examination of the influence of flow conditions was prompted by concerns of other researchers of the phenomena of non-linear flow (Maini, 1972; Elsworth & Doe, 1986; Atkinson, 1994; McElwee & Zenner, 1998), and fracture dilation/formation compressibility (Svenson et al., 2007; Choi et al., 2008).

The performance of the equipment was assessed by applications in boreholes in a 100m thick, fractured dolostone aquifer in Guelph, Ontario, overlain by Quaternary deposits and bounded below by a shale aquitard. The injection tests were conducted in four boreholes as part of a contaminated site investigation, where a large range in T coupled with a low permeable rock matrix, makes the flow dominated by the fractures. These tests were conducted in four boreholes approximately 40 m deep with test interval lengths of 1.5m, 3m, and 6m. The City of Guelph was conducting a water resource evaluation in this same aquifer further from the town, in which reef mounds had been identified in the three cored boreholes based on core examination (Brunton, 2008). Withdrawal tests conducted in these boreholes indicated much higher matrix permeability. Smaller intervals intersect fewer fractures and are best when using hydraulic tests to characterize apertures, and therefore the 1.5m interval was used most frequently In addition to describing the equipment, examples of test results illustrating enhancements in knowledge gained through application of multiple types of tests and multiple tests of different magnitudes in particular intervals are presented.

2.2 TEST EQUIPMENT AND MEASUREMENT RESOLUTION

Development of this packer testing system began with use of an adaptation of the system first presented conceptually by Gale (1982) and described operationally by Lapcevic (1988). Figure 2-1 is schematic of the modified system and includes a composite of photos of the system. The system is housed in a trailer containing a series of tanks of different diameter with sight gauges used to measure flow rates by timing the rate of water level drop and knowing the tank inside diameter. Tank diameters range from 2.5 to 40 cm with the smaller tanks used for less permeable test intervals. All tanks are connected through a manifold system to a nitrogen cylinder used to pressurize the void space above the water in the tanks. This is the driving force for all constant head injection pumping tests. A second nitrogen cylinder is used to inflate the packers.

Based on descriptions of other packer systems (Hseih, 1983; Shapiro, 2001), the equipment was modified to improve flow control and measurement in the constant head tests and to allow for pneumatic slug tests and the conduction of injection/withdrawal pumping tests while allowing monitoring of the pressure in the open borehole above and below the test interval. This was achieved by using 2 inch diameter Solinst well casing (5 foot lengths) extending from the top packer to the ground surface. This creates a temporary 2 inch well in each test interval in which all four tests can be conducted.

Large sliding head P packers made by RST Instruments are used (7.1 cm deflated, 14.7 cm max confined inflated diameter) to isolate test intervals. A high pressure regulator (1500 psi) is used on the nitrogen cylinder used for packer inflation to enable testing at greater depths. (i.e. greater packer pressures are needed as the open borehole water pressure increases with depth). The packers are separated by 1 ¼” diameter perforated steel pipe and the through pipe in the packers is 1 ¼” in diameter. Because the maximum working pressure of the packers is dependant on the water column height and the borehole diameter, a fortran program was developed to calculate the maximum working pressure throughout the borehole before testing begins using a caliper log and the operational curve of the packers. This program determines the maximum safe working pressure of the packers allowed throughout the borehole.

The accuracy of the test depth is important for correlating different borehole test results. All of the 2 inch well casing was marked at 0.5 m intervals relative to the top of the test interval, which made accurate depth measurement. Depths were referenced to either the top of casing when the casing was above the ground surface, and to the ground surface when testing a flush mounted borehole or vault. The uncertainty arising from using sliding head packers arises from the fact that the bottom of the top packer will move upward as the packer expands when it is inflated. This sliding movement allows the use of thicker material for the packer gland making the packers more resilient in rough borehole environments. However, the amount of this movement changes depending on the size of the hole because the packer will expand less in small diameter holes than it will in larger holes. This distance was measured while inflating the packer inside a 4 inch pipe (4 cm movement). Therefore the depth measurements are highly accurate when conducting tests in a 4 inch borehole (± 0.5 cm). Most of the data collected as part of this study was obtained from 4 inch diameter coreholes and therefore depth measurements can be considered to be correct to within ± 0.5 cm.

Three pressure transducers are used, one measuring pressure in the test interval, one measuring the free standing water level in the annulus between the 2 inch casing and the borehole wall above and one measuring the pressure in the open hole below the packed off interval. Louis (1972) and Maini (1971) identified the need for measuring above and below the test interval in their triple packer systems. The transducer for the pressure measurement in the test interval is attached with an elbow compression fitting to the riser pipe, measuring the pressure in the riser pipe just above the packed off interval. Measurement below the packed off interval is done through a ¼” flexible tubing that is run through the system and is fixed with a bored through compression fitting on the top of the top packer and on the end cap at the bottom of the bottom packer. The transducer connects to the tubing at the same depth as the transducer measuring the interval pressure, above the top packer. Data resolution was very poor measuring the pressure in this fashion because it was inevitable that air would become entrapped in the ¼” throughput tube as the equipment is lowered into the borehole. The transducer measuring the pressure in the open borehole above the test interval was fixed in the same location as the other transducers making total head calculations simpler because all transducers are located at the same depth. A new system is being developed that will use underwater plugs to allow each transducer to be situated at the measurement point which should allow better resolution of pressure measurement in the test interval and below and eliminate the effects of equipment non-linear flow.

Three types of transducers were used in the data collection in this study including vented Druck PDCR 1830 (0-100 mV output), and vented, current output PMC VL400 series (4-20 mA output) and a set of Schlumberger Mini-Divers (20 m, 50 m, and 100 m full scale) that measure absolute pressure. Transducers vented to the atmosphere alleviate the need to correct for atmospheric changes. The mV output transducer had a consistently higher resolution than the current output transducer and was therefore used for test interval measurements for all tests. Both transducers are rated to have an accuracy of 0.1% of full scale (± 20 cm). However, accuracy is only needed for the head profiles constructed at the end of the borehole testing. For the hydraulic tests, resolution is most important because all tests are recording changes in the pressure. At constant pressure throughout the entire range of pressures encountered during testing, the mV output transducer consistently would measure the pressure with a resolution of ± 2 cm and therefore can be considered the pressure resolution of all constant head tests conducted. These transducers were periodically calibrated using a Druck DPI 603 portable pressure calibrator. Calibration curves consistently had a very good regression factor (R^2=1) when calibrated over the transducer full range. Recovery tests and slug tests used Mini Divers for pressure measurements because these transducers have a slightly higher resolution (± 1 cm). When the Divers were used to measure pressure a barologger was hung in the trailer to correct for barometric fluctuations.

In addition to the manual flow measurement using the sight gauges, flow is also measured through a series of flow meters including a McMillan G111 (13 – 100 ml/min, 0-5 mV output), an Omega FTB 601B (0.1-2 L/min), and an Omega FTB 603B (0.5-15 L/min). The redundancy of flow measurement with the flow meters and the sight gauges ensures reliability in the flow measurement. Both Omega flow meters have a square wave pulse output. The McMillan flow meter has a rated accuracy of 0.5% of full scale (± 0.5 ml/min). The Omega flow meters are rated as 1% of the reading with a repeatability of 0.1% of the reading. Therefore the middle ranged flow meter has an accuracy of ± 1 ml/min to ± 20 ml/min, and the high range flow meter has an accuracy of ± 5 ml/min to ± 150 ml/min. However, routine calibration of all flow resulted in very good linear regressions (R^2 = 1) for the entire flow range and the values measured by volume output were very similar to values measured electronically (± 3%).

Because transmissivity is slightly dependant on water viscosity and density, temperature was measured in the test interval and in the trailer before injection with high resolution RTD sensors (± 0.03 °C) obtained from Waage Electric (NJ). The test interval temperature was measured inside the bottom of the 2” pipe, (Figure 2-1) and the surface measurement was made at the main manifold for the injection tanks outlet. Test interval temperature can be affected by the injection process when the injection water is much warmer than the ground water temperature. This can occur on hot days as the water tank is in full sunlight. Data from all of the electronic measurement devices was collected using a Campbell Scientific data logger (CR 10X).

2.3 HYDRAULIC TESTS AND PROCEDURE

Each different category of test requires specific equipment, and procedures were developed to allow for consistency in data collection. For constant head tests, injection is done through a mini-packer that is lowered to below the water table in the 2 inch pipe. Three different mini-packers are used to control flows, depending on the flow rate required, the differences being the size of the injection line connected to the mini-packer. The injection lines include 1/8 inch OD and 1/4 inch OD flexible tubing for low flow rates, 3/8 inch OD and 1/2 inch OD for middle flow rates, and 5/8” OD tubing for very high flow rates. For the lowest flow rate mini-packer, the 1/8” and 1/4” lines along with the 1/8” mini-packer inflation line were pulled through a section of 5/8” OD flexible tubing for ease of manipulation. A series of valves are used to control flows from the injection tanks. One benefit of this injection configuration is that once the mini-packer is inflated, the interval is isolated from the atmosphere and becomes a closed system in which the induced pressure rapidly achieves steady state. In low permeable test intervals the mini-packer inflation creates a pressure pulse that can be analyzed as a slug test. Another advantage of this injection system is that the shorter, variable diameter injection lines allow for very good flow control at all injection rates. Test injection times varied between 5 and 15 minutes, with the test ending after the flow and pressure record clearly showed that neither was changing with time.

A 2 inch submersible Grundfos pump is used for withdrawal recovery tests and an injection line without the mini-packer is lowered into the 2” pipe for injection recovery tests. Because the injection and withdrawal lines are routed through the flow meters, a wide range of flow rates can be used during the constant flow period. A check valve fitting was required on the pump for rising head recovery tests to prevent water in the outflow line from falling back into the test interval when the pump was turned off. Flexible tubing is connected to this fitting to allow for the water in the line to be purges with compressed nitrogen before pump removal to lighten the hose weight and minimize leakage when transporting the pump. The outflow from withdrawal tests was routed through the largest flow meter (0.5 - 15 L/min) for accurate flow measurements. However, the pump is capable of a maximum flow rate of 20 L/min, so higher flow rates (15-20 L/min) must be measured manually.

Pneumatic slug tests are conducted using a special fitting (Figure 2-1) that locks on top of the 2 inch casing. Pressure from a nitrogen tank is used to push the water table down and a 2 inch valve on the fitting is used to release the pressure and begin the test. Two pressure gauges are used to monitor the pressure in the 2 inch pipe prior to beginning the test, a 0-5 psi gauge and a 0-30 psi gauge, which can be easily interchanged. This setup makes it easy to conduct multiple slug tests over a large initial head displacements range (5 cm to 20 m).

2.4 EQUIPMENT PERFORMANCE AND DISCUSSION

In all of the constant head step testing with this equipment to date the range of T measured varies from $1x10^{-8}$ to $5x10^{-4}$ m^2/s when using 30 m as the assumed radius of influence. The equipment test range is governed by the range of flow and pressure measurements. Because the sight gauge on the one inch diameter tank will allow measurement of flow rates as low as 6 ml/min, it is anticipated that extremely low T values can be measured with this equipment. It should also be possible to measure higher T values if non-linear flow and fracture dilation can be accounted for because it is difficult to achieve any change in head in extremely permeable zones without causing nonlinear flow or fracture dilation near the test well.

Response to Isolating the Test Interval

During the process of inflation of the main packers prior to testing, different responses were observed in the test interval and above and below the test interval. Some of these responses are due to the fact that all boreholes act as short circuits between the fractures it intersects creating a vertical flow field in the hole from the locations of higher head to lower head. Interrupting this flow field causes changes that can be observed during packer inflation. Figure 2-2 shows the response to isolating the packed off interval identifying a downward gradient because once the test zone is isolated from the upper portion of the hole the interval pressure drops while the pressure above the interval rises. This is caused by plugging the flow system at the depth of the top packer. The downward flow is stopped and the test interval pressure decreases, while the pressure above the top packer increases. Based on packer testing head profiles this hole does have a large downward gradient.

Identification of Connection to the Open Borehole

Sensitivity to pressure changes is greater below the test interval than it is in the open hole above. This is due to the fact that the open hole below the test interval is a closed system which will instantly react to pressure changes. Above the test interval, the water level in the hole must rise to reflect the increased pressure. However, in fractured sedimentary rock, it is conceivable that even though the pressure is increased just above the test interval the water level in the open hole does not change because the pressure is relieved by highly conductive zone(s) above the test interval but below the water level in the open borehole. For this reason the pressure in the open hole was measured just above the top packer to ensure the detection of any pressure changes caused by leakage and/or short circuiting.

Short circuiting is defined as flow around the packers through the formation to the open borehole above or below the test interval (Figure 2-3A & 2-4A). In some zones the fracture network is so dense that part of the network is connected to the open borehole above or below the test interval. In other zones when the rock matrix permeability is large enough, the connection to the open hole may be through the rock matrix. In both of these instances, the injected water travels through the formation to the open borehole causing a delayed pressure response above or below the test interval.

Another type of connecting to the open hole is leakage between the packers and the borehole wall (Figure 2-3B & 2-4B). In portions of the borehole the walls are not smooth because of the presence of extensive vugs or fossils, or in highly fractured zones, where pieces of the rock have broken out and fallen to the bottom of the hole. When the borehole walls are not completely smooth, there is a propensity for leakage caused by incomplete packer seal along the borehole wall. There is no delay in the response above or below the test interval when leakage occurs between the packers and the borehole wall.

Level of Confinement

The response to inflating the mini-packer prior to an injection test may also supply additional information about the test interval as illustrated in Figure 2-5. The mini-packer is lowered into the 2 inch riser pipe to the same depth below top of casing (TOC) in all intervals prior to any packer inflation. In Figure 5A when the main packers hit the borehole wall the pressure below the test interval drops while the pressure in the test interval increases without any change in the water level in the open borehole above. The decrease in pressure below the test interval is indicative of a downward gradient as described above, but the lack of response above suggests that there is a very permeable zone above the test interval capable of dissipating the additional downward flow. The increase in interval pressure can be interpreted as a lower permeable zone under a confining pressure. Upon mini-packer inflation the interval pressure shows an initial slug followed by a large drop, approximately 1 m. When the mini-packer is deflated the pressure returns to the value before inflation. This behavior can be explained by understanding that the transducer is measuring a pressurized system when it is shut in and when the 2 inch vent is opened to the atmosphere the water level rises in the amount of the overpressure. This behavior is indicative of a confined unit with the pressure increase equal to the confining pressure. This zone was subsequently determined to have low permeability based on the constant head tests (T = 4.2e-7 m^2/s) which supports this interpretation.

On the other extreme, in very highly permeable intervals there may or may not even be an initial slug, but the pressure after inflation does not change from pre-inflation values as seen in the single packer test conducted at the bottom of this hole illustrated in Figure 2-5b. This behavior indicates that the packed off interval is well connected to the atmosphere, probably through the fracture network. The entire hole was tested in this fashion and it was observed that there was a gradation from low permeable zones (confined) towards the zones of high permeability (unconfined) with progressively less confinement. Table 2-1 summarizes the data for this borehole. The data indicates that this fractured dolostone aquifer acts as an unconfined aquifer at three depths (14m 28m and 40m), and the level of confinement is maximum in between these depths. This is important information when determining the type of data analysis.

Constant Head Step Tests

Figure 2-6 illustrates typical constant head data collected at the Guelph field site. Measuring above and below the test interval gives greater confidence that no leakage or short circuiting is occurring. The data also suggests that 10 minutes is an adequate time for the system to achieve equilibrium. However, this time appears to increase as perturbations increase as it will take a longer time for the flow rate to come to equilibrium as shown in the flow rate measurement in the last step in this data set. The resulting Q vs dP plot illustrates the ease of identifying non-linear flow with this type of hydraulic test.

Slug Tests

Figure 2-7 shows representative raw slug test data collected with this system. Once again the lack of a response above and below the test interval indicates no leakage or short circuiting. The slug response curves all show a pressure spike prior to the slug recovery. This is caused by the pressurization of the 2 inch pipe that pushes the water level down replacing the water column with pressurized nitrogen and can be considered a falling head slug test. When the 2 inch valve is opened to atmosphere, the water column instantly drops and begins to recover to the static water level (rising head slug test). Based on the results of this study, nonlinear flow in both the test equipment and in the formation causes the calculated T to decrease while fracture dilation causes T to increase, when the initial displacement increases.

Pumping and Recovery Tests

Multiple pumping and recovery tests were conducted at many test intervals and typical data are shown in Figure 2-8. The withdrawal pumping and recovery tests conducted in the rural holes commonly indicate a connection to the open hole above the test interval and the connection appears to be greater as the pumping rate increases. This violates a radial flow model for the test and illustrates the effect of a long term displacement on the large scale fracture network and rock matrix. If the pumping period is long enough to achieve equilibrium in the larger scale fracture network and rock matrix, the recovery period will reflect the permeability of the large fractures near the test interval which will recover first, followed by the permeability of the larger scale fracture network after the large fractures have recovered (Pollard, 1959).

2.5 CONCLUSIONS AND IMPLICATIONS

The packer testing equipment has been shown to achieve high resolution measurements over a broad range of test conditions with operational ease. Monitoring pressure above, below, and within the test interval provides improved understanding of the test conditions prior to and during each test including the degree of connection to the open hole and levels of confinement for each test interval and recording the pressures as the packers are inflated can give insight into the flow environment in the open hole. Application of the equipment in six boreholes at the Guelph field sites provided results showing the value of conducting different types of tests over a wide range of test conditions. When multiple step constant head tests are conducted in the same test interval at increasing injection flow rates, it is relatively easy to identify non-linear flow. Slug tests show non-linearity at higher displacements due to both the formation and the test equipment. Test equipment non-linearity can be eliminated if the transducer is situated in the test interval outside the test equipment which would require using absolute pressure transducers with underwater plugs to pass through the equipment. Pumping and recovery tests give insight into the surrounding fracture network and matrix.

Tables

Table 2-1 Confining pressures based upon mini-packer inflation. The highest permeable zones are highlighted.

Year	Well	Zone	Top Depth (mbTOC)	Bot Depth (mbTOC)	Confining Pressure (m)
2008	MW-26	24	6	7.5	0
2008	MW-26	23	7.5	9	0.58
2008	MW-26	22	9	10.5	0.57
2008	MW-26	21	10.5	12	0.47
2008	MW-26	20	12	13.5	0.31
2008	MW-26	19	13.5	15	0.04
2008	MW-26	18	15	16.5	0.32
2008	MW-26	17	16.5	18	0.67
2008	MW-26	16	18	19.5	0.44
2008	MW-26	15	19.5	21	0.65
2008	MW-26	14	21	22.5	0.64
2008	MW-26	13	22.5	24	0.51
2008	MW-26	12	24	25.5	0.65
2008	MW-26	11	25.5	27	0.04
2008	MW-26	10	27	28.5	0
2008	MW-26	9	28.5	30	0
2008	MW-26	8	30	31.5	0
2008	MW-26	7	31.5	33	0.05
2008	MW-26	6	33	34.5	0.4
2008	MW-26	5	34.5	36	0.59
2008	MW-26	4	36	37.5	1.03
2008	MW-26	3	37.5	39	0.12
2008	MW-26	2	39	40.5	0.04
2008	MW-26	1	40.5	43.04	0

Figures

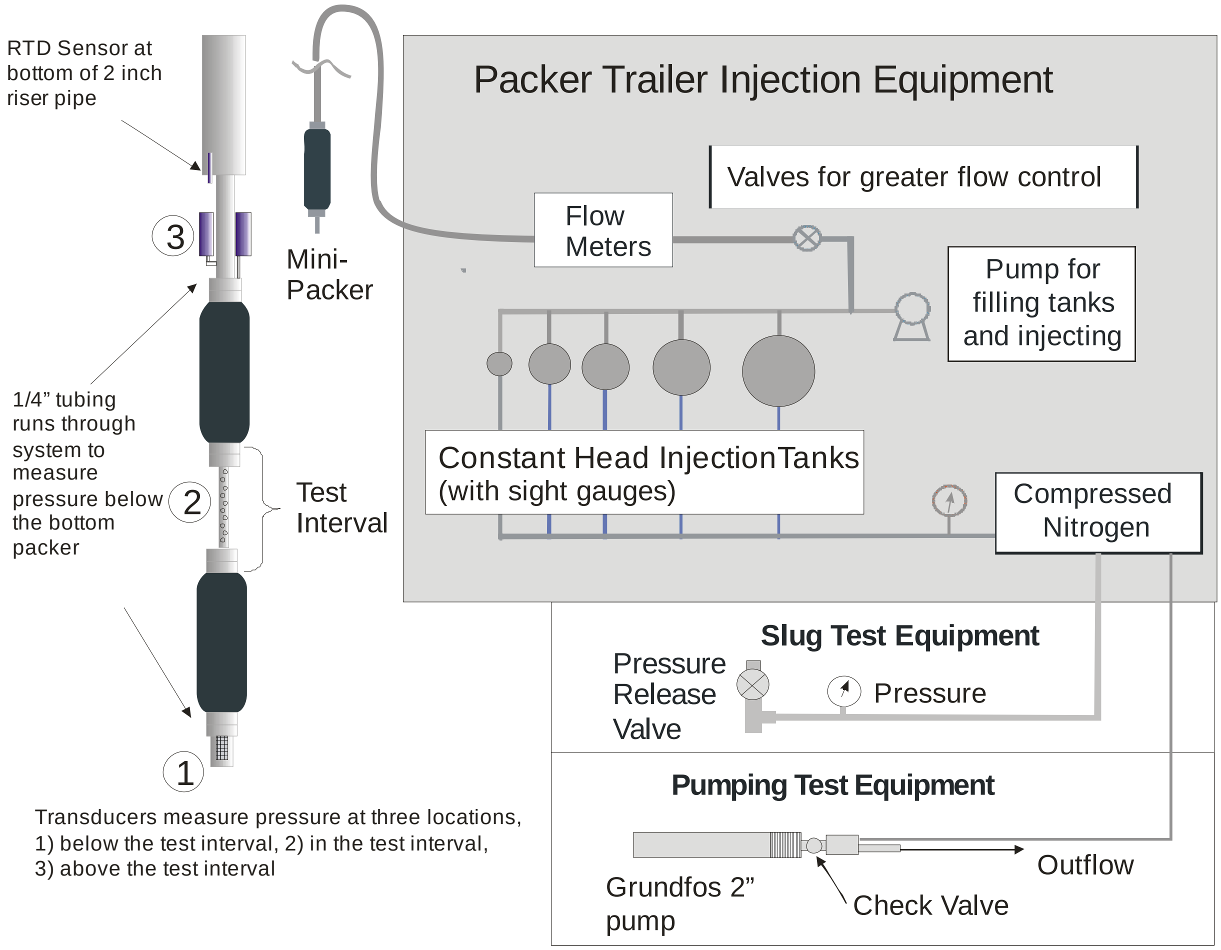


Figure 2-1 Schematic of Packer Testing System

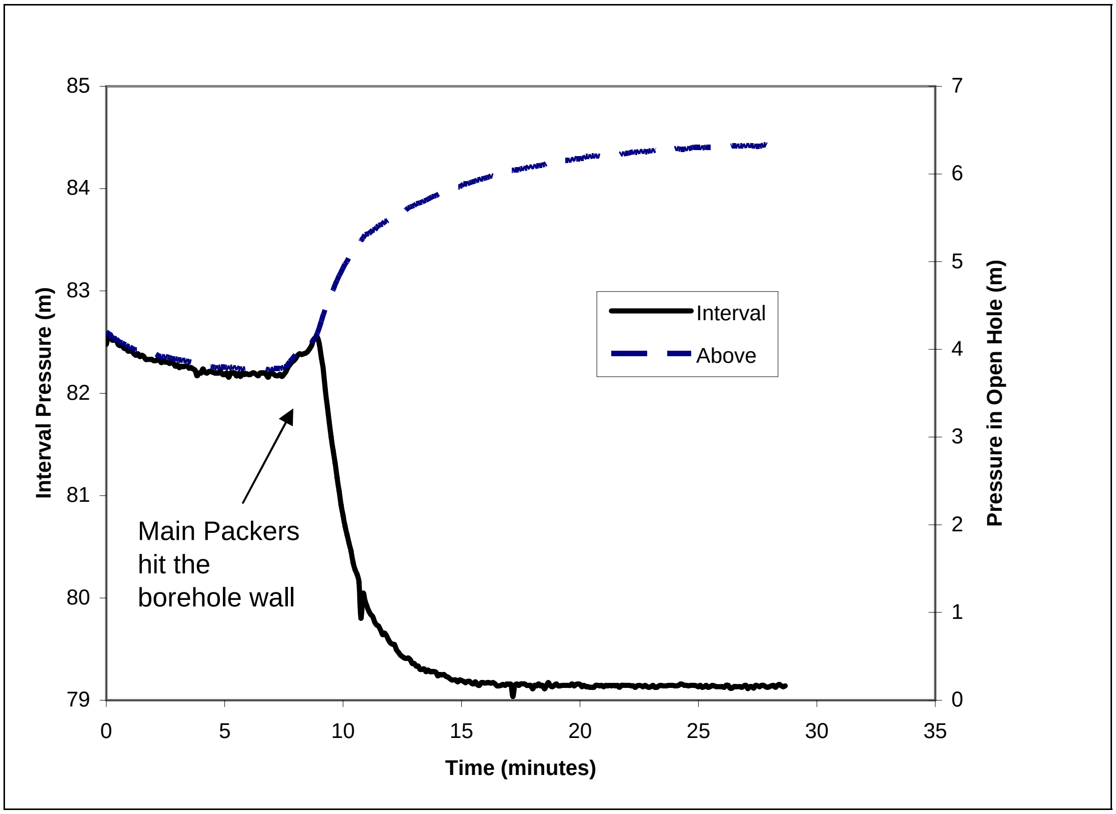


Figure 2-2 Equilibrium pressures in the test interval and above the test interval in the open hole and evidence of a downward gradient

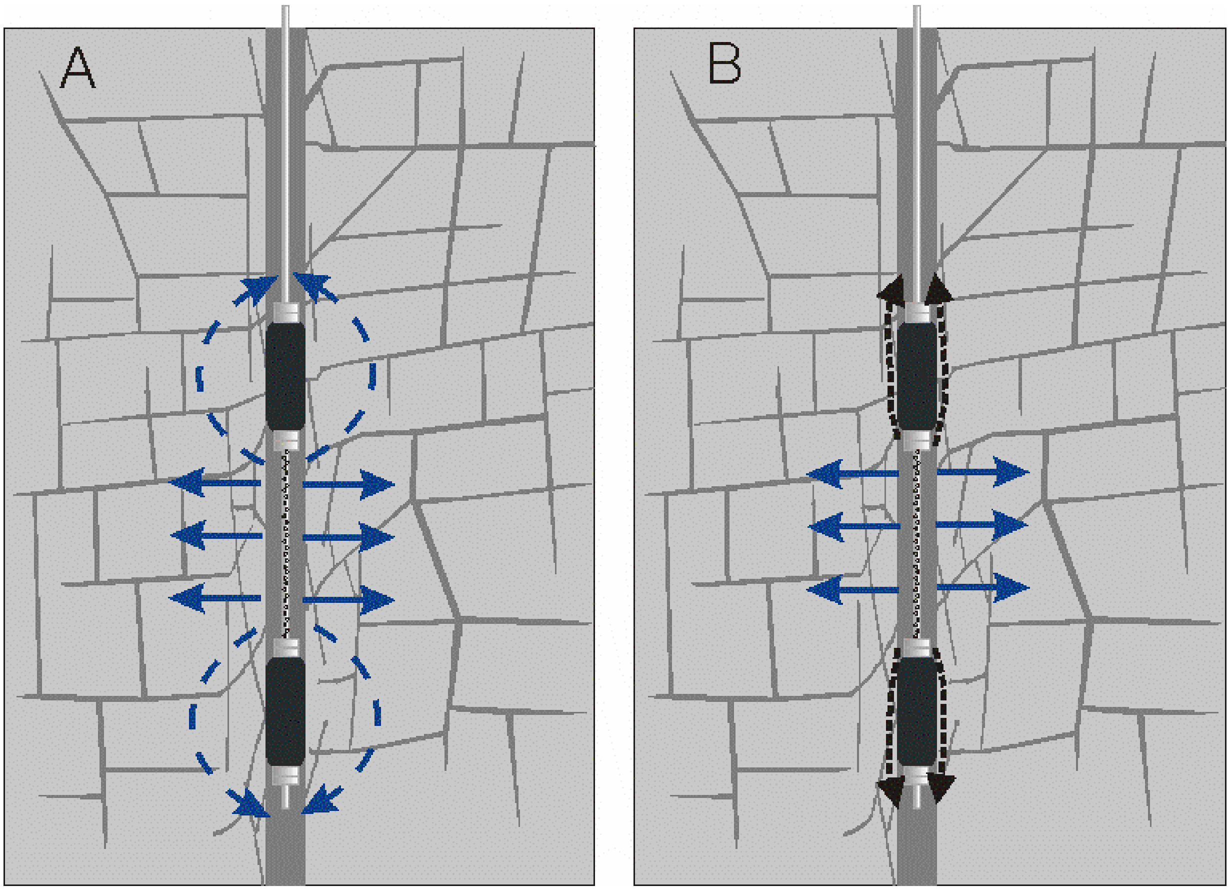
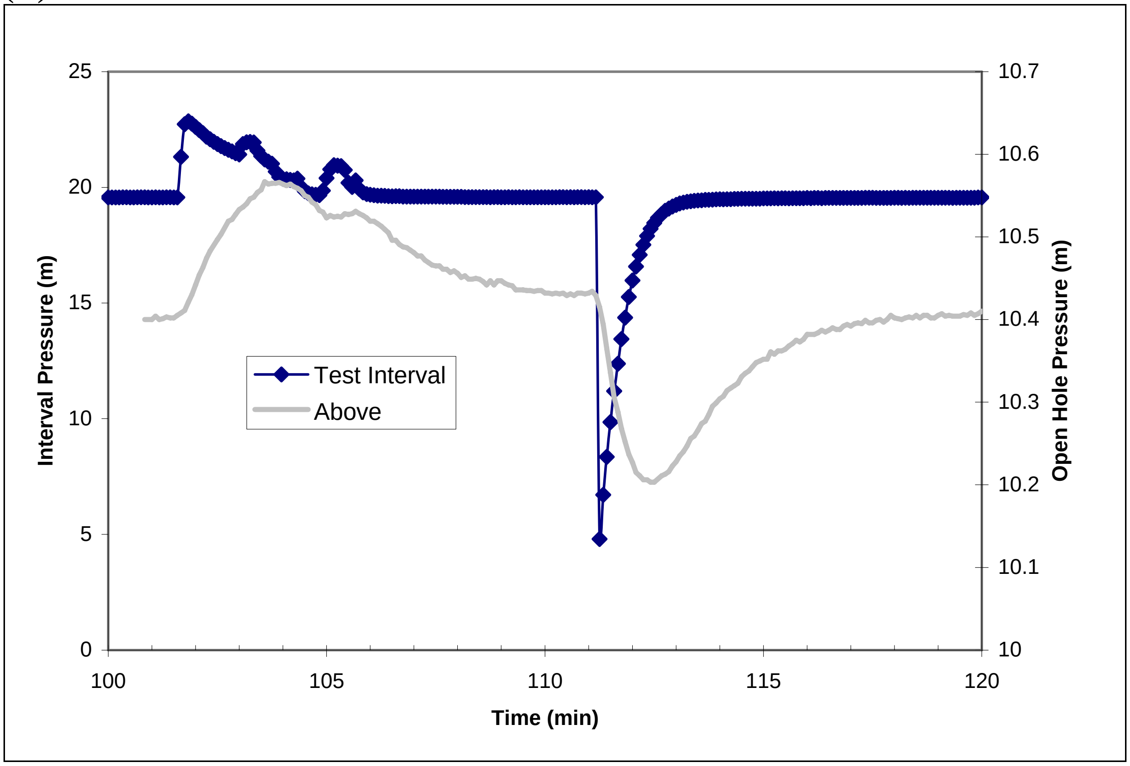


Figure 2-3 (A) Short circuiting occurs when injected water reaches the open hole above or below the test interval through the formation. (B) Leakage occurs when injected water reaches the open hole above or below the test interval between the packers and the borehole wall.

(A)



(B)

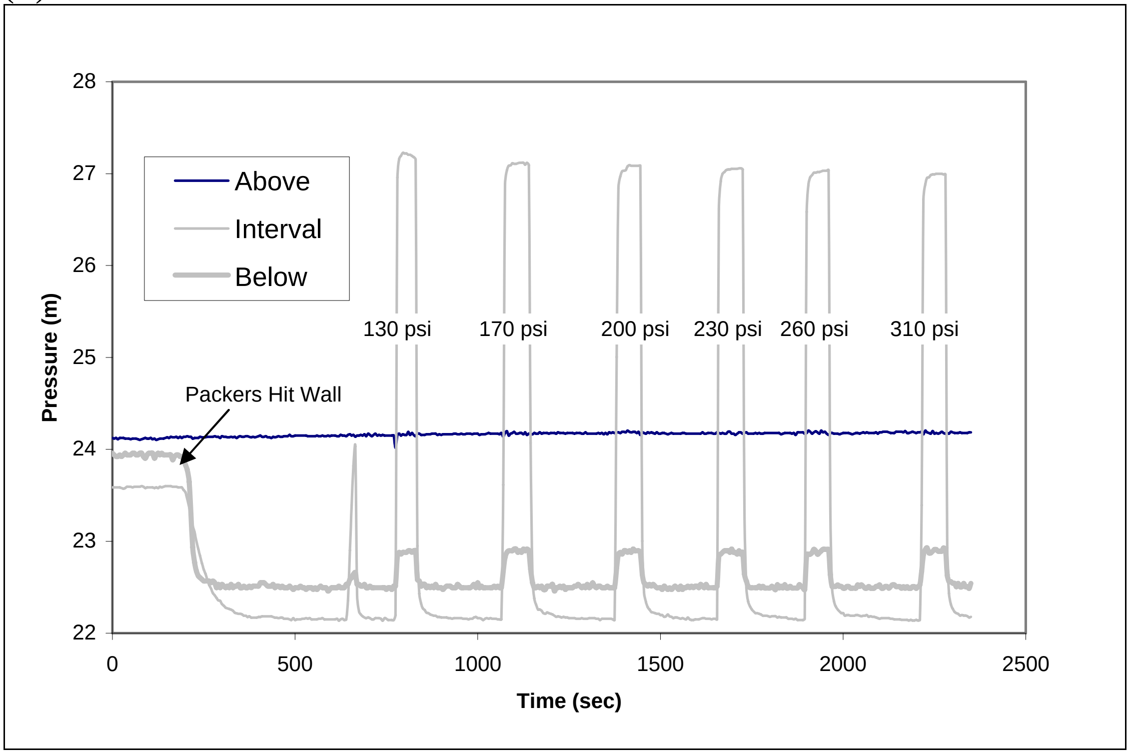
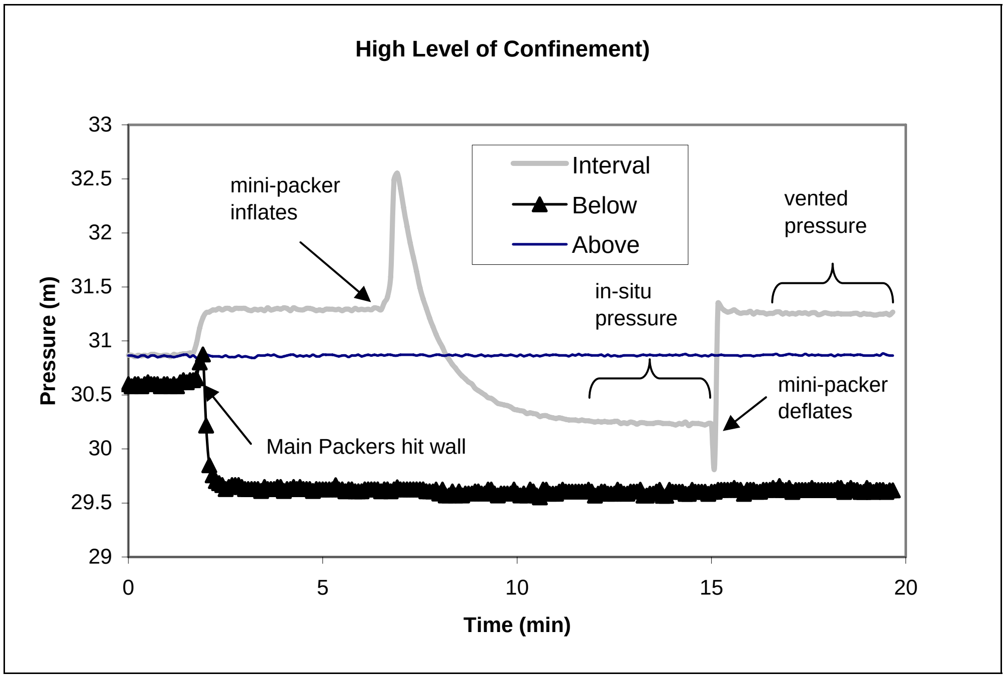


Figure 2-4 (A) Short circuiting through the formation is indicated by a delayed response. (B) Packer leakage between the packer and the borehole wall is indicated by an immediate response. Increasing the packer pressure does not lessen the leakage.

A



B

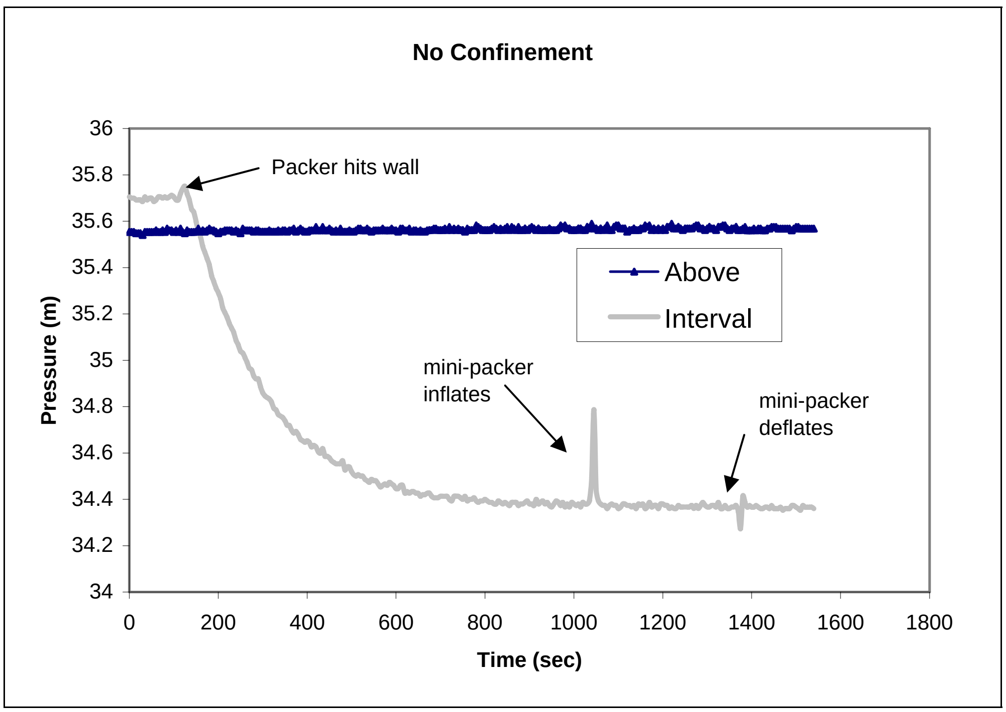
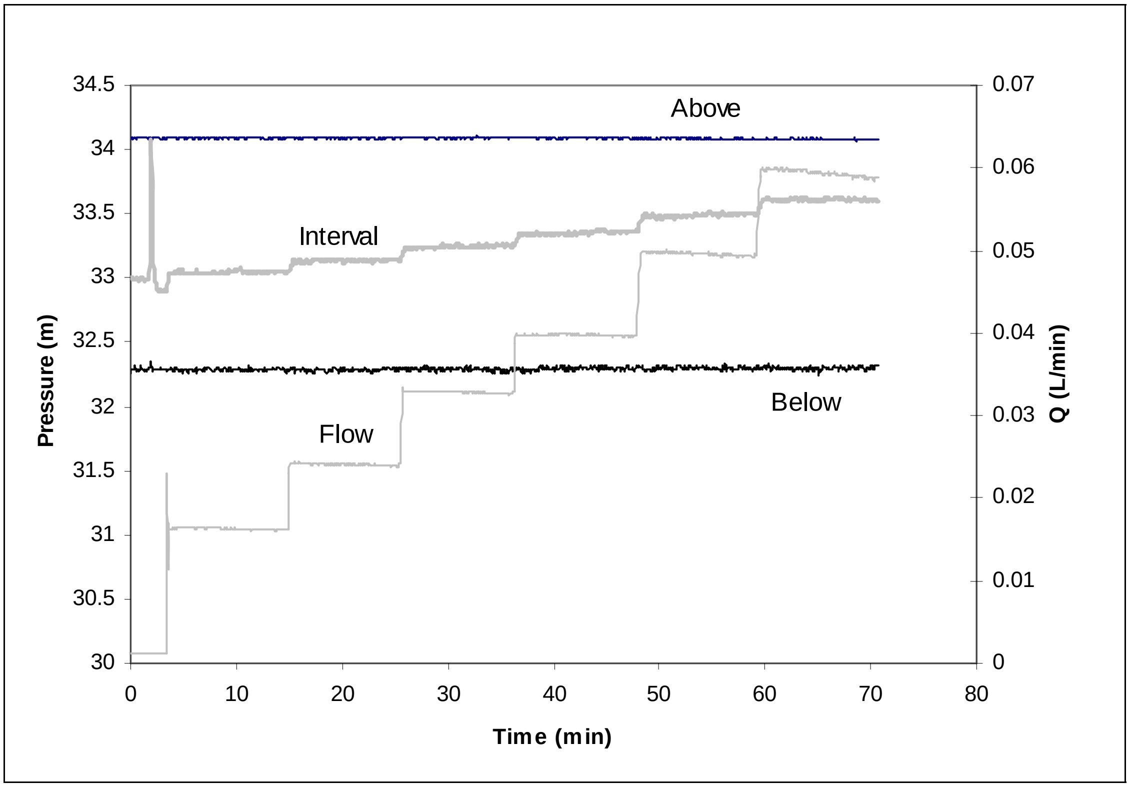


Figure 2-5 (A) Once the zone is isolated the pressure below the test interval drops indicating a downward gradient. The pressure in the test interval rises due to the presence of confining pressure and when the 2 inch conduit to the surface is opened, the actual confining pressure is revealed. (B) The response of seating the packers in high permeable test intervals does not exhibit this phenomenon.

A



B

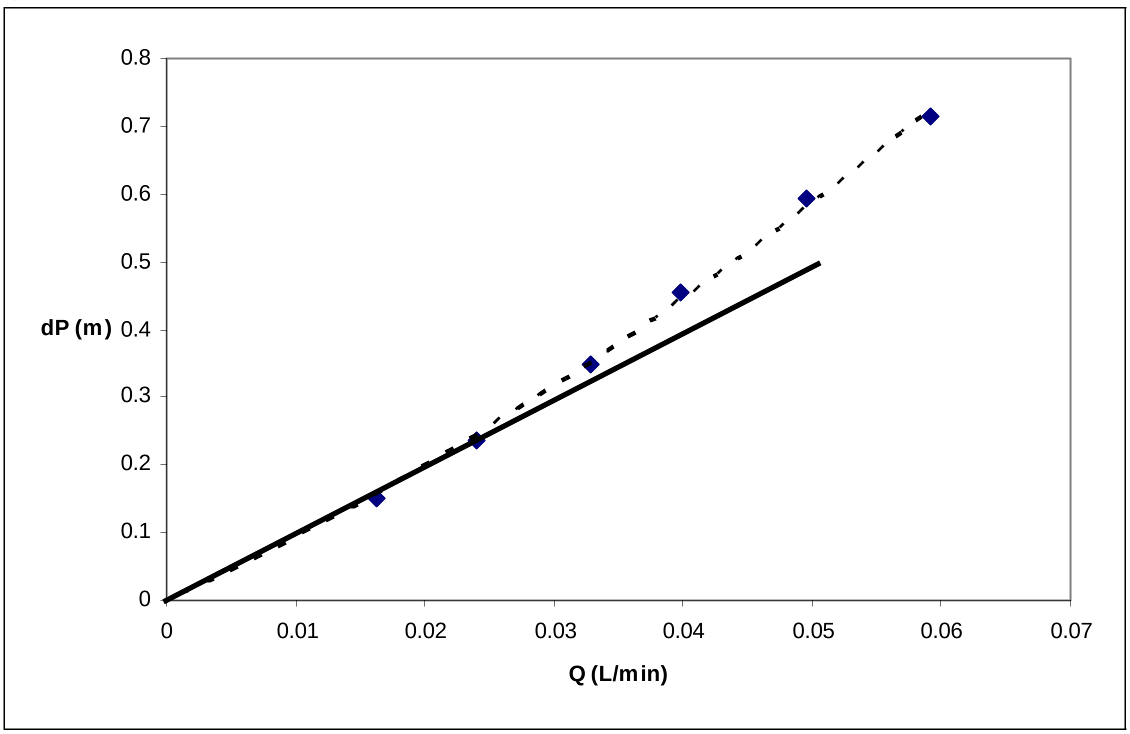


Figure 2-6 (A) Example of Constant Head injection test raw data and (B) the resulting Q vs dP plot illustrating slightly non-linear behavior.

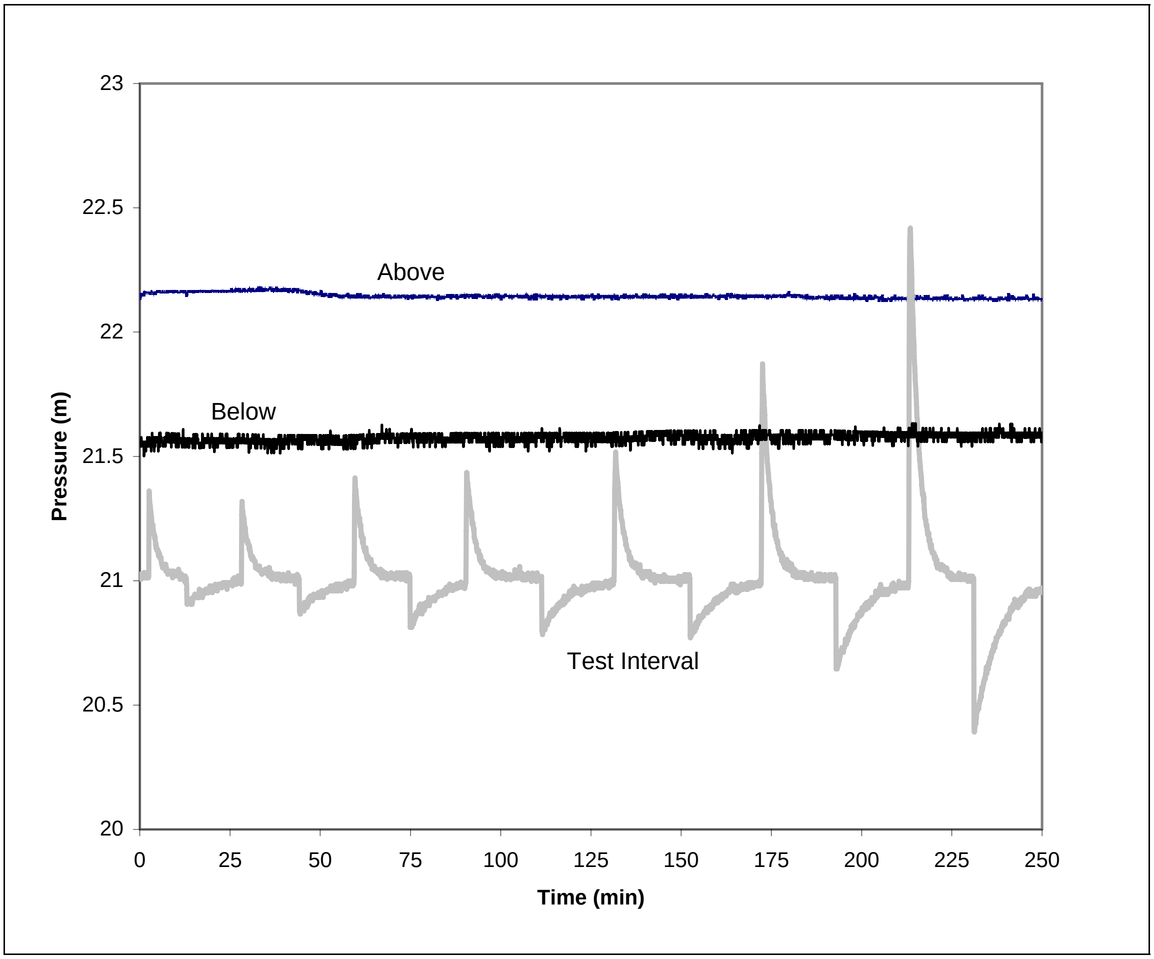
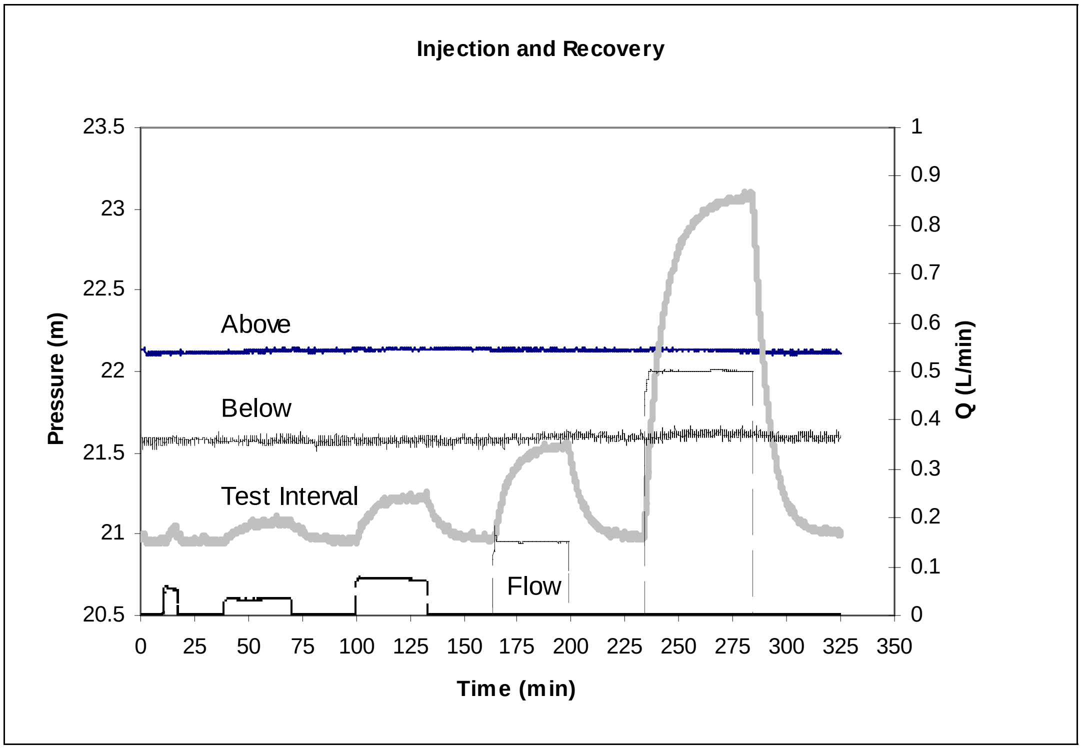


Figure 2-7 Typical Slug Data showing the falling head and rising head test pairs.

A



B

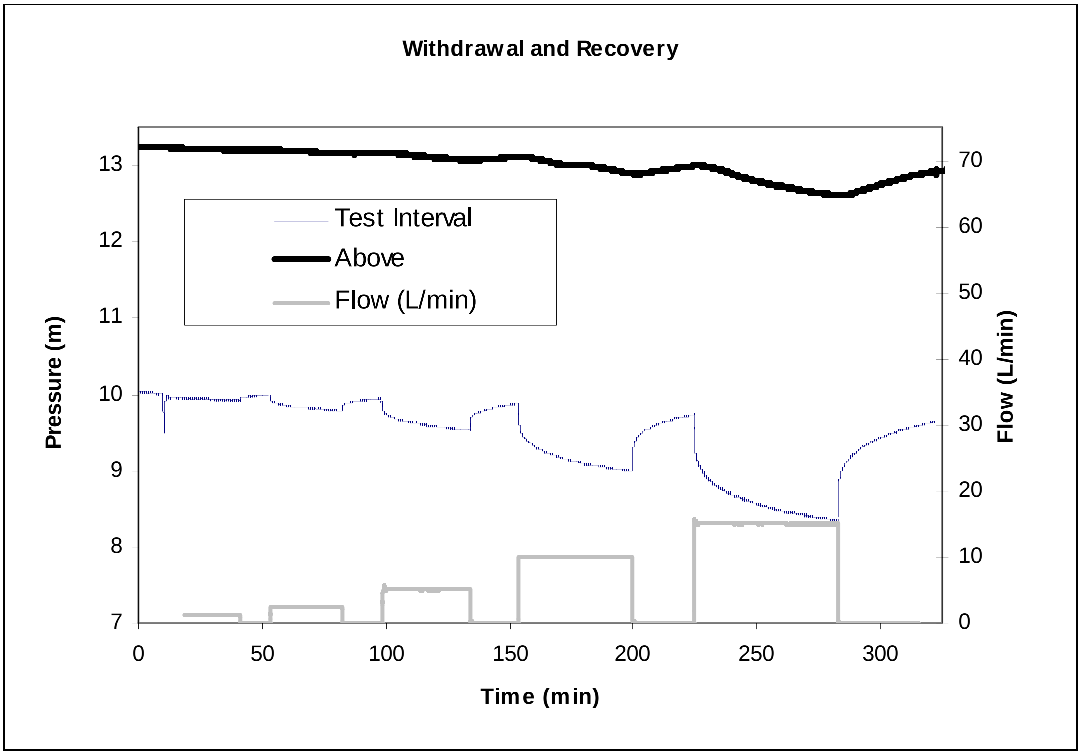


Figure 2-8 (A) Injection data from the Guelph Tool Site (low matrix permeability) and (B) Withdrawal data from the Guelph Tier 3 Site (high matrix permeability).

Chapter 3 Quantification of non-Darcian flow encountered during packer testing in fractured rock

3.1 INTRODUCTION

In analysis of packer test data collected from fractured rock, the transmissivity values are commonly derived using mathematical models based on the assumption of Darcian flow in the fractures (Witherspoon et al., 1980; Barker, 1981; Braester & Thunvik, 1984; Bliss & Rushton, 1984; Novakowski et al., 1997). In Darcian flow, the relation between Q and dP is linear and therefore the Darcian condition is commonly referred to as linear flow. There is abundant literature concerning Darcy-based mathematical models for analysis of packer testing data to obtain values of T or hydraulic conductivity (K), however, lacking knowledge of whether or not the test data are from the Darcian range imposes errors irrespective of the model used. Elsworth and Doe (1986) used mathematical modeling of packer tests in fractured rock to show that calculation of T using non-Darcian constant head data can lead to underestimation errors as much as an order of magnitude. However, detailed examination in field tests of the condition at which the flow regime changes from linear to non-linear is lacking.

There are two steps involved in the traditional determination of T from steady state hydraulic tests. In the first step, flow (Q) and applied pressure (dP) values are plotted for all steady state data in a test interval and a determination is made as to which points are within the linear flow regime. Figure 1 is a comparison of linear and non-linear packer testing data. Typically, the linear portion will not pass exactly through zero, but the offset (y intercept) will be very small. Figure 3-1B shows an example where non-linear results appear linear, but the y-intercept is much larger (3 orders of magnitude).

The second step is to use the value Q/dP where the graph is linear to calculate T of the test interval using the Thiem equation.

$$T = \frac{Q}{2\pi\Delta h}\ln\left(\frac{r_o}{r_w}\right) \quad (1)$$

Where:

Q = flow rate (m3/s)
Δh = change in head from ambient (m)
r_o = radius of influence of the test (m)
r_w =well radius (m)

The Thiem equation is based on the assumption that all flow is radial and Darcian through a horizontal, confined, mathematically “infinite” homogeneous aquifer. It was originally developed for pumping tests in a confined porous media aquifer where two observation wells are used (Wenzel, 1936), but it is commonly used in the single well context for packer tests in fractured rock. (Doe & Remer, 1980; Gale, 1982; Haimson & Doe, 1983; Lapcevic, 1988; Novakowski et al., 1997)

In Darcian flow, Q/dP = constant, but excessive injection pressure or flow can cause this value to deviate. Figure 3-2 illustrates the common causes of deviation from linear flow (Atkinson, 1986). If inertial forces begin to dominate because of excessive flow, Q/dP will decrease but if the fractures dilate, due to excessive injection pressure, there will be an increase of Q/dP. In contrast to flow in smooth parallel plates where there is a relatively abrupt transition between laminar and turbulent flow, in fracture flow the transition zone is much larger due to asymmetrical fracture geometry characteristics such as fracture roughness, dead end voids, aperture variations, and contact area (tortuosity) that cause deviation from linearity to begin much sooner (Maini, 1971; Louis, 1972; Atkinson, 1986; Konzuk & Kueper, 2004).

There is an abundance of laboratory experiments involving flow in single fractures in rock or concrete blocks where the transition from linear to non-linear flow has been observed (Rasmussen, 1995; Nicholl et al., 1999; Belhaj et al., 2003; Konzuk & Kueper, 2004; Zimmerman et al., 2004; Qian et al., 2005; Ranjith et al., 2007). There have also been field studies where non-linear flow during hydraulic testing was identified in both fractured rock (Maini, 1972; Gale 1975) and unconsolidated deposits (McElwee & Zenner, 1998). However, only minimal attention has been directed in field studies to quantify the Q vs dP relationship during the deviation from linearity in borehole tests.

In this study, a methodology involving improved packer testing equipment and procedures for constant Q injection tests was developed for fractured rock boreholes to identify and investigate the transition from Darcian to non-Darcian flow. This methodology was applied intensively in studies of a fractured dolostone aquifer where contaminant behavior is being assessed. The packer tests were conducted in four boreholes approximately 40 m deep using multiple interval lengths to discern whether the test results can be described by a general Q vs dP relationship. Based on the results of previous studies it is anticipated that deviation from a linear relationship will occur at relatively low flow rates, but the magnitude of this deviation is not known, and it is unclear whether this deviation can be adequately described mathematically in a useful manner.

3.2 FIELD APPROACH AND TEST METHOD

The packer testing equipment used in this study is an adaptation of the system originally illustrated conceptually by Gale (1982) and described operationally by Lapcevic (1988). Design modifications were directed at achieving greater accuracy of Q vs dP relations covering a large flow range starting at very low flow rates. This modified packer testing system illustrated in Figure 3-3 and described in detail in Chapter 2, consists of a trailer containing a series of tanks of different diameter with sight gauges used to measure flow rates by timing the rate of water level drop and the tank diameter. All tanks are connected through a manifold system to a compressed nitrogen cylinder used to pressurize the void space above the water in the tanks. A different nitrogen cylinder is used to inflate the packers. Three turbine flow meter devices collect water injection rate data electronically in the range of 13 ml/min to 15 L/min. Three pressure transducers are used, one measuring pressure in the test interval, one measuring the water level in the open hole above and one measuring the pressure below the packed off interval. Data from all of the electronic measurement devices is collected using a Campbell Scientific data logger (CR 10X). Large sliding head P packers made by RST Instruments are used to isolate the test interval (7.1 cm deflated, 14.7 cm max inflated) requiring a higher pressure regulator (1500 psi) on the nitrogen cylinder used for packer inflation. The water injection line consists of 2 inch diameter Solinst well casing (5 foot lengths) to the ground surface. In order to maintain a closed system in which the pressure changes rapidly reach equilibrium, injection is done through a mini-packer that is lowered to below the water table, inside the 2 inch pipe, and inflated. A third nitrogen cylinder is used to inflate the mini-packer. Two flow lines are connected to the mini-packer, 1/8 inch OD and 1/4 inch OD flexible tubing (3/8 inch OD and 1/2 inch OD for higher flow rates) and a series of valves are used to control flows. This system configuration allows for high accuracy of flow measurements over a large range of flow rates.

The injection tests were conducted in four open boreholes at a site in Guelph, Ontario, where the rock is predominantly fractured Silurian dolostone (Dekeyser et al., 2006) overlain by

Quaternary deposits and underlain by a massive shale formation. The rock units identified at the Guelph site extend over a large area and are part of an important dolostone aquifer regionally (Singer et al., 2003, Dekeyser et al., 2006). The HQ holes were cored with a diamond bit, creating a nominal diameter of 96.1 mm (3.78 inches) to depths ranging from 40 to 43 m. Top of rock was typically encountered at 3-5 mbgs and well casings were keyed into the rock. All cores were examined to identify geologic and physical features and fractures were identified as open (core separates at the fracture), closed (core does not separate at the fracture), broken zone (too broken to identify individual fractures) and signs of historical flow effects (weathering, mineralization) were recorded. Samples were also collected from the cores for analysis of contamination and rock physical properties. Lab permeability tests indicate that the rock matrix has a very low permeability so fracture flow should dominate the flow in packer tests. Various geophysical logs were also collected in the boreholes before packer testing. All holes were packer tested from the bottom upward with a 1.5 m test interval and packer inflation tests were conducted to ensure proper interval sealing following the procedures recommended by Maini (1971). Finally, all tests were completed after pressure equilibrium has been established in the test interval and also in the open hole above and below the test interval.

The injection rate at which flow becomes non-linear is not known prior to testing in each interval and therefore, to ensure the collection of linear flow data, the initial constant head step test was conducted at the lowest flow rate possible producing a measurable increase in interval pressure. This flow rate varied from 10 ml/min to 150 ml/min for each 1.5 m test interval depending on the permeability. Subsequent step tests were then conducted at regular increases in flow to determine the flow pressure relationship over a large range of flow rates.

3.3 CONCEPTUAL FRAMEWORK FOR DATA ANALYSIS

A linear flow model can cause errors in the determination of T in fractured rock because much of the data collected during packer testing can be non-linear due to flow occurring in transition between linear and fully turbulent flow (Sharp, 1970; Maini, 1971). Therefore in many cases, much of the data collected during a steady state packer test should not be used in the determination of T. However, it is postulated that if the data in the non-linear flow range can be described mathematically, it may be possible to either use all of the data collected to determine T, or very accurately eliminate all non-linear data, either of which will result in a more accurate calculation of T.

Early researchers considered all non-linear flow to be turbulent (i.e. $Q^2 \propto dP$), analogous to flow through pipes and assumed that the proportionality constant between Q and dP, the hydraulic conductivity (K), is different for linear flow and non-linear flow (Louis, 1972; Atkinson, 1986; Elsworth & Doe, 1986). Technically, K and T are considered to be properties of both the flow medium and the fluid because these values are dependant on the temperature of the fluid which affects its density and viscosity.

$$K = \frac{k\rho g}{\mu} \qquad (2)$$

Where: K = hydraulic conductivity
k=permeability
ρg=specific weight of water
μ=absolute viscosity

Based on the temperature measured during the packer tests, the small temperature changes observed (ΔT< 1°C) result in no significant changes in the properties of water. Therefore, in isothermal systems in which the fluid is considered incompressible, the values of T and K should not change based on flow regime change. However, their values could change if significant fracture dilation and/or hydrofracing occur during the test.

Sunada (1965) used the Navier-Stokes equations to develop the governing equation for flow through porous media without neglecting the viscous term to account for non-linearity. He states that flow non-linearity is caused by three processes, viscous effects at low velocities and convective acceleration (e.g. changing flow direction) and turbulence at high velocities. Experiments using dye showed that even though the Q vs dP relationship is not linear, the flow will still exhibit laminar characteristics. Because of this Sunada postulates that the initial deviation from linearity is caused by convective acceleration of the flow, not turbulence, and dP is never proportional to Q^2 except at very high velocities when turbulence actually occurs. Dryden (1955) in his studies of the transition zone of air over a flat plate comes to the same conclusions stating that the breakdown of laminar flow does not constitute full transition to turbulence. Acosta et al. (1985) conducted a study of flow through narrow capillary channels for the determination of the rates of mass and momentum transport. The apertures studied ranged from 200 to 500 μm. A pump capable of producing an outlet pressure of 250 psi was necessary in order to increase the velocity high enough for the flow to be fully turbulent. Because the pressures used during packer testing is much lower than this it is unlikely that flow through the fractures in the formation is fully turbulent.

The Forchheimer equation was first used by Jacob (1946) to describe the entire flow field in a confined aquifer during a pumping test including the non-linear portion near the well, and the linear portion further away when determining the effective radius of the pumping well in unconsolidated deposits, and others have adapted its use for flow through fractured media.

$$dP = aQ + bQ^2 \qquad (3)$$

A disadvantage of this non-linear model is that the data should be divided into the linear and non-linear portions before application, because there are no turbulent losses in linear flow. However, it has been shown that it can be applied to all of the data with reasonable accuracy within the range of the data collected (Zimmerman et al., 2004), but because it is a simple quadratic equation representing all non-linear losses as a function of Q^2, its ability to predict outside the range of the data is questionable. Some researchers have mathematically derived the Forchheimer constants by integrating over the radial flow field in a field test assuming that Q^2 is proportional to dP from the well bore to the critical radius where flow becomes linear again ($Q \propto dP$). However, in radial flow the velocity decreases exponentially away from the well because of the increased flow area (e.g. $A_{flow}=2\pi rb$) and because the flow regime is based upon the flow velocity it is unlikely that the flow will remain turbulent to the critical radius and suddenly return to linearity. Instead the flow will gradually return to linearity as the flow area is increased, and throughout this transition the flow will still be non-linear but not fully turbulent.

Another non-linear model is identified as the Missbach Equation by Maini (1971) and Atkinson (1986). This equation can also be used to describe the flow field in the formation during a field test.

$$Q^n = C\frac{dh}{dr} \qquad (4)$$

Where: n describes the flow regime at a location in the flow field varying between 1 and 2.
C is a constant depending on the water viscosity and the geometry of the fracture

$\frac{dh}{dr}$ is the radial gradient

Taking the log of both sides of (4) results in the equation for a straight line. Therefore a plot of log Q vs log $\frac{dh}{dr}$ should result in a straight line and C and n can be evaluated. This is the traditional use of the Missbach equation assuming that the exponent will remain constant over a small range of flow rates.

In this study the Missbach equation is used in a slightly different manner. In field packer tests the two parameters measured are the flow rate and the applied pressure. If it is not assumed that the exponent is constant over any range of flow rates a more general equation can be developed involving the two measured parameters.

$$dP = CQ^n \tag{5}$$

Where: C is the linear proportionally constant for radial flow (n=1)
n=describes the deviation from linearity ($1 \leq n \leq 2$)

This is a more practical attempt at quantifying non-linear flow using a Darcy-Missbach conceptual model to determine the deviation from linearity. This is an empirical relationship, Darcy’s Law with Missbach’s exponent introduced to account for the decrease in flow observed at higher pressure gradients because of non-linear flow. Non-linear behavior is dependant on the transmissivity of the test interval which is represented by the constant of proportionality during linear flow. This equation applies to a point in the flow field at the borehole wall where the non-linearity is the greatest. This empirical incorporation of Missbach into the Darcy equation assumes that all pressure losses occur in the formation and that the linear behavior is adequately expressed by Darcy’s Law (Thiem equation). The constant used in this equation is numerically equal to $\frac{\ln\left(\frac{ro}{rw}\right)}{2\pi T}$ when the entire system is linear, meaning that T does not change with the flow regime, while quantifying the reduction of flow due to non-linearity at higher gradients. Derivation of the constants when non-linear flow is present is outlined in Appendix A. The exponent ‘n’ in the Darcy-Missbach model can then be calculated using the linear constant from (5), taking the natural log, and solving for n.

$$dP = CQ^n$$

$$\ln dP = \ln C + n \ln Q$$

$$n = \left(\frac{\ln dP - \ln C}{\ln Q} \right) \tag{6}$$

When exponents are calculated for all the steady state tests conducted in the same test interval, a plot of Q^n vs dP results in a straight line with a slope equal to the linear slope. The magnitude of the exponent quantifies the degree of deviation from linearity.

A comparison is made of the performance of the Forchheimer equation with the Darcy-Missbach equation to describe all the packer testing data within the range of data collected and to make predictions of applied pressure at higher flow rates. Because the Darcy-Missbach model contains an exponent that is constantly changing, it is not possible to plot in the same fashion as Forchheimer. However, examination of various plots of ln Q vs ln dP and a review of the underlying theory indicates this plot is more than just a straight line. First of all, because the Q vs dP plot theoretically passes through the origin (0, 0), the ln Q vs ln dP plot must theoretically pass through the point (1,1). This is very difficult to achieve by applying a linear relationship to the log data. Instead, the data can be better represented as a very gradual curve beginning at (1,1) that can be described by a quadratic equation. This equation can then be used as a predictive tool for higher or lower flow rates. By plotting the data in natural log form the non-linear exponent is essentially removed and incorporated into the slope of the log relationship and this slope guides the quadratic equation at predictions involving higher flow rates. The shrinking of the axes scale also puts more emphasis on the non-linear data as these points are spread out to a greater degree than the linear data implying good accuracy for predictions at higher flow rates.

3.4 RESULTS AND DISCUSSION

Most of the data used here was collected in borehole MW-26, a 40m deep borehole in a fractured dolostone aquifer at the Guelph field site. All twenty two 1.5 m intervals in this hole were tested more than once using the constant head method to assure reliability of the data. All of the test results showed some deviation from linearity at relatively low injection flow rates, with greater deviation observed in higher permeable intervals. This is consistent with the few previous field studies that have identified non-linear flow during packer tests in fractured rock (Louis, 1972; Gale, 1975; Mackie, 1982). Figures 3-4 and 3-5 are typical plots showing non-linearity observed in high permeable and low permeable zones respectively. The high permeable zones show a much greater deviation from linearity than the low permeable zone illustrating that flow through fractures is very restricted in very small fractures and this restriction lessens as the fracture aperture increases. Because non-linearity is a function of flow rate, greater deviations from linearity will be seen in larger fractures.

In this study of packer testing, non-linearity was observed in almost all tests and the onset of nonlinearity occurred at water injection rates of 0.02 to 0.5 L/min. The non-linearity observed can be explained as either a deviation due to flow regime or fracture dilation. Fracture dilation can interfere with the Q vs dP relationship in an opposite fashion, however, it can be rationalized that it is likely that non-linearity caused convective acceleration will occur first in a fracture, followed by non-linearity resulting from fracture dilation, and once the fracture is fully dilated, a final transition towards turbulent flow. In the 22 step tests conducted in this borehole, only 4 intervals showed an indication of fracture dilation. In these cases the data collected prior to the dilation was used for the model comparison.

Figure 3-6 illustrates the comparison of the Forchheimer equation and the Darcy-Missbach model to predict data collected in one test interval. For this comparison the Forchheimer equation is fitted to the data collected in the Q vs dP plot and the Darcy-Missbach model is a quadratic equation is fitted to the ln Q vs ln dP plot. The linear regression of both models is very good in both cases ($R^2 \approx 1$). Tables 1 through 3 shows the comparison of these models in predicting the observed dP based on the observed flow rate in three zones in this hole. For this comparison the quadratic equation obtained from fitting to all of the data collected in arithmetic space (Forchheimer) and log log space (Missbach) is used to predict the dP from the measured Q. The calculated dP is then compared to the measured dP. Both models performed very well in predicting the measured dP within the range of the data collected.

Figure 3-7 illustrates the predictive capability of both models. For this comparison a test interval in which 13 step test were conducted is used. However, only the first 7 data points are used to fit the respective models and the resulting equations are used to predict the dP at higher flow rates. The predictions are then plotted along with the full data set collected. The

Forchheimer equation over predicts the dP at higher flow rates, while the Darcy-Missbach equation appears to be much more accurate. In all of the tests conducted in this borehole, when both models are used to predict dP at higher flow rates outside the data range, the Forchheimer equation predicts a higher dP than the Darcy-Missbach model. The differences are greater in intervals in which a greater degree of non-linearity was observed.

The exponents of the Darcy-Missbach model were calculated for all data collected and in the resulting Q^n vs dP plot all of the data falls on a straight line with the slope of the linear data with a very good regression (R^2=1) as illustrated in Figure 3-8. This implies that this model adequately accounts for the deviation from linear flow. The small exponents calculated indicate that other factors besides turbulent flow must be causing flow non-linearity. This trend is consistent for all tested intervals in this borehole.

The Darcy-Missbach model was also used to analyze tests in which all of the data collected was non-linear to see if improvements could be made on the prediction of the linear data and the subsequent calculation of T. Figure 3-9A shows the data that was collected in this test interval. It is reasonable to assume that the first point of this data set is part of the linear data and the resulting slope is shown on the plot which translates into a value of $6.8x10^{-6}$ m^2/s for T. If the Darcy-Missbach model is applied to the data and dP is calculated at lower flow rates as in Figure 3-9B, it can be seen that the first collected data point is not part of the linear flow regime and the linear data in this case results in $1.1x10^{-5}$ m2/s, a substantially larger value of T.

3.5 CONCLUSIONS AND IMPLICATIONS

The results of the constant head step tests in the dolostone aquifer at the Guelph site show deviation from linear flow at relatively low injection rates and the tests were generally conducted to the highest flow rates possible with the modified equipment resulting in flows that were definitely not linear. An analysis of the data was conducted using two non-linear flow models, the Forchheimer equation and a new Darcy-Missbach equation. The Darcy-Missbach equation provides a better basis for predicting the degree of deviation from linear flow at higher flow rates suggesting that the non-linearity observed during the packer tests is not due to fully turbulent flow and therefore dP will not be proportional to Q^2 causing the Forchheimer equation to err in the prediction of dP due flow rates outside the measurement range. This conclusion is further supported by the fact that the exponents calculated in this study were not very large (< 1.05) indicating that significant non-linearity is possible in packer testing with flows much below the velocity needed for fully turbulent flow. This is consistent with previous studies of non-linear flow in unconsolidated media (Sunada, 1965).

In the packer tests conducted in this study many steps were used in the constant head tests resulting in a good resolution of the linear range and identification of the transition point to non-linearity. To extend the tests to identify directly the onset of fully turbulent flow, it would be necessary to use much higher flow rates resulting in a much greater dP in the test interval. However, the Darcy-Missbach equation provides a reasonable basis for estimating the onset of turbulence if the geometry of the fractures intersecting the borehole remains constant, but the high predicted pressures would likely cause fracture dilation and/or hydrofracing before the onset of fully turbulent flow. The methodology used in this study to acquire sufficient data to define the transition from linear to non-linear flow involves more time for testing each interval than may be available in most site investigations. The alternative is to conduct a more limited number of tests and then attempt to discern the point of deviation from linear flow. This may be possible using the Darcy-Missbach model to analyze the more limited data set.

Tables

Table 3-1 Comparison of Forchheimer and Missbach models with the data collected in zone 10 of MW-26. Both models fit the data well. The equations for this prediction are the result of fitting a quadratic equation to the collected data in both arithmetic (Forchheimer) and ln-ln space (Missbach).

Measured Q (mm3/s)	Measured Delta P (mm)	Forchheimer Delta P (mm)	Missbach Delta P (mm)	% Diff Forchheimer	%Diff Missbach
2676	33	34	33	-1%	0.2%
4786	60	63	61	-5%	-2.2%
7255	94	97	95	-3%	-0.9%
10931	153	150	149	2%	3.0%
13271	184	185	184	-0.2%	0.2%
15866	226	224	225	1%	0.8%
17926	250	255	258	-2%	-2.9%
28792	444	430	442	3%	0.5%
41274	657	649	671	1%	-2.0%
67072	1167	1160	1191	1%	-2.0%
74099	1317	1313	1343	0.3%	-2.0%
87279	1643	1616	1636	2%	0.5%
95619	1849	1818	1827	2%	1.2%

Table 3-2 Comparison of Forchheimer and Missbach models with the data collected in Zone 9. Both models fit the data well. The equations for this prediction are the result of fitting a quadratic equation to the collected data in both arithmetic (Forchheimer) and ln-ln space (Missbach).

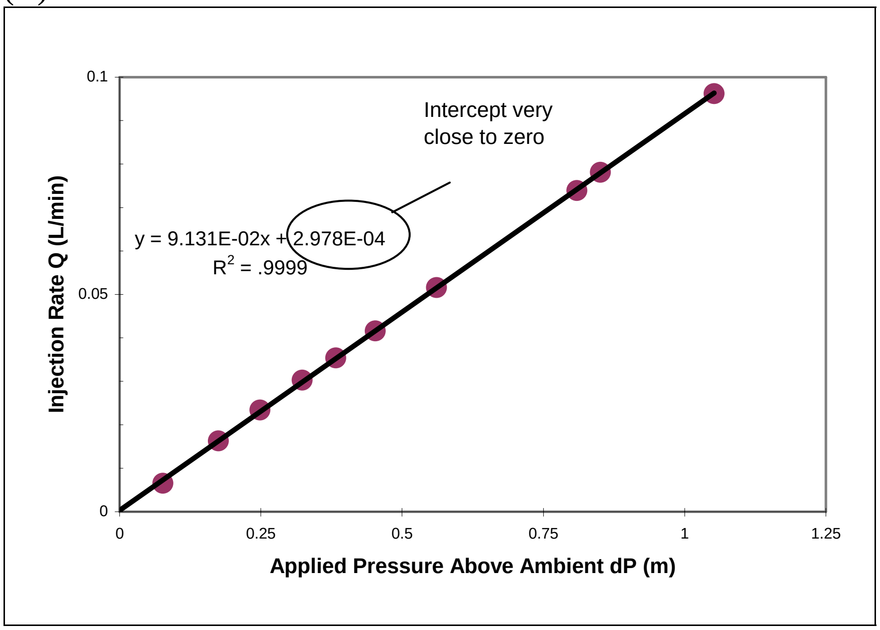
Measured Q (mm3/s)	Measured Delta P (mm)	Forchheimer Delta P (mm)	Missbach Delta P (mm)	% Diff Forchheimer	%Diff Missbach
1440	40	29	40	28%	1.2%
2946	85	82	85	3%	-0.5%
3780	109	111	112	-2%	-2.6%
4417	133	134	133	-1%	0.0%
5584	168	177	172	-5%	-2.4%
6676	217	217	211	0.1%	2.8%
6775	221	220	214	1%	3.2%
33165	1383	1334	1385	4%	-0.1%
45031	2021	1925	2016	5%	0.2%
48325	2197	2099	2200	4%	-0.1%
54736	2547	2451	2569	4%	-0.9%
67995	3425	3229	3372	6%	1.5%

Table 3-3 Comparison of Forchheimer and Missbach models with the data collected in Zone 5. Both models fit the data well. The equations for this prediction are the result of fitting a quadratic equation to the collected data in both arithmetic (Forchheimer) and ln-ln space (Missbach).

Measured Q (mm3/s)	Measured Delta P (mm)	Forchheimer Delta P (mm)	Missbach Delta P (mm)	% Diff Forchheimer	%Diff Missbach
201	101	103	102	-2%	-0.4%
362	188	191	190	-1%	-0.8%
485	267	259	259	3%	3.0%
699	385	381	384	1%	0.3%
819	454	452	456	0%	-0.5%
1076	599	606	612	-1%	-2.1%
1168	663	662	668	0.1%	-0.9%
1381	799	795	801	0.5%	-0.2%
1535	915	894	898	2%	1.8%
1827	1090	1086	1085	0.3%	0.5%

Figures

(A)



(B)

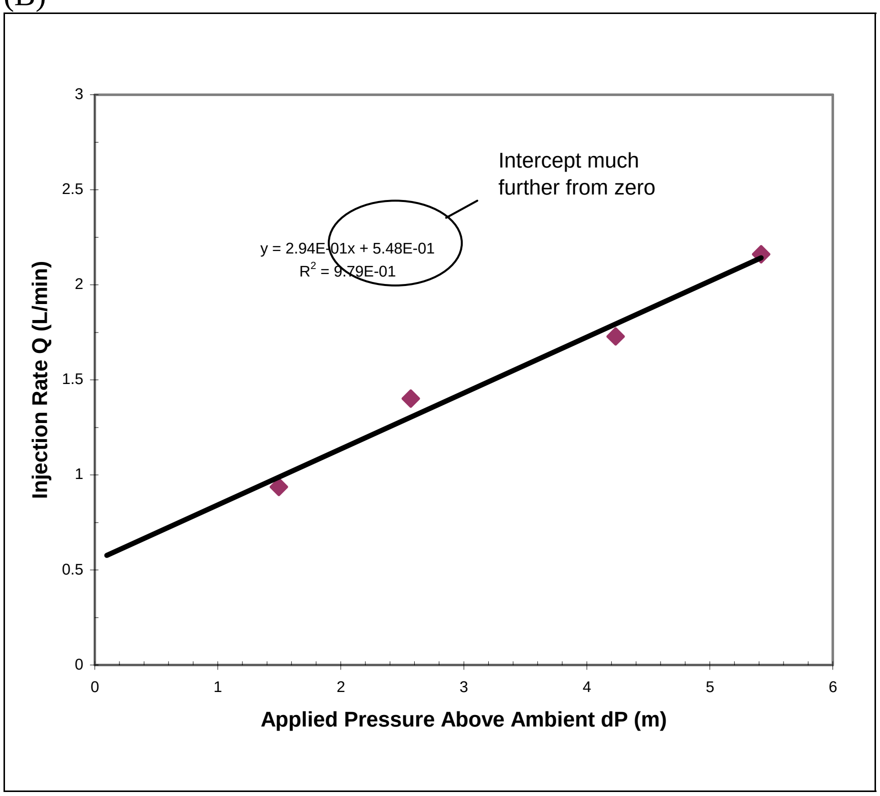
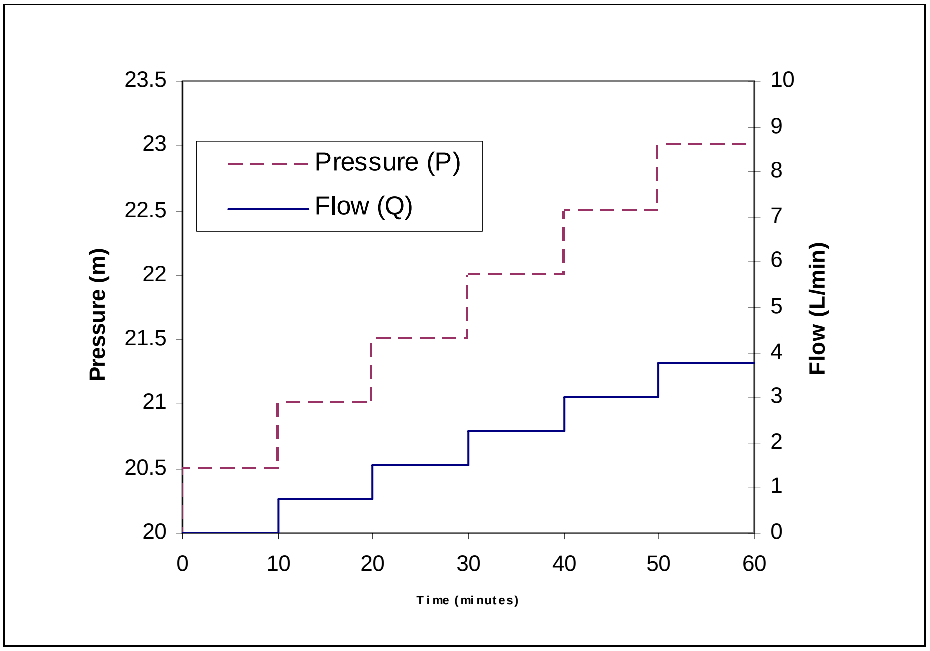


Figure 3-1 (A) Accurate packer testing step data is linear ($R^2 \approx 1$) and is very close to passing through zero (0.0003 L/min offset) compared to (B) less accurate data in which the data appears linear ($R^2 \approx 0.98$) but the y-intercept is much larger (0.55 L/min offset).

(A)



(B)

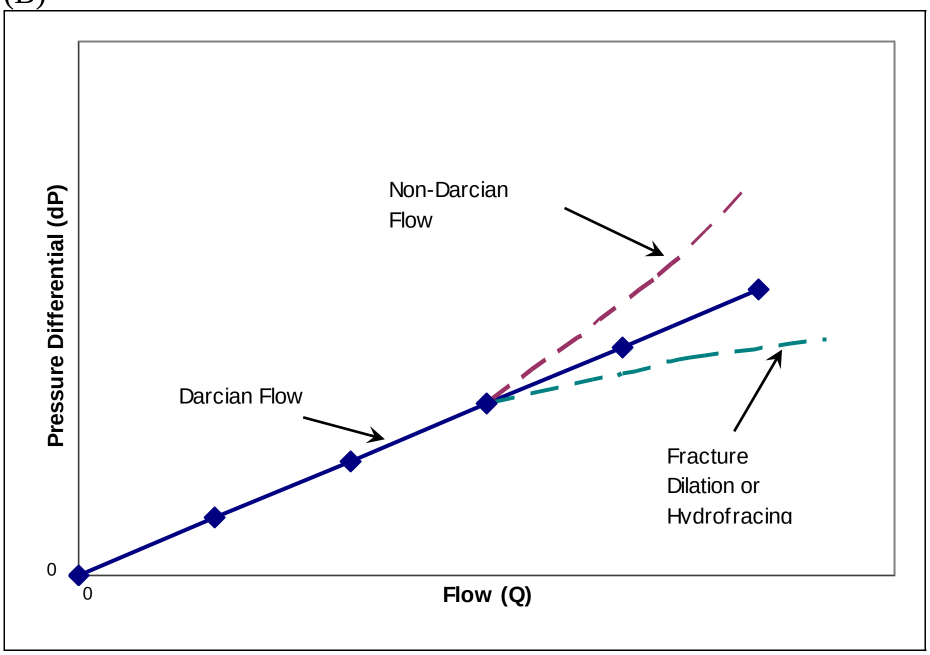


Figure 3-2 (A) Illustration of idealized hydraulic step test in which the pressure and flow rate are measured throughout the test. The ambient pressure in this example is 20.5 m and the pressure increases as a result of increased flow rates. Typical test time required for equilibration is 10 minutes. (B) Illustration of Possible Flow Regimes during hydraulic tests in rock boreholes showing Linearity (Injection rate sufficiently low to achieve Darcian flow), and Non-linearity due to excessive flow rate causing viscous forces to become significant, and Non-linearity due to excessive injection pressure causing fracture dilation and/or hydrofracing.

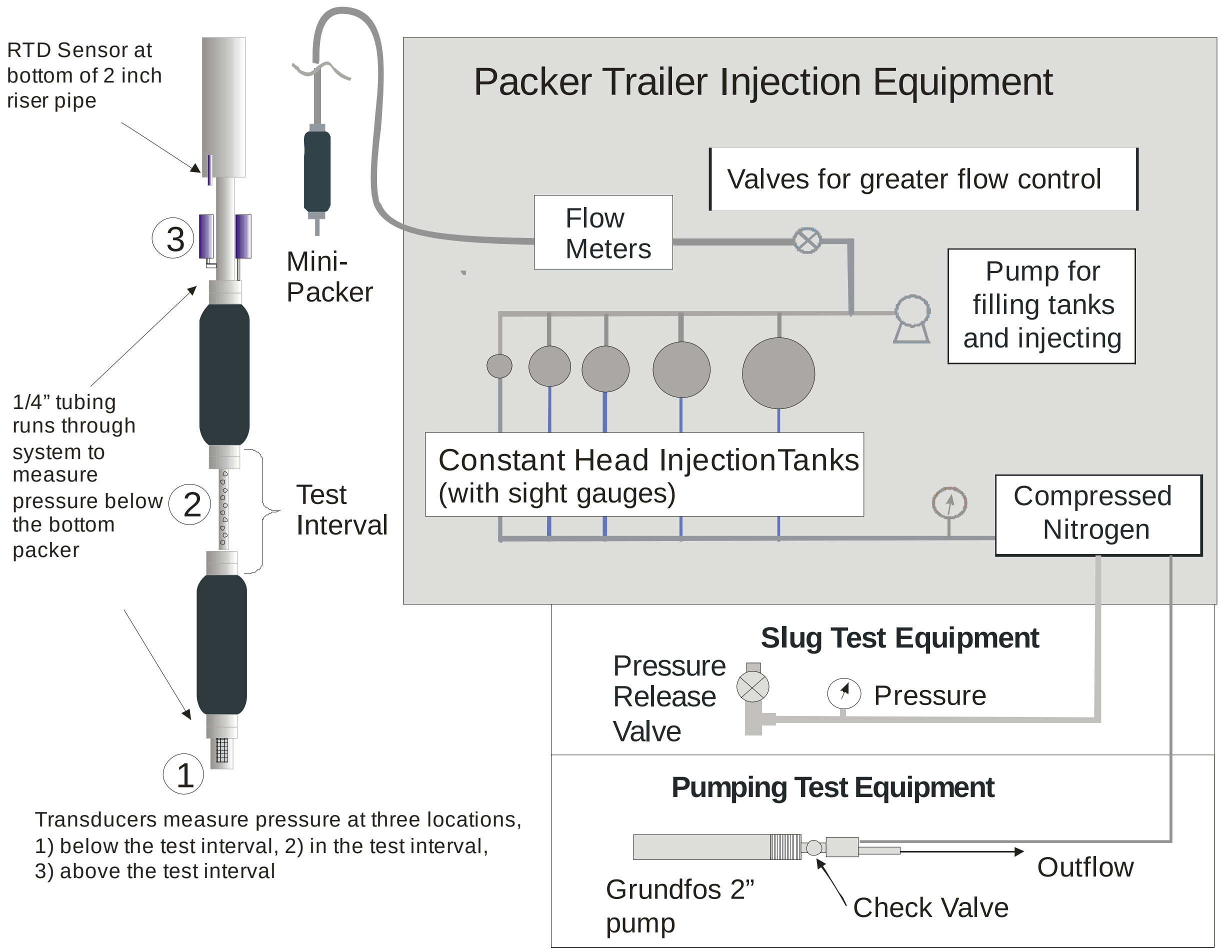
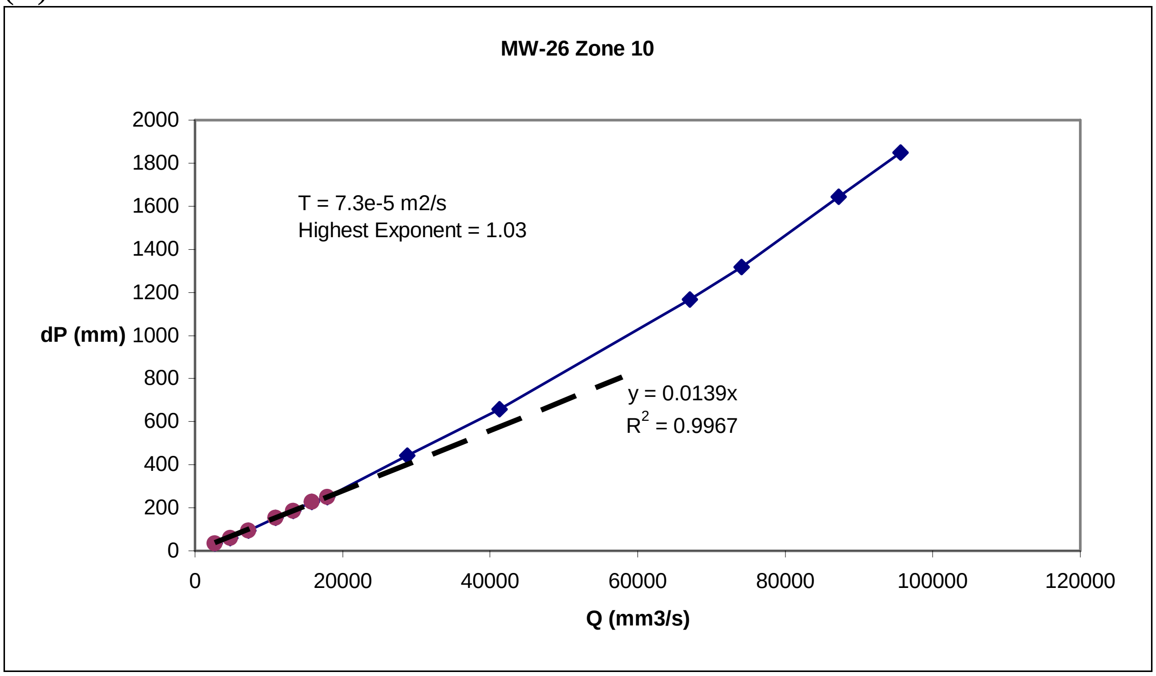


Figure 3-3 Schematic of Packer Testing System

(A)



(B)

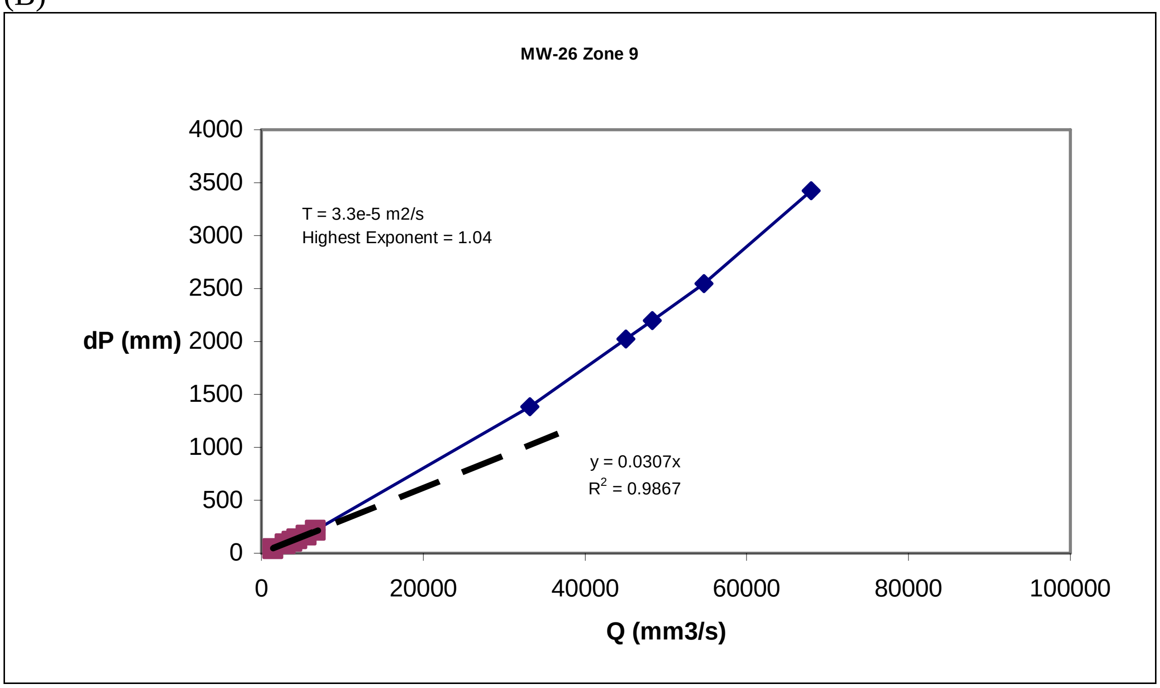
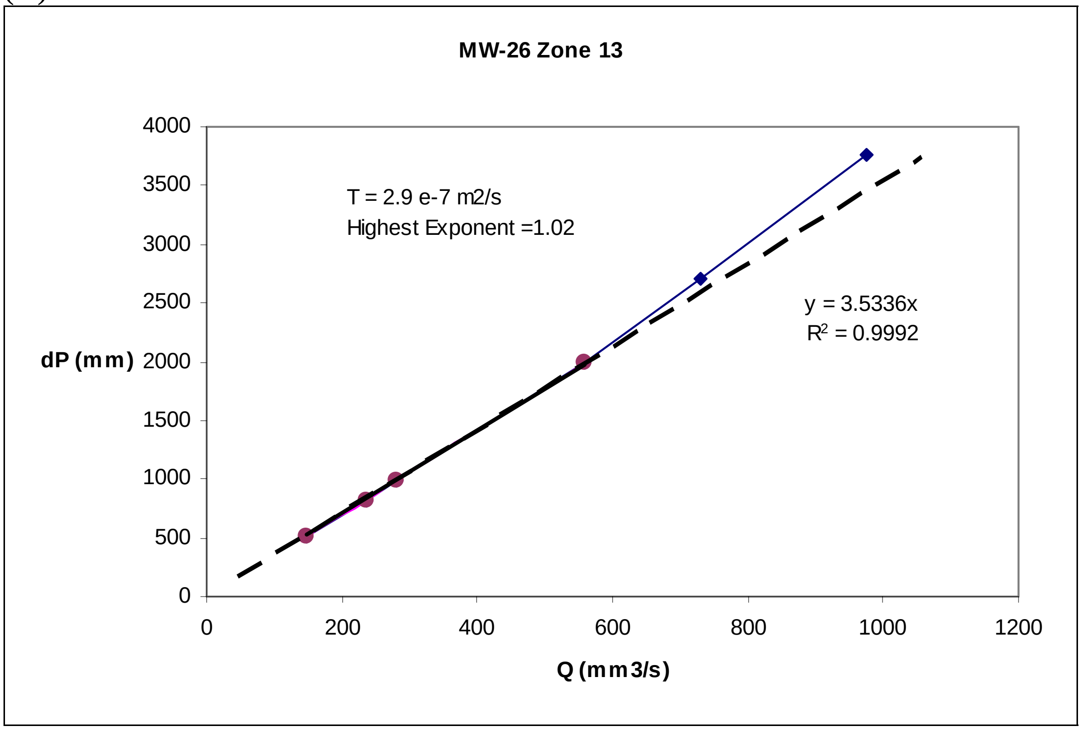


Figure 3-4 Observed non-linearity in the most permeable zones in this borehole. The T calculated using a radius of influence of 30 m and the highest exponent calculated are listed. The linear data used for the calculations is shown.

(A)



(B)

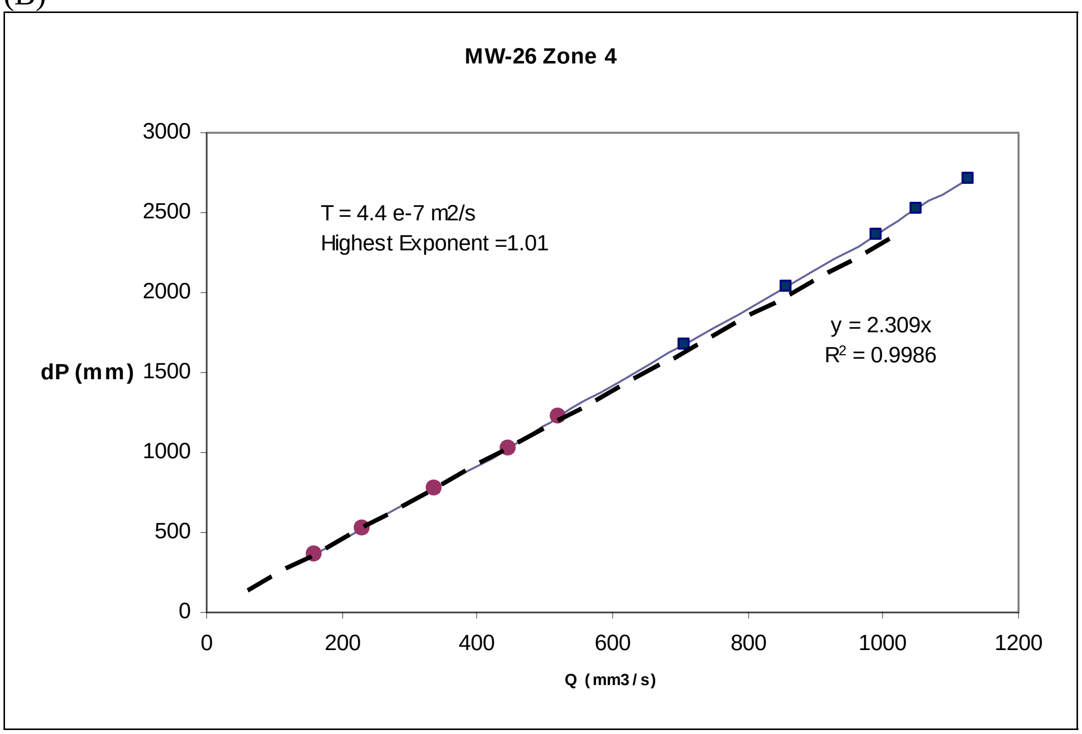
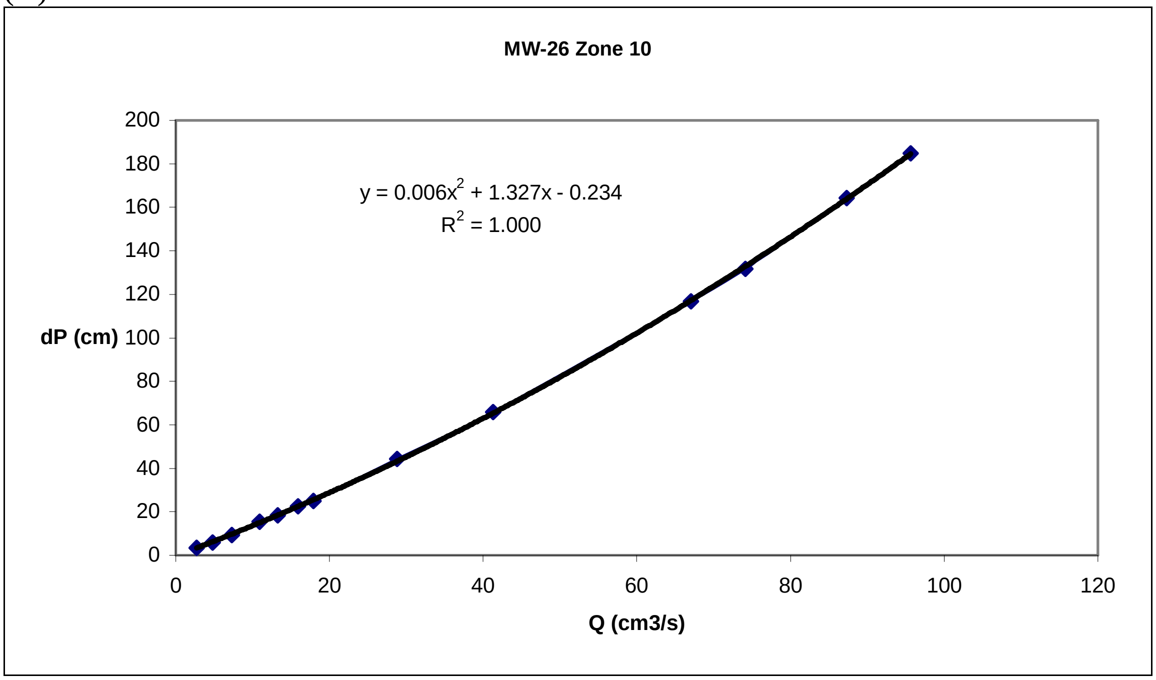


Figure 3-5 Observed non-linearity in the least permeable zones in this borehole. The T calculated using a radius of influence of 30 m and the highest exponent calculated are listed. The linear data used for the calculations is shown.

(A)



(B)

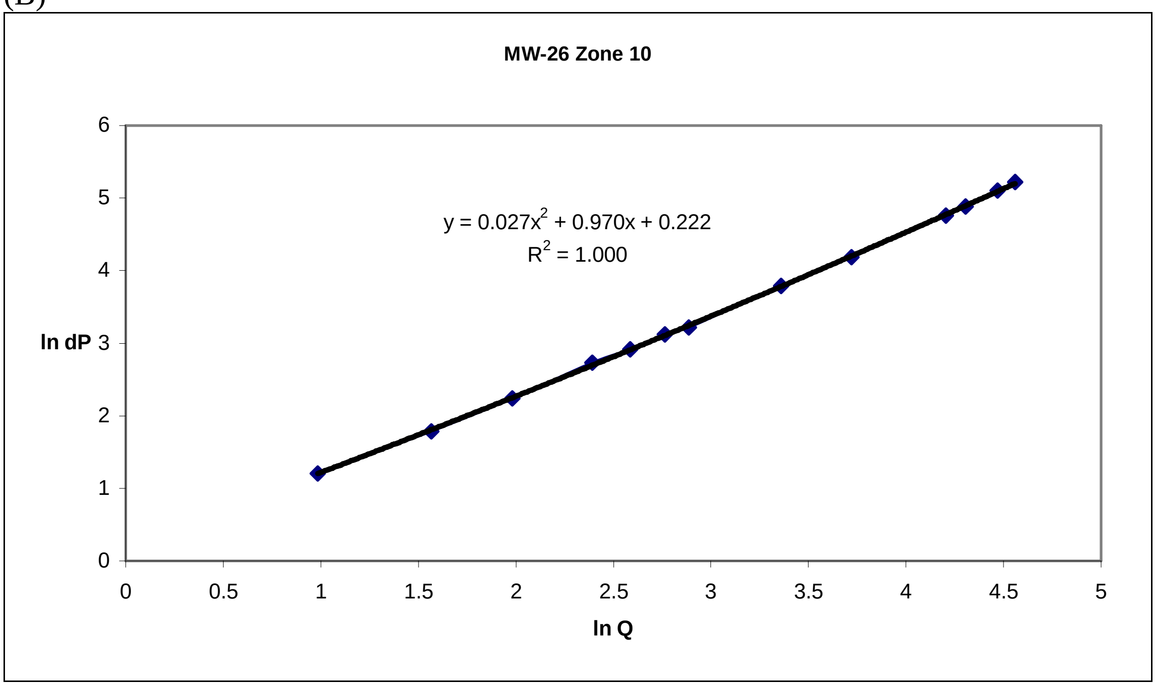


Figure 3-6 (A) Forchheimer Equation fit the data collected in all test intervals extremely well. (B) Darcy-Missbach model also fit the ln-ln data in all test intervals extremely well.

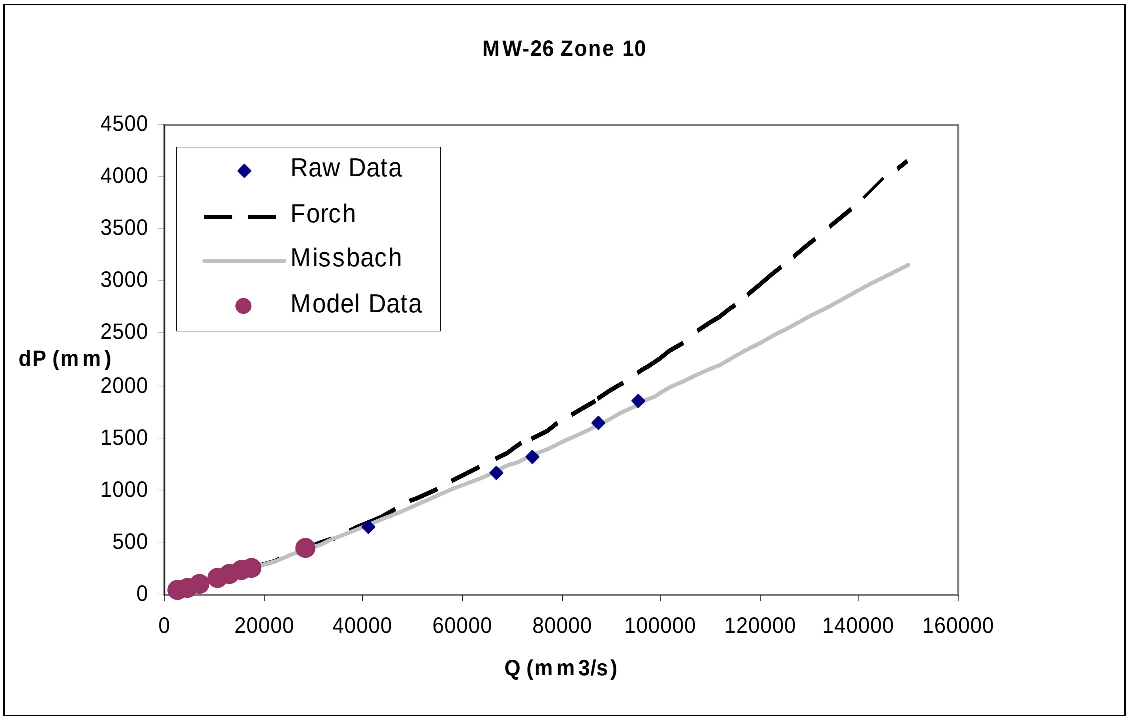


Figure 3-7 Comparison of the Forchheimer and the Darcy-Missbach models to predict data outside the data collection range. For this comparison only part of the data collected is used to obtain the respective equations, which is then used to predict the dP at higher flow rates. The Forchheimer model consistently overpredicts the measured dP.

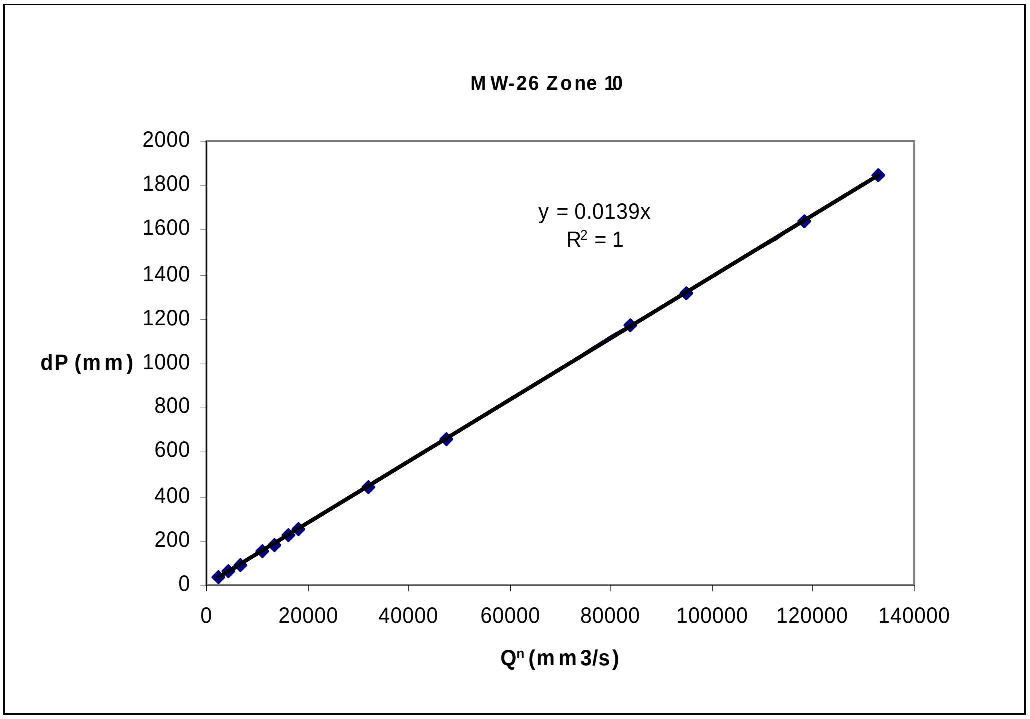
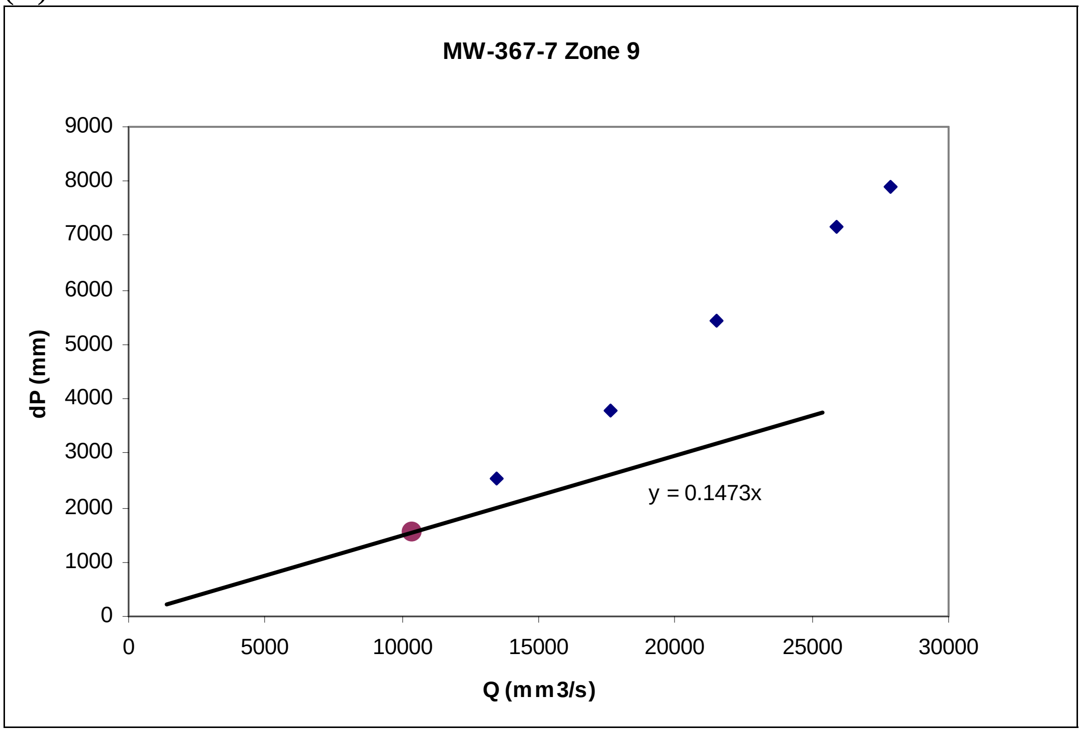


Figure 3-8 A plot of Q^n vs dP indicates that the Darcy-Missbach model adequately accounts for deviations from linearity observed in the packer tests.

(A)



(B)

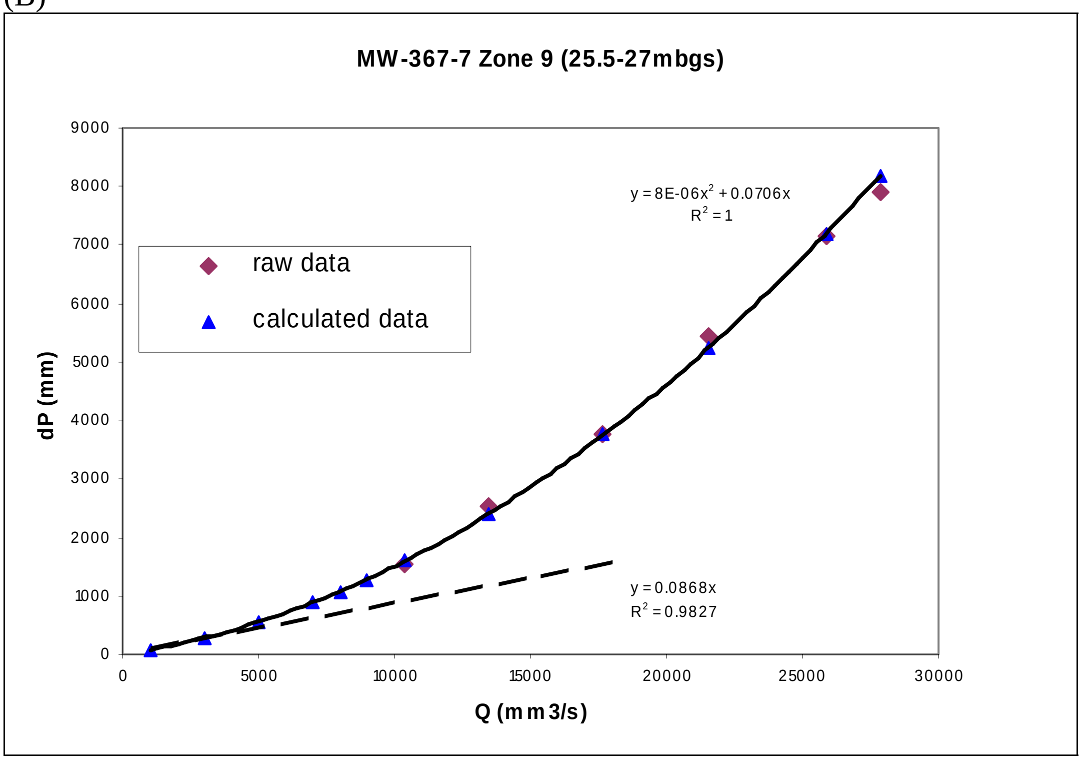


Figure 3-9 Using Darcy-Missbach to determine the linear data. (A) show the raw data collected in this zone and the resulting slope of the linear data if it is assumed that the first point is linear (B) shows the linear data when the Darcy-Missbach equation is used to calculate dP at lower flow rates.

Chapter 4 Aperture determination from constant head packer testing in fractured rock

4.1 INTRODUCTION

Hydraulic tests using packers to isolate specific borehole intervals are common for determining transmissivity (T) in fractured rock at dam sites, mining sites, and in water supply investigations. In these tests a borehole segment (interval) is isolated from the rest of the hole by a single packer (single packer tests), or with two packers (straddle packer test). Water is injected or withdrawn from the packed off borehole interval while measuring the flow rate and the water pressure. For the purposes indicated above, the accuracy of the measurements in these tests is often not important as long as order-of-magnitude T estimates are obtained. However, for studies of contaminant migration in fractured rock, greater accuracy is required, particularly when fracture aperture values are calculated from the T measurements using the Cubic Law. In analysis of packer test data, the T values are commonly derived using mathematical models based on the assumption of Darcian flow in the fractures (Braester and Thunvik 1984; Bliss and Rushton, 1984; Barker, 1981; Witherspoon et al., 1980; Novakowski et al., 1997). In Darcian flow, the relation between the injection flow rate (Q) and the induced pressure change (dP) is linear and therefore the Darcian condition is commonly referred to as linear flow. However, the literature reports very few field studies showing actual evidence of Darcian flow during packer testing. Elsworth and Doe (1986) used mathematical modeling of packer tests in fractured rock to show that calculation of T using non-Darcian data can lead to underestimation errors as much as an order of magnitude. In Darcian flow, Q/dP = constant, but excessive pressure or flow can cause this value to either increase or decrease.

In contrast to flow in smooth parallel plates where there is a relatively abrupt transition between the two flow regimes, in flow through natural fractures the transition zone is much larger due to asymmetrical fracture geometry characteristics such as fracture roughness, dead end voids, aperture variations, and contact area (tortuosity) that cause deviation from linearity to begin much sooner (Maini, 1971; Louis, 1972; Atkinson, 1986; Konzuk & Kueper, 2004).

In one of the few field focused studies concerning nonlinear flow in packer testing in fractured rock, Mackie (1982) reviewed the results of carefully conducted step drawdown tests using straddle packers in fractured rock aquifers. Based on the non-linearity of the Q vs dP relationship, he concluded that non-Darcian flow can occur at relatively low flow rates. However, he did not express the results using critical Reynolds number values (Re_c) and therefore the generality of the results is limited. On the other hand, there is an abundance of laboratory flow experiments in single fractures in rock or concrete blocks in which deviation from linear flow has been observed (Rasmussen, 1995; Nicholl et al., 1999; Belhaj et al., 2003; Konzuk & Kueper, 2004; Zimmerman et al., 2004; Qian et al., 2005; Ranjith et al., 2007). In these laboratory studies, the Reynolds number (Re), which is the dimensionless ratio of inertial forces to viscous forces during flow, is used as the index parameter to describe regime change from Darcian to non-Darcian. The critical Reynolds number (Re_c) is defined as Re when flow begins to deviate from linearity. This concept was also used by Elsworth and Doe (1986) and Brush and Thompson (2003) in their mathematical modeling to distinguish between Darcian and non-Darcian flow in fractures during simulations of flow in fractured rock.

It is useful to identify Reynolds number (Re) values that represent the field test conditions best suited for comparison to the Re values cited in laboratory studies. However, most laboratory studies are conducted using unidirectional flow in relatively uniform single fractures, while field studies are conducted using radial flow in intervals that commonly have more than one fracture of mostly unknown geometry. The intersection angles with the borehole can be determined from core inspection and/or borehole imaging, but the apertures cannot be measured directly in the field.

In steady state tests either pressure (P) or flow rate (Q) is measured during the injection or withdrawal of water until the pressure and flow rate stabilizes. These tests commonly include multiple stages whereby the flow rate is stepped up or down in stages with the monitoring of P and Q during each stage (Sara, 2005). In multiple stage, steady-state tests, Darcian flow can be identified based on the Q vs dP relationship. However, in the literature providing guidance concerning equipment and testing procedures for constant P or Q tests in fractured rock (e.g. U.S. Bureau of Reclamation, 1974 & 77; Sara, 2005; Nielson, 2006), no advice is provided for discerning whether the flow regime is Darcian or non-Darcian, although use of multiple test stages is recommended. Therefore, in general, whether or not the packer testing procedures typically used in practice in groundwater investigations in fractured rock operate in the Darcian flow regime is unknown. There is abundant literature concerning Darcy-based mathematical models for analysis of packer testing data to obtain values of T or K, however, lacking knowledge of whether or not the test data are from the Darcian range imposes errors irrespective of the model used.

In Chapters 2 and 3 of this thesis, packer testing equipment and procedures for constant head injection tests were developed and applied in fractured rock boreholes to investigate the transition from Darcian to non-Darcian flow. This methodology was applied extensively in studies of a fractured dolostone aquifer where assessment of contaminant behavior is on-going. In Chapter 3 a non-linear form of Darcy’s Law was developed to account for the deviation from linearity observed during the step tests and to predict the effects of higher flow rates. These same data is used for calculations in this chapter.

T values were calculated from the both Darcian and non-Darcian flow regimes for each test interval and fracture hydraulic apertures were calculated using the Cubic Law. To be consistent, the non-linear relationship developed in Chapter 3 was used to predict the flow rate when the applied pressure is 10m for all non-linear determinations. A comparison of using a single equivalent fracture in the test interval with using the number of fractures identified in the ATV log and the core log is completed for aperture determination and a method is described for selecting the number of active fractures in the test interval based on non-linear behavior. Implications of the error due to non-linearity associated with obtaining T, aperture (2b), and average linear groundwater velocity ($\bar{\upsilon}$) in rock with well connected fracture network are also assessed.

4.2 APPROACH AND TEST METHOD

The packer testing equipment used in this study is an adaptation of the system originally described conceptually by Gale (1982) with design modifications directed at achieving greater accuracy of Q vs dP relations over a larger range starting at exceptionally low injection pressures and flow rates. This packer testing system (Figure 4-1) is described in greater detail in Chapter 1. Excessive pressure or flow during a test can cause the value of Q/dP to either increase or decrease as illustrated in Figure 4-2. If the fractures dilate, due to excessive injection pressure, there will be an increase of Q/dP, but when inertial forces begin to dominate, due to excessive flow, Q/dP will decrease (Atkinson, 1986).

The injection tests were conducted in four open boreholes at a site in Guelph, Ontario, where the rock is predominantly fractured Silurian dolostone overlain by Quaternary deposits and underlain by a massive shale formation. The rock units identified at the Guelph site extend over a large area and are part of an important dolostone aquifer regionally and also in the study area (Singer et al., 2003; Dekeyser et al., 2006). The holes were cored with a HQ diamond bit, creating a nominal diameter of 0.096 m to depths ranging from 40 to 43 m. Top of rock was typically encountered at 3-5 mbgs and well casings were keyed into the rock. All cores were examined to identify geologic and physical features and fractures were identified as open (core separates at the fracture), closed (core does not separate at the fracture), broken zone (too broken to identify individual fractures) and signs of flow (weathering, mineralization) were recorded. Samples were also collected from the cores for analysis of contamination and rock physical properties. Various geophysical logs were also collected in the borehole before packer testing. The acoustic televiewer log was analyzed to identify fracture locations, and produce a virtual caliper log of the borehole (Pehme et al, accepted). The hole diameters varies from 101 to 108 mm. This caliper log (r_w) was used to calculate transmissivities and to determine the safe working pressures of the packers. All holes were packer tested from the bottom upwards with a 1.5 m test interval so that all parts of each hole was tested and packer inflation tests were conducted to ensure proper interval sealing following the procedures recommended by Maini (1971). Finally, pressure equilibrium was established in the test interval and in the open hole above and below the test interval before beginning all step tests.

The flow rate at which flow in the fracture becomes non-linear is not known prior to testing in each interval and therefore, to ensure the collection of linear flow data, the initial constant head step test was conducted at the lowest flow rate possible producing a measurable increase in interval pressure. This flow rate varied from 10 to 100 ml/min for each 1.5 m test interval depending on the permeability (e.g. low permeable zones can detect a pressure increase caused by injecting 10 ml/min, but high permeable zones will not show an increase in pressure until the flow rate is 100 ml/min). Subsequent steps were then conducted at regular increases in flow to determine the flow versus pressure relationship over a large range of flow rates.

4.3 CONCEPTUAL FRAMEWORK FOR DATA ANALYSIS

There are three steps involved in the determination of aperture from steady state hydraulic tests. In the first step, flow (Q) and induced pressure (dP) are plotted for all tests in a specific test interval and a determination is made as to which points are within the linear flow regime. Figure 4-3 is an example of linear packer testing data. Typically, the linear portion will not pass exactly through zero, but the offset (y intercept) will be very small. The linear value of Q/dP obtained from the packer tests is then used to calculate the T of the test interval. The Thiem equation was used for all T calculations in this study and is based on the assumption that all flow is radial and laminar through a mathematically "infinite" homogeneous aquifer. It was originally developed for pumping tests in granular porous media using two observation wells (Wenzel, 1936) but it is commonly used in a single well context for packer tests in fractured rock. (Doe & Remer, 1980; Gale, 1982; Haimson & Doe, 1983; Lapcevic, 1988; Novakowski et al., 1997)

$$T = \frac{Q}{2\pi \Delta h} \ln\left(\frac{r_o}{r_w}\right) \qquad (1)$$

Where:

Q = flow rate (m3/s)
Δh = change in head from ambient (m)
r_o = radius of influence of the test (m)
r_w =well radius (m)

When the Theim method is used to determine T for single well tests, the only parameter not known is the radius of influence (r_o). Traditionally the uncertainty in r_o has not been of great concern because it is located in the natural log term, and thus the uncertainty was considered insignificant in the calculation of T. Various assumptions concerning r_o are reported in the literature (e.g. r_o =60 m (Maini, 1971), r_o =2 ft (Ziegler, 1976), r_o =30 m (Haimson & Doe, 1983), 10 <r_o < 15 m (Bliss & Rushton, 1984 r_o=10 m, Novakowski et al., 1997). This study will follow the example of Haimson and Doe because it is mathematically defensible.

The Navier-Stokes equation, first developed by Navier in France in 1822 based on molecular arguments, is also known as the 'equation of motion' (Bird et al, 1960). For unidirectional, uniform flow through two smooth, parallel plates there is a simple solution of the Navier-Stokes equations for the average velocity at constant temperature and density: In addition, if all flow is assumed to occur in the fracture(s), then the Darcy flux (q) = average linear groundwater velocity ($\bar{\upsilon}$).

$$\bar{v} = \frac{\rho g (2b)^2}{12\mu}\left(\frac{dh}{dL}\right) \tag{2}$$

$$q = \bar{v} = K_f \frac{dh}{dL} \tag{3}$$

$$K_f = \frac{\rho g (2b)^2}{12\mu} \tag{4}$$

Where:
ρg = specific weight of water
μ = water absolute viscosity
2b = aperture height
K_f = hydraulic conductivity of one fracture present
$\frac{dh}{dL}$ = pressure gradient

Thus, the Cubic Law is one solution of the Navier-Stokes equation for parallel plate flow (Snow, 1965; Witherspoon et al., 1980) and 2b represents the aperture required between smooth parallel plates to accommodate the flow. In this study it is assumed that all fractures in the test interval have the same size (2b). The transmissivity of a single fracture (T_f) is determined using the Theim equation with the selection of an appropriate number of equal sized fractures. Then, through a simple rearrangement of Theim and substitution of the solution for the K_f from above, we obtain the Cubic Law, where Q $\propto$ $(2b)^3$.

$$T_f = \frac{T}{N} = \frac{\ln\left(\frac{r_o}{r_w}\right)}{2\pi\Delta h} Q^n \qquad (5)$$

$$Q = \left(\frac{2\pi\Delta h}{\ln\left(\frac{r_o}{r_w}\right)}\right) K_f (2b) \qquad Q = \left(\frac{2\pi\Delta h}{\ln\left(\frac{r_o}{r_w}\right)}\right)\left(\frac{\rho g (2b)^3}{12\mu}\right) \qquad (6)$$

In the data analysis we have used the common assumption for fractured rock wherein all flow and storage is assumed to occur in the fractures and no significant hydraulic interactions occur within the rock matrix. This assumption is supported by laboratory tests on rock matrix samples which indicate that the matrix hydraulic conductivity varies from 3.5×10^{-10} to 2.5×10^{-7} m/s and the porosity from 6.8 to 17.5% for the boreholes tested. Most matrix conductivities are much smaller than the conductivity measured in the field and therefore the Thiem conceptual model, with all flow occurring through the fractures, is valid for the intervals tested except when test results show anomalous behavior.

A non-linear model was developed in Chapter 3 that accurately describes the deviation from linearity observed in packer tests. This Darcy-Missbach relationship was shown to accurately describe the Q vs dP relationship within the data range and to accurately predict at higher flow rates.

$$dP = CQ^n \tag{7}$$

Where: dP = the applied pressure
Q = the flow rate
C = the value of the proportionality constant in linear flow (n=1)
n = the degree of deviation from linear flow ($1 \leq n \leq 2$)

Analyzing the data in this fashion allows for a precise selection of the linear data and the point of deviation from linearity. A quadratic equation fitted to the ln Q vs ln dP data is used to calculate dP from any flow rate and the exponent n calculated for each test can act as a guide when determining the deviation from linearity (Chapter 3).

4.4 RESULTS AND DISCUSSION

The geophysical data, core logging data, and packer testing results for one of the boreholes used in this study are shown in Figure 4-4. The virtual caliper log (produced from the acoustic televiewer log) was used to determine the borehole diameter used in T calculations, and to identify the number of fractures intersected by the borehole. The core log was examined to identify the number of fractures present and likely because the acoustic televiewer does not identify very small fractures, there were consistently more fractures identified in the core log than the televiewer log.

The packer testing results for one of the boreholes tested are summarized in Table 4-1. The linear data has a good regression (R^2 ~1.0) and very small offsets from zero (<50mm), but even though the non-linear data also has a good regression (R^2 ~1.0). it will have very large offsets from zero (> 50 mm). More than 95% of the test results showed deviation from linearity at relatively low injection flow rates. This is consistent with the few previous field studies that have identified non-linear flow (Louis, 1972; Gale, 1975; Mackie, 1982). Figure 4-5 shows some representative data collected from the boreholes at the Guelph field site illustrating this deviation. The data for each tested interval clearly show a linear portion passing through zero at lower flow rates representing Darcian flow. The slope (Q/dP) of the linear data is used to calculate the true transmissivity for each test interval. These graphs also show that at higher flow rates three consecutive data points could be considered linear and, if the low flow data are absent, the data still appears linear but have a much larger offset from zero.

Non-linearity in field test results causes a decrease in the magnitude of the parameter values calculated from the data: T, $\bar{\upsilon}$, and 2b, but that decrease is not manifested equally in each of these parameters. (i.e. $\downarrow T > \downarrow \bar{\upsilon} > \downarrow 2b$), due to the fact that $T \propto (2b)^3$ and $\bar{\upsilon} \propto (2b)^2$. Table 4-2 indicates some of the consequences of using non-linear data for the calculation of these parameters. Because the equipment was redesigned for operation at lower flow rates, a non-linear relationship was used to determine the flow rate necessary to cause a dP of 10m in the test interval for comparison purposes. A single equivalent fracture is assumed for each test interval and a gradient of 0.01 is used for velocity calculations. The largest decreases in parameter values caused by non-linearity were observed in the zones of higher permeability where T consistently decreased by more than 50%.

Reynolds Number to Represent Flow Conditions

For comparison purposes it is useful to consider the results from the field tests presented in this paper in a manner in which they can be compared to laboratory studies. This is commonly done by expressing results in terms of dimensionless numbers such as the Reynolds number. First defined in 1883 by Osborne Reynolds for flow through pipes, Re is often used to determine the similarity of two different flow systems, and by extension, the flow regime present. In order for two systems to be considered similar, all of the forces acting on a fluid particle must be present at equal ratios. These forces can include fluid compressibility, gravity, inertia, and friction (viscosity). Re is the ratio of the inertia forces to the viscous forces. In order for two flows to be similar, the Re must be equal (Schlichting, 1979).

$$\mathrm{Re} = \frac{\rho \bar{v} D}{\mu} \tag{8}$$

Where:

ρ = water density
$\bar{\upsilon}$ = average fracture velocity
μ = water viscosity
D = characteristic length based on system geometry

For flow in pipes the characteristic length is the pipe diameter. Studies involving flow through porous media commonly use the average grain size diameter for the characteristic length based on the conceptualization that this is proportional to the pore throat diameter (Sunada, 1965). There is disagreement regarding the definition of the characteristic length (D) for flow through fractures. Some investigators use the mean hydraulic radius to determine the characteristic length [2(2b)] (e.g. Witherspoon, 1980; Elsworth, 1984; Elsworth & Doe, 1986; Jones et al., 1988; Acosta et al., 1985; Yeo et al., 1998; Konzuk &Kueper, 2004), while others use [2b] as the characteristic length (e.g. Nicholl et al., 1999; Zimmerman et al., 2004; Ranjith et al., 2007). Bird et al. (1960) advise that hydraulic diameter concept be used only for turbulent flows through non-circular flow channels. They recommend the aperture, 2b, be used for the characteristic length for laminar flow through a slit. Appendix B outlines the derivation using both methods. We follow this recommendation and the aperture (2b) is used for the characteristic length in Reynolds number calculations. The velocity used in this calculation is that occurring at the borehole wall, which is the location of highest velocity in a radial flow field.

Many lab studies of flow through fractures identify the point of deviation from linear flow as the critical Reynolds number, Re_c (Maini, 1971; Iwai, 1976; Atkinson, 1986; Nicholl. 1999; Zimmerman. 2004) so the field data were analyzed similarly for comparison to the lab based literature. Table 4-3 outlines the lab studies from literature used for this comparison. However, the comparison is complicated by the fact that the lab Re values are for the unidirectional uniform flow occurring in lab experiments while there is radial flow in the field tests. In radial flow, the velocity in the fracture decreases exponentially away from the borehole and because packer tests must be conducted as radial flow injection tests, the Re cannot be uniquely defined for the entire flow region. Therefore, Re calculations were computed at the borehole wall where velocities are the highest.

Table 4-4 compares Re_c calculated assuming a single fracture in the test interval with comparable size laboratory fractures. In the more permeable zones the field Re_c values are higher than the laboratory values. This implies that more flow can be transmitted through the fractures in the field than the lab before non-linearity begins. This anomaly could be due to the fact that the tested interval actually has more than one fracture present. The velocity, which is used to calculate Re is substantially greater in larger sized apertures. In other cases, the field

Re_c values are smaller than the laboratory values. This implies that the flow capacity of the fractures in the field is less than that observed in the laboratory. This could also be due to intervals with few or no fractures present.

To examine the influence of the number of fractures in the test interval on Re_c, 2b and Re_c are compared for the tests assuming a single aperture in the test interval, using the number of fractures identified in the ATV log and using the number of open fractures identified in the core log. When more than one fracture is present, it is assumed that all fractures have equal apertures. In this approach T used for the aperture and velocity calculations is T for a single fracture (T_f). For example, if there are 10 fractures present in the test interval, T_f = T/10. The aperture is then obtained by the cubic law and the velocity is calculated by $Q/(2\pi r^*2b)$. This comparison is summarized in Table 5. Deviation from linearity begins at Re_c between 0.1 and 12 depending on the number of fractures assumed. Most Lab studies on single fractures agree that Re_c range is from 1 to 5 (e.g. Zimmerman, 2004; Nicholl, 1999; Konzuk & Kueper, 2004). Based on this comparison, it appears that there is more than one active fracture present in many test intervals.

Because in contaminant transport studies, $\bar{\upsilon}$ is commonly needed, it is also useful to examine the influence of the number of fractures in the test interval on $\bar{\upsilon}$, Table 4-6 compares the number of fractures and $\bar{\upsilon}$ calculated from the transmissivity values for the aforementioned three scenarios (1 fracture, ATV fractures, core log fractures). The aperture determined assuming a single fracture is typically >50% larger than if the number of fractures identified in the test interval by the acoustic log or the core log is used for the high T intervals. The calculated velocity can be an order of magnitude higher.

If the dominant flow through a fractured rock is through the fractures (e.g. relatively low permeable matrix), the number of active fractures present in the test interval is an important factor that must be taken into account. According to Maini (1971) "The influence of fracture frequency within the test cavity of a water test is of extreme importance. A reasonable estimate of this frequency is a prerequisite to a meaningful test". However, whether or not all of the fractures identified from either the acoustic log or the core log are hydraulically active is unknown. Therefore, the actual number of active fractures present in the test interval is bounded by one and the number of fractures identified based on core logs.

Because the Rec is dependant on the velocity when flow becomes non-linear it should increase with increasing aperture. Therefore the point of deviation from linearity was used as a guide to choosing the number of active fractures present in the test interval as illustrated in Table 4-7. For approximately one third of the intervals tested a single fracture is assumed and all others intervals assume more than one fracture. Re vs 2b plots assuming a single fracture in all intervals and for the final choice of number of fractures are shown in Figure 4-6. Initially it is assumed that all intervals contain a single equivalent aperture, the most conservative choice resulting in the largest aperture and highest velocity. Then based on Re_c, more fractures are assumed to be present in select intervals until all data reflect the increasing trend of Re_c with increasing aperture. Table 4-8 summarizes the chosen number of fractures selected by this method and the resulting aperture and bulk fracture porosity.

4.5 CONCLUSIONS AND IMPLICATIONS

In this study of packer testing in a fractured dolostone aquifer, non-linearity was observed in most tests and the onset of nonlinearity occurred at Re values of < 5, corresponding to water injection rates of 0.01 to 0.5 L/min in 1.5 m test intervals. When the data from the non-Darcian flow regime are used to calculate T values, the values are typically >50% smaller. This translates to >25% difference in the value for aperture and a >40% decrease in velocity. The largest differences are associated with the higher transmissive intervals. However, even in the highest transmissive test zones, linear flow was achieved by restricting flow to under 1 L/min in the 1.5 m test intervals. Re_c values calculated from these tests are consistent with those determined in lab studies for single fractures in rock if more than one fracture is assumed for aperture and velocity calculations. If it is assumed that a single fracture is present in the test interval, aperture and velocity are exaggerated, and Re_c is consistently different than lab values.

To achieve best possible accuracy in the $\bar{\upsilon}$ calculated for groundwater flow it is necessary to conduct the packer test following a procedure that avoids influences on the T values of non-ideal conditions such as non-Darcian flow and fracture dilation/contraction. It is also necessary to have the best possible estimate of the number of hydraulically active fractures in the test interval. Fractures identified by televiewing and core inspection are not necessarily hydraulically active. This study shows that use of the Re_c approach provides a new basis for founding judgments on the number of hydraulically active fractures.

In the procedures typically used for packer testing in fractured rock linear flow is commonly assumed without consideration to the test conditions and high flow rates and/or high pressure differentials are used based on the desire to engage a relatively large volume of rock in the test. In this approach non-Darcian flow should be expected to be the norm rather than the exception. Therefore, conventional practice has a strong propensity to underestimate T due to non-Darcian flow. Gross estimates of T may be all that is needed when packer testing is done for purposes of mine or dam site dewatering studies and for aquifer yield evaluations and therefore for these cases avoidance of non-Darcian flow may be unnecessary. However, for assessment of contaminant migration, avoidance of the non-Darcian flow regime is most appropriate. Steady state tests are the most convenient way to conclusively show that the tests are conducted in the Darcian flow regime.

Publications providing guidance concerning procedures and conditions for straddle packer tests in fractured rock do not specifically identify the need to achieve Darcian flow even though Darcy based mathematical models are used to calculate T values from the test results. In Site Assessment and Remediation Handbook Sara (2005) states: “regardless of which pressures are used a minimum of three pressures should be used for each section tested. The magnitude of these pressures are commonly 15, 30, and 45 psi above the natural piezometric levels.” A few documents recognize the need to keep the flow Darcian but do not provide specific guidance as to how this is done. For example, Lapsevic et al. (1999) advise not to exceed a pressure differential greater than 10 m during testing, but this is to prevent hydrofracing, not non-Darcian flow. Based on the field results, it is reasonable to expect that all of the above mentioned pressures will result in nonlinear flow with the results appearing linear with a large y-intercept. Guidance using a differential pressure is too narrow because for a given flow rate, intervals with lower permeability will have a greater pressure increase than higher permeable intervals. Because flow regime change is a direct result of flow rate, not pressure, guidance should be about flow rate recommendations, not pressure differentials. Finally, the critical flow rate (Q_c) is a function of the interval length (i.e. larger intervals have access to a larger number of flow paths). For example, as a result of this study, it is appropriate that for 1.5 m intervals, flow rates do not exceed 1 L/min in high permeable zones and be kept below 100 ml/min in low permeable zones. Therefore, when packer testing in fractured rock, the flow rates used for hydraulic testing should be guided, not dictated by the observed induced pressure change.

Tables

Table 4-1 Packer testing results for MW-26 including QA/QC variable (y-intercecpt). Non-linear data are included for comparison. The non-linear data results in a smaller value for T and even though all of the data appears linear (R^2~1) the y-intercept is very large.

Linear Data			Non-Linear Data			
T (m2/s)	y-intercept (mm)	Linear Regression R^2	Q (L/min) 10m dP	T (m2/s)	y-intercept (mm)	Linear Regression R^2
1.78E-06	NA	NA	0.335	3.92E-07	-4511	0.999
1.29E-06	NA	NA	0.243	3.11E-07	-3348	0.996
4.47E-07	-13	1.000	0.227	3.07E-07	-18575	0.992
1.97E-06	-8	0.997	0.835	1.32E-06	-726	1.000
1.58E-06	-7	1.000	0.854	1.42E-06	-220	1.000
2.98E-06	-13	0.997	0.818	1.05E-06	-3156	0.999
7.29E-06	-8	1.000	3.76	6.10E-06	-449	1.000
4.47E-05	2	0.999	9.52	1.34E-05	-2051	0.999
4.23E-05	0	1.000	22.3	3.18E-05	-1889	1.000
2.37E-06	NA	NA	0.454	5.35E-07	-4422	0.999
6.12E-07	-18	0.999	0.307	4.87E-07	-673	1.000
3.00E-07	-31	0.998	0.141	2.15E-07	-1064	1.000
3.81E-07	NA	NA	0.076	8.75E-07	-468	1.000
1.27E-06	-50	0.990	0.425	3.19E-07	-12574	0.998
6.12E-07	-38	0.995	0.265	3.89E-07	-1518	1.000
5.95E-07	-12	1.000	0.472	5.95E-07	-3422	1.000
1.30E-06	-31	0.996	0.429	5.82E-07	-2495	1.000
9.57E-06	-3	0.999	2.10	2.54E-06	-4002	0.999
3.73E-06	-10	0.998	0.965	1.24E-06	-3137	0.999
1.07E-06	-8	0.998	0.335	4.60E-07	-2330	1.000
3.94E-06	-2	1.000	0.668	7.06E-07	-6031	0.999

Table 4-2 The significance of non-linear flow on the determination of T, 2b, and $\bar{\upsilon}$ using one equivalent aperture for each test interval. Velocities are calculated using a gradient of 0.01. Non-linear flow can cause the test results to underestimate these parameters substantially.

Zone	Linear Data			Non-linear Data			% T Reduction	% 2b Reduction	% $\bar{\upsilon}$ Reduction
	T (m^2/s)	2b (μm)	$\bar{\upsilon}$(m/d)	T (m^2/s)	2b (μm)	$\bar{\upsilon}$(m/d)			
2	1.78E-06	140	11	3.92E-07	84	4	78	40	64
3	1.29E-06	125	9	3.11E-07	78	3	76	38	61
4	4.47E-07	93	4	3.07E-07	82	3	31	12	22
5	1.97E-06	152	11	1.32E-06	133	9	33	12	23
6	1.58E-06	141	10	1.42E-06	136	9	10	4	7
7	2.98E-06	174	15	1.05E-06	123	7	65	29	50
8	7.29E-06	235	27	5.98E-06	220	24	18	6	12
9	3.53E-05	397	77	1.34E-05	288	40	62	28	48
10	7.93E-05	520	132	3.18E-05	384	72	60	26	46
11	2.37E-06	161	13	5.35E-07	98	5	77	39	63
12	6.12E-07	103	5	4.87E-07	95	4	21	7	14
13	3.00E-07	81	3	2.15E-07	73	3	28	11	20
14	1.61E-06	142	10	8.75E-07	116	7	46	18	33
15	6.86E-06	230	26	3.19E-07	83	3	95	64	87
16	6.12E-07	103	5	3.89E-07	88	4	36	14	26
17	1.86E-06	149	11	5.95E-07	102	5	68	32	53
18	1.30E-06	132	9	5.82E-07	101	5	55	24	41
19	9.57E-06	257	32	2.54E-06	165	13	73	36	59
20	3.73E-06	188	17	1.24E-06	130	8	67	31	52
21	1.07E-06	124	7	4.60E-07	93	4	57	24	43
22	3.94E-06	191	18	7.06E-07	108	6	82	44	68

Table 4-3 Literature review of Lab studies in single fractures

Author	Setup	2b Range (μm)		D in Re	Re Critical*	Comments
Ranjith et al (2007)	Triaxial setup with granite sample with axial stress at 1.89 Mpa and confining P from .55 to 5 Mpa	Mean = 1820		2b	~10 (5)	T decreases with increasing confining P (aperture) Re_c smaller at higher confining P Forchheimer equation works well.
		Max = 4000				
		Min = 0				
Zimmerman et al (2004)	Epoxy cast of one natural horizontal fracture in sandstone	Mean = 149		2b	~10 (2)	T is independent of Re (Darcy) Additional dh/dL α Q^3 (Weak Inertia) Additional dh/dL α Q^2 (Strong Inertia)
Konzuk & Kueper (2004)	Single man made fracture in dolomite from Kingston, ON	Mean = 381		2(2b)	~5 (2.5)	CL works well with hydraulic 2b not measured 2b due to roughness and 2b variation. Nonlinear flow due to deviations from ideal velocity profile, flow direction and turbulent flow.
		Max = 3233				
		Min = 0				
Nicholl et al (1999)	Hele-Shaw cell with 2 smooth plates (no confining P), 2 textured glass (confining P = 20 psi) and 1 textured and 1 smooth glass (confining P = 20 psi)	Mean = 194	Smooth-Smooth	2b	3.6	2b measured with light transmission and dye. Hydraulic 2b ≈ measured 2b in Smooth-Smooth Hydraulic 2b 50% less in Rough-Rough
		Mean = 226	Rough-Rough		4.3	
		Mean =124	Smooth-Rough		1.3	

Table 4-4 Comparison of using one equivalent effective aperture for the calculation of Rec with laboratory experiments using a single fracture. The starred intervals have broken zones associated with them. The single effective fracture Rec in the more transmissive zones are too high when compared to a similar size fracture laboratory Rec. This indicates that either packer leakage was occurring or that the true fracture is smaller requiring more fractures in the test interval. Some of the single effective fracture Rec are the same or smaller than the laboratory values.

<table>
<tr><th>Zone</th><th>T (m2/s)</th><th>1 Fracture Equivilent 2b (μm)</th><th>1 Fracture Equivilent Rec</th><th>Zimmerman (2004)
2b ave = 149 μm
2b max=204 μm
2b min=94 μm
Rec</th><th>Nicholl (1999)
2b ave =226 mm
2b max = 301 μm
2b min =113 μm
Rec</th><th>Konzuk (2004)
2b ave =381 μm
2b max = 3233 μm
2b Min = 0 μm
Rec</th><th>Ranjith (2007)
2b ave = 1820 μm
2b max = 4000 μm
2b min = 0 μm
Rec</th></tr>
<tr><td>10</td><td>4.2E-05</td><td>422</td><td>7.4</td><td rowspan="4"></td><td rowspan="7">4.3</td><td rowspan="7">~2.5</td><td rowspan="7">~5</td></tr>
<tr><td>9</td><td>4.5E-05</td><td>409</td><td>12.4</td></tr>
<tr><td>1</td><td>1.6E-05</td><td>294</td><td>5.0</td></tr>
<tr><td>19</td><td>9.6E-06</td><td>257</td><td>2.3</td></tr>
<tr><td>22</td><td>3.9E-06</td><td>191</td><td>1.4</td><td rowspan="18">~2</td></tr>
<tr><td>20</td><td>3.7E-06</td><td>188</td><td>1.2</td></tr>
<tr><td>7</td><td>3.0E-06</td><td>174</td><td>1.7</td></tr>
<tr><td>11</td><td>2.4E-06</td><td>161</td><td>0.7</td><td rowspan="15" colspan="3"></td></tr>
<tr><td>8*</td><td>2.6E-06</td><td>159</td><td>0.6</td></tr>
<tr><td>5</td><td>2.0E-06</td><td>152</td><td>0.8</td></tr>
<tr><td>17*</td><td>1.9E-06</td><td>149</td><td>1.0</td></tr>
<tr><td>6*</td><td>1.6E-06</td><td>141</td><td>0.8</td></tr>
<tr><td>2</td><td>1.8E-06</td><td>140</td><td>0.7</td></tr>
<tr><td>18</td><td>1.3E-06</td><td>132</td><td>0.8</td></tr>
<tr><td>15*</td><td>1.3E-06</td><td>131</td><td>0.5</td></tr>
<tr><td>3</td><td>1.3E-06</td><td>125</td><td>0.6</td></tr>
<tr><td>21</td><td>1.1E-06</td><td>124</td><td>0.5</td></tr>
<tr><td>12</td><td>6.1E-07</td><td>103</td><td>1.8</td></tr>
<tr><td>16</td><td>6.1E-07</td><td>103</td><td>0.7</td></tr>
<tr><td>4</td><td>4.5E-07</td><td>93</td><td>1.0</td></tr>
<tr><td>14*</td><td>3.8E-07</td><td>88</td><td>0.5</td></tr>
<tr><td>13</td><td>3.0E-07</td><td>81</td><td>0.5</td></tr>
</table>

Broken zones were identified in the zones outlined below.

6*	7 cm broken zone
8*	1 cm broken zone
14*	2 cm broken zone
15*	5 cm broken zone
17*	1,7,9 cm broken zone

Table 4-5 Comparison of Re_c assuming a single fracture in the test interval, using the fractures identified with the acoustic log and the core log. Many Re_c values are more similar to those measured in the laboratory if more than one fracture is assumed to be present in the test interval.

T (m2/s)	1 Fracture Equivilent 2b (μm)	1 Fracture Re_c	ATV Equivilent 2b (μm)	ATV Fractures Re_c	Open Fractures Equivilent 2b (μm)	Open Fractures Re_c
1.59E-05	294	4.97	185	1.24	172	0.99
1.78E-06	140	0.68	82	0.14	97	0.23
1.29E-06	125	0.62	79	0.15	60	0.07
4.47E-07	93	0.96	58	0.24	46	0.12
1.97E-06	152	1.04	89	0.21	68	0.09
1.58E-06	141	1.87	78	0.31	74	0.27
2.98E-06	174	1.75	102	0.35	84	0.19
2.62E-06	159	0.92	159	0.92	93	0.18
4.47E-05	409	12.38	258	3.09	190	1.44
4.23E-05	422	7.41	247	1.48	203	0.82
2.37E-06	161	1.03	89	0.17	73	0.09
6.12E-07	103	1.82	65	0.45	45	0.15
3.00E-07	81	0.51	39	0.06	39	0.06
3.81E-07	88	0.55	42	0.06	36	0.04
1.27E-06	131	0.67	91	0.22	61	0.07
6.12E-07	103	0.74	82	0.37	48	0.07
1.86E-06	149	0.99	94	0.25	69	0.10
1.30E-06	132	0.83	73	0.14	66	0.10
9.57E-06	257	3.68	134	0.53	116	0.33
3.73E-06	188	1.20	103	0.20	90	0.13
1.07E-06	124	0.66	72	0.13	59	0.07
3.94E-06	191	1.36	105	0.23	92	0.15

Table 4-6 Comparison of using one equivalent effective aperture for each test interval vs using the number of fractures identified in the acoustic log and the core log for each test interval for $\bar{\upsilon}$ calculations.

Zone	T (m2/s)	One Fracture Equivilent $\bar{\upsilon}$ (m/day)	Number of ATV Fractures in Test Interval	ATV Fractures $\bar{\upsilon}$ (m/day)	Number of Open Fractures in Test Interval	Core Fractures $\bar{\upsilon}$ (m/day)
1	1.59E-05	47	4	19	5	16
2	1.78E-06	11	5	4	3	5
3	1.29E-06	9	4	4	9	2
4	4.47E-07	4	4	2	8	1
5	1.97E-06	11	5	4	11	2
6	1.58E-06	10	6	3	7	3
7	2.98E-06	15	5	5	9	3
8	2.62E-06	14	1	14	5	5
9	4.47E-05	94	4	37	10	20
10	4.23E-05	87	5	30	9	20
11	2.37E-06	13	6	4	11	3
12	6.12E-07	5	4	2	12	1
13	3.00E-07	3	9	1	9	1
14	3.81E-07	4	9	1	14	1
15	1.27E-06	8	3	4	10	2
16	6.12E-07	5	2	3	10	1
17	1.86E-06	11	4	4	10	2
18	1.30E-06	9	6	3	8	2
19	9.57E-06	32	7	9	11	7
20	3.73E-06	17	6	5	9	4
21	1.07E-06	7	5	3	9	2
22	3.94E-06	18	6	5	9	4

Table 4-7 Comparison of using a single equivalent aperture for each test interval and using the appropriate number of fractures based on the ATV log, core log and Rec.

Zone	T (m2/s)	One Fracture Equivilent $\bar{\upsilon}$ (m/day)	Number of Fractures Chosen	Selected Fractures $\bar{\upsilon}$ (m/day)	% 2b Reduction	% $\bar{\upsilon}$ Reduction
1	1.59E-05	47	3	22	36	70
2	1.78E-06	11	1	11		
3	1.29E-06	9	1	9		
4	4.47E-07	4	3	2	36	70
5	1.97E-06	11	1	11		
6	1.58E-06	10	6	3	58	107
7	2.98E-06	15	3	7	36	70
8	2.62E-06	14	2	9	23	45
9	4.47E-05	94	4	37	45	86
10	4.23E-05	87	2	55	23	45
11	2.37E-06	13	2	8	23	45
12	6.12E-07	5	6	2	58	107
13	3.00E-07	3	3	2	36	70
14	3.81E-07	4	2	2	23	45
15	1.27E-06	8	1	8		
16	6.12E-07	5	2	3	23	45
17	1.86E-06	11	1	11		
18	1.30E-06	9	2	5	23	45
19	9.57E-06	32	5	11	52	98
20	3.73E-06	17	1	17		
21	1.07E-06	7	1	7		
22	3.94E-06	18	1	18		

Table 4-8 Summary of using Rec to choose the appropriate number of hydraulically active fractures in each 1.5m test interval.

Zone	T (m2/s)	Number of Fractures Chosen	Selected Equivilent 2b (μm)	Fracture Porosity
1	1.59E-05	3	204	4.1E-04
2	1.78E-06	1	140	9.3E-05
3	1.29E-06	1	125	8.4E-05
4	4.47E-07	3	64	1.3E-04
5	1.97E-06	1	152	1.0E-04
6	1.58E-06	6	78	3.1E-04
7	2.98E-06	3	121	2.4E-04
8	2.62E-06	2	126	1.7E-04
9	4.47E-05	4	258	6.9E-04
10	4.23E-05	2	335	4.5E-04
11	2.37E-06	2	128	1.7E-04
12	6.12E-07	6	57	2.3E-04
13	3.00E-07	3	56	1.1E-04
14	3.81E-07	2	70	9.3E-05
15	1.27E-06	1	131	8.7E-05
16	6.12E-07	2	82	1.1E-04
17	1.86E-06	1	149	9.9E-05
18	1.30E-06	2	105	1.4E-04
19	9.57E-06	5	150	5.0E-04
20	3.73E-06	1	188	1.3E-04
21	1.07E-06	1	124	8.2E-05
22	3.94E-06	1	191	1.3E-04

Figures

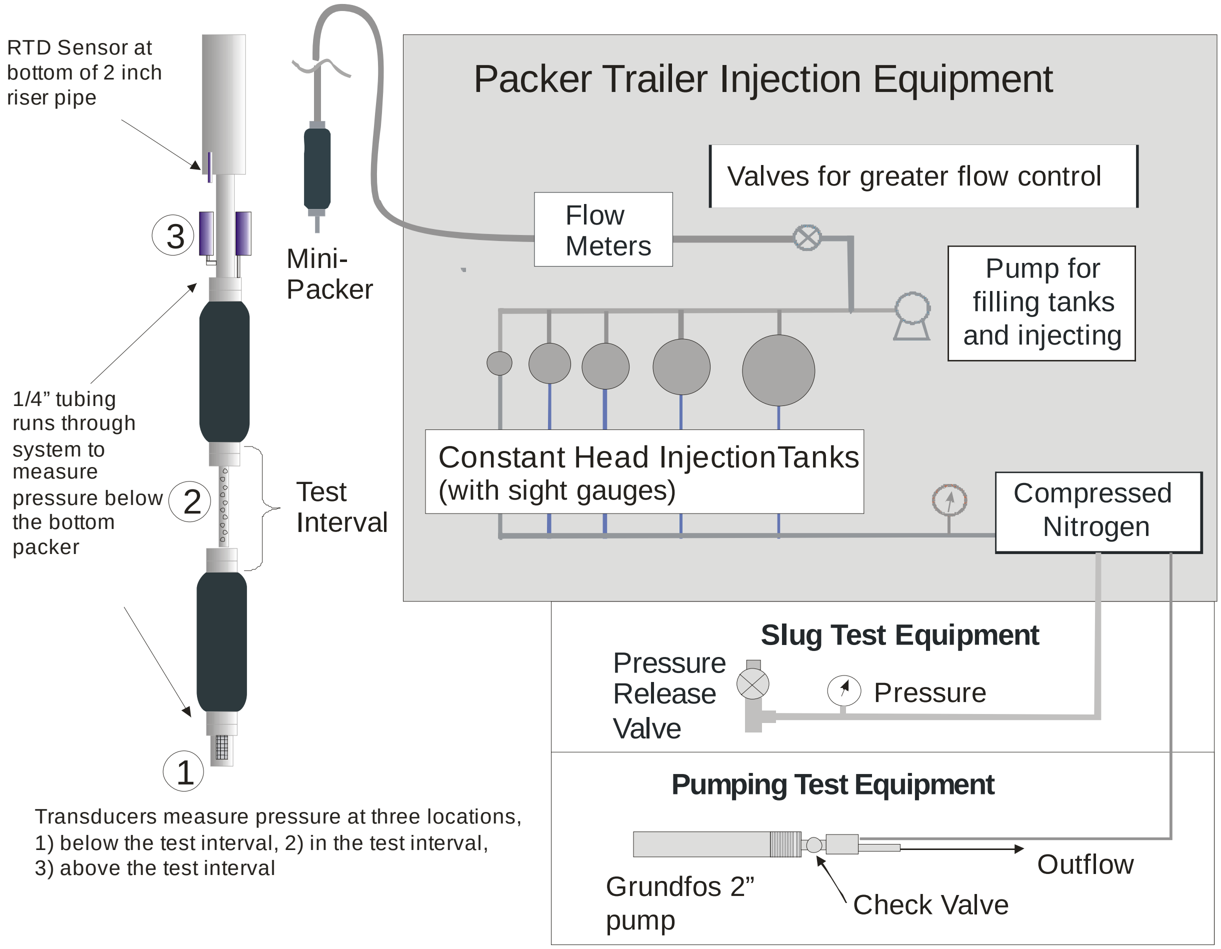


Figure 4-1 Schematic of Packer Testing System used for constant head tests

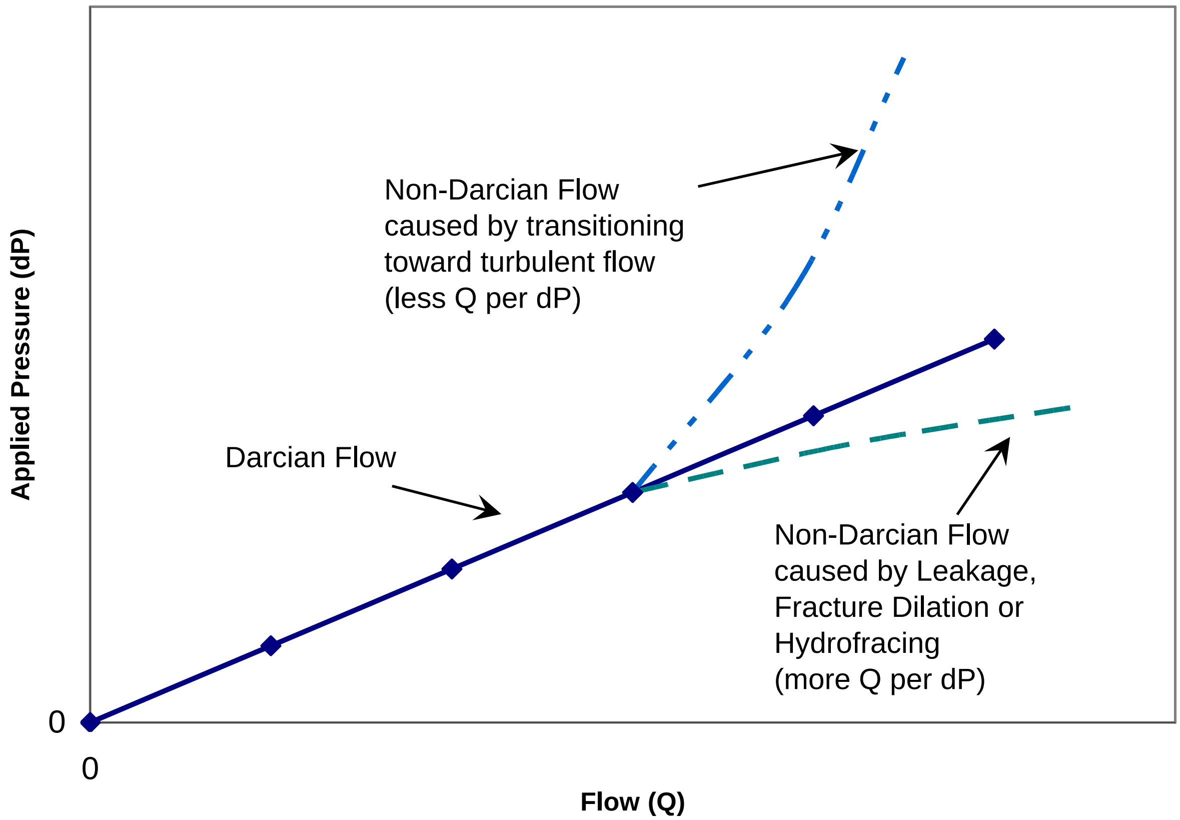


Figure 4-2 Illustration of possible flow regimes and influences during constant head hydraulic tests in rock boreholes Linearity is achieved at sufficiently low injection rates (Darcian flow). Non-linearity caused by an excessive flow rate causes a transition toward turbulent flow (less Q per dP). Non-linearity caused by excessive injection pressure causes fracture dilation and/or hydrofracing (more Q per dP).

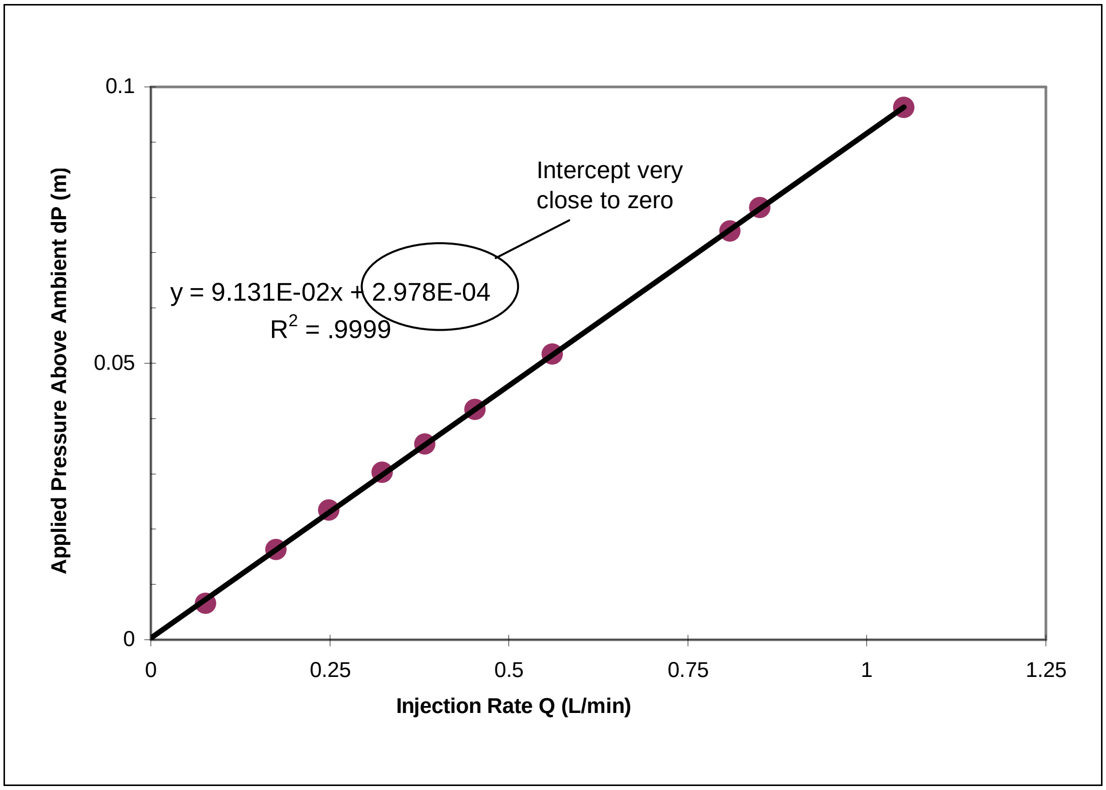


Figure 4-3 Accurate packer testing step data is linear (R2 = .9999) and is very close to passing through zero (0.0003 L/min offset).

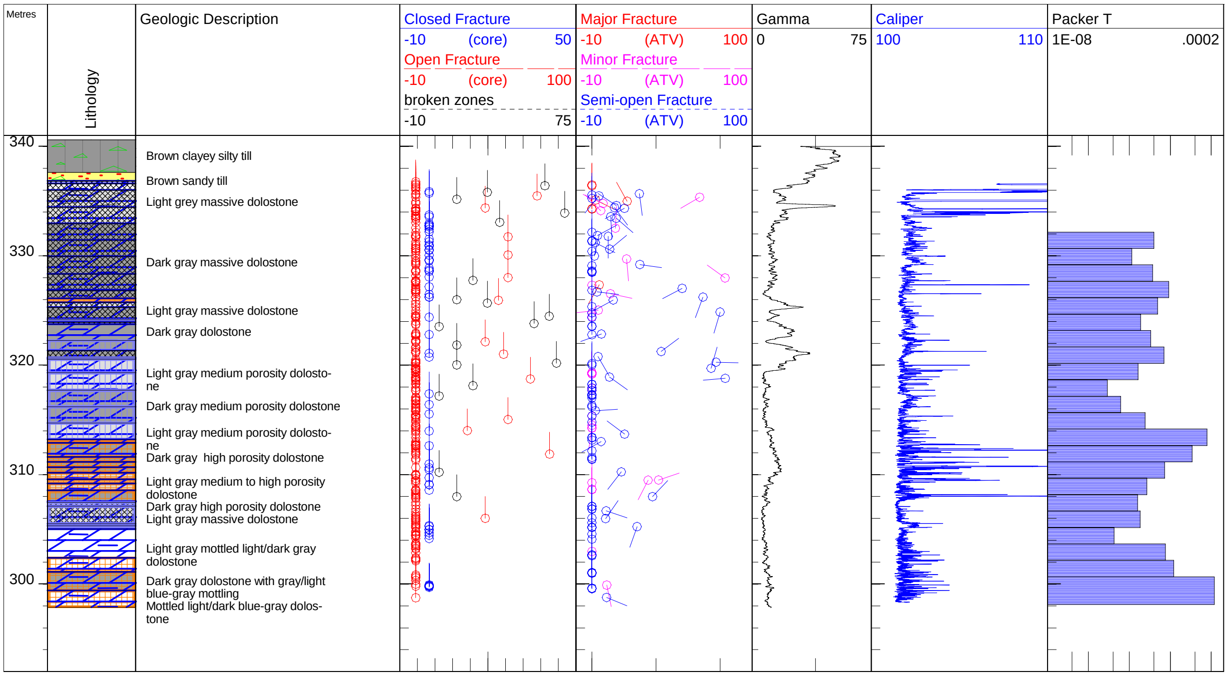


Figure 4-4 Geophysical Data, Core log data, and Packer Testing Data for MW-26

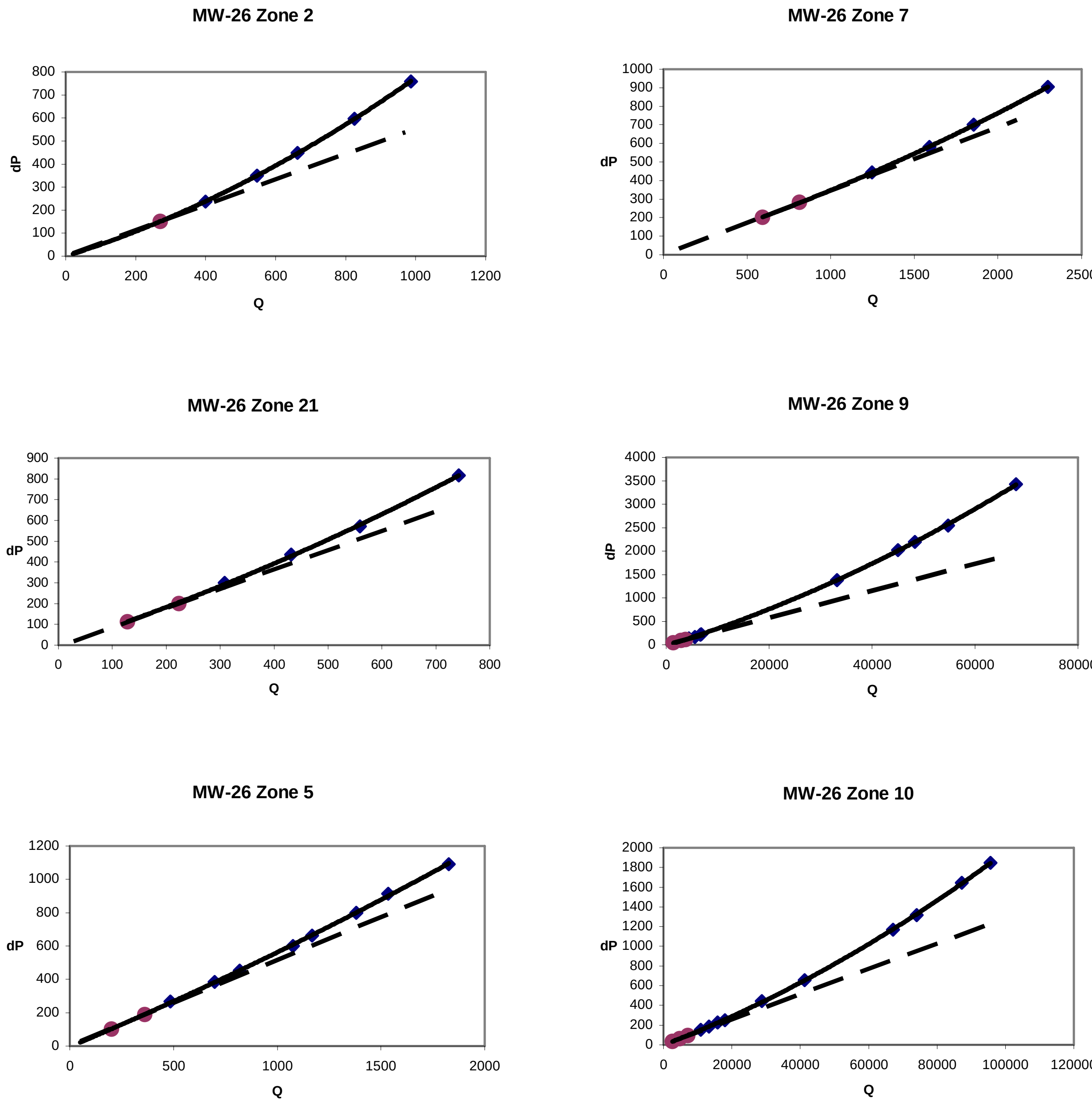
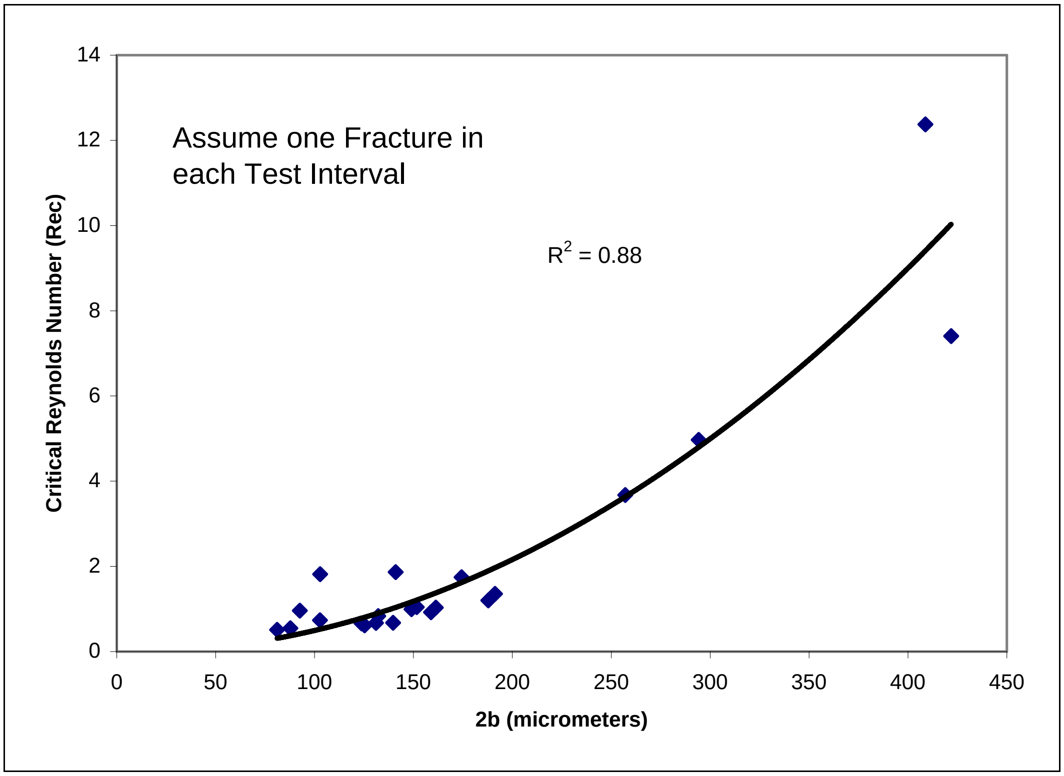


Figure 4-5 Examples of deviations from linearity during packer testing in a fractured dolostone. Linear data points are highlighted with dashed lines.



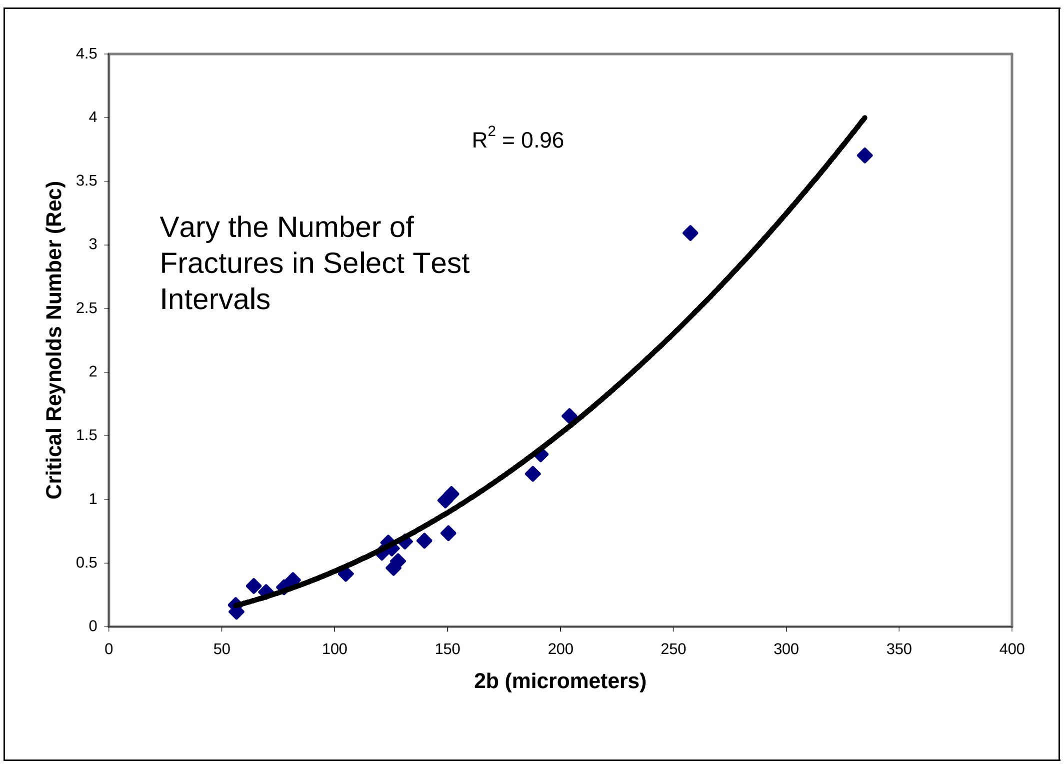


Figure 4-6 The correlation between Rec and 2b assuming one fracture and after the number of fractures for each test interval is determined. The correlation improves when more than one fracture is assumed for some test intervals.

Chapter 5 The influence of initial displacement on slug tests conducted in a fractured dolostone aquifer

5.1 INTRODUCTION

Hydraulic tests in rock boreholes are commonly conducted using inflatable packers to isolate borehole intervals where water is injected or withdrawn (i.e. straddle packer hydraulic tests) for measurement of the transmissivity in the test interval (e.g. NRC, 1996; Sara, 2005). The two general approaches include steady state tests, involving constant applied head and/or constant flow rate and transient tests in which recovery are analyzed from an instantaneous pressure pulse or after steady state injection or withdrawal.

The instantaneous pulse method, generally referred to as slug tests, is commonly used in contaminated site investigations because of the ease of execution and avoidance of the need to extract water from or inject foreign water into the formation. The main purpose of slug tests is to identify the most permeable zones in the borehole and obtain T or S values for use in groundwater flux analysis (bulk volumetric flow rates) and commonly order of magnitude values are acceptable for most purposes (Shapiro & Hsieh, 1998). Therefore, in the slug test literature, minimal attention is directed at the biases / errors that can cause erroneous values.

In the approach generally used for analysis of data from slug tests ideal conditions are assumed and semi log plots of a head or pressure parameter versus time provide the basis for the calculation of T. This approach was introduced to the geotechnical field by Hvorslev (1951) for piezometer slug tests to obtain K values in porous media assumed to be homogeneous and incompressible. Hvorslev provided examples of ideal case results and deviations from the ideal. The alternative to the semi log plot approach is a type curve analysis based on log log plots such as that developed by Cooper et al. (1967) assuming a homogeneous fully confined compressible horizontal aquifer. Maini (1971) was the first to examine slug tests as a means to obtain hydraulic aperture values using the Cubic Law. He developed equations, independent of recognition of the Hvorslev publication, for application to straddle packer slug tests in fractured rock. He also includes a volumetric radius of influence for radial flow through a fracture and used additional data (core logs, fracture mappings) to determine fracture apertures in the test interval. Maini's method of slug test data analysis is essentially the same as the Hvorslev analysis when both are expressed as T or apertures, with the addition of a volumetric radius of influence.

Although slug tests have been used in bedrock site characterization for a long time and the test method is relatively simple, there are several factors that can cause biases or uncertainties in the T values derived from the data. In this context bias refers to deviations of the T calculated from the test data from the true value. For example, short circuiting and packer leakage have been identified during constant head tests and slug tests in fractured dolostone (Chapter 2), non-linear flow (i.e. non-Darcian flow) has been observed during slug tests in unconsolidated media (McElwee & Zenner, 1998), formation compressibility effects have been identified in unconsolidated deposits (Hvorslev 1951, Choi et al., 2008), and fracture aperture changes have been observed in fractured igneous and sedimentary rock during slug tests. (Rutqvist et al., 1992;, Svenson et al., 2007; Schweisinger et al., 2009)

Non-linearity of the flow regime in both the test equipment and the formation has been quantified during slug testing in unconsolidated deposits (McElwee & Zenner, 1998) and T values were shown to be influenced by the initial displacement at higher applied pressures.

They recommend that multiple slug tests at different initial displacements be conducted to determine the T dependence. Non-linear flow has also been identified during constant head step tests in fractured dolostone at relatively low flow rates (Chapter 3), attributed to a transitioning from linear to turbulent flow in the formation since no non-linearity was observed in the test equipment. However, no studies in fractured rock have been conducted that examine non-linearity of the flow regime during slug tests.

Svenson et al. (2007) conducted falling head slug tests in fractured igneous rock using extensionometers to measure fracture geometry changes throughout the test. They report that the fracture dilates initially during the falling head slug test and gradually returns to the original geometry as the pressure is relieved. Because of the short term stresses in slug tests, changes in fracture geometry may be more readily apparent because the dilation of fractures appears to lag behind the applied pressure (Schweisinger et al., 2009) and dilation will not be masked by long term constant pressure as in steady state tests.

The literature generally agrees that the dual permeability components of a fractured sedimentary rock system (matrix and fractures) may affect the recovery response following a pumping test but there is no general agreement on the best way to analyze the data. Schwartz (1975) used recovery concepts developed in the petroleum industry by Pollard (1959) to enable the determination of the hydraulic conductivity of both the matrix and fracture systems from slug test data in fractured sedimentary rock. However, Warren & Root (1962) showed the Pollard analysis to be flawed when few fractures are present. Barker & Black (1983) also developed an analytical model for slug tests that includes matrix and fracture permeability and storativity, but the non-uniqueness of the type curves makes it impracticable to use for calculation of T from field data.

Although factors such as flow non-linearity, fracture dilation/contraction, and rock matrix permeability have been recognized as important potential influences on slug tests in fractured rock, no studies are reported where field test results have been examined to assess the magnitude of these influences on T and the values of aperture obtained from the T values. The goal of this study is to conduct slug tests in fractured sedimentary rock in a manner aimed at identifying these influences to minimize their influence in the slug test procedures and data analysis.

Site Selection and Characteristics

The fractured rock selected for this study is located in and near the City of Guelph in southern Ontario , Canada where a fractured dolostone aquifer , 100 m thick , provides water to the City and farms in the area. The straddle packer hydraulic testing took place in three cored boreholes in the City and three cored holes in the outlying area. The boreholes were open and available for limited time for geophysical logging and the hydraulic testing after which multilevel monitoring devices were installed in most of the holes for hydraulic head monitoring and sampling. Therefore much is known about the hydrogeologic conditions in the holes to provide context for assessment of the slug test results.

The three boreholes in the City of Guelph are located at a contaminated site where numerous fractures were identified in rock core and by acoustic televiewing. Figure 5-1 shows typical data collected by others prior to the slug testing including a lithologic log, acoustic televiewer log with interpretations, core log fracture identification, gamma log, and results of laboratory permeability measurements on core samples in the holes tested. Laboratory permeability tests conducted on twenty cores from boreholes in the near vicinity of the test holes indicated low matrix permeability values ($2x10^{-7}$ to $2x10^{-11}$ m2/s; $6x10^{-9}$ m2/s geometric mean). Therefore, the bulk hydraulic conductivity of the dolostone aquifer is attributed to fractures and infrequent karst conduits and it is reasonable to expect that the slug tests involve flow exclusively or primarily in the fractures. The three holes subjected to slug testing at this site were also subjected to hydraulic testing using the constant head method along their entire length using 1.5 – 6 m intervals (Chapter 3).

The three holes in agricultural areas have geologic characteristics different from those at the contaminated site. Brunton (2008) outlines the key regional hydrogeologic units based on core logs from more than 40 new boreholes in the Guelph region (Figure 5-2). One of these units identified in the boreholes was the Gasport Formation consisting of a basal cross-bedded crinoidal grainstone–packstone succession with incipient microbial-crinoidal reef mound lithofacies that change upward to bivalve coquinas and large-scale microbial reef mounds dominated by crinoidal holdfasts. This rock unit varies in thickness from 25 to more than 70 m and is the key hydrogeologic unit in the Guelph–Cambridge region. It has a characteristic white to dark blue-grey matrix (reef mound microbial matrix) and is known in the subsurface terminology of the Michigan Basin as the “White Niagaran” (Brunton, 2008). Unfortunately, no lab permeability or porosity tests have been conducted on the rock core to support the geologic findings.

Equipment and Test Procedure

The original test equipment described by Lapcevic (1988) and Novakowski (1993) was modified to improve flow control and measurement in constant head tests and to allow for the conduction of injection/withdrawal pumping tests as well as pneumatic slug tests while monitoring pressure in the test interval and in the open borehole above and below the test interval (Figure 5-3). This was achieved by using 2 inch diameter Solinst well casing (5 foot lengths) extending from the top packer to the ground surface creating a temporary 2 inch well in each test interval in which all three tests can be conducted. Large sliding head P packers made by RST Instruments are used (7.1 cm deflated, 14.7 cm max confined inflated diameter) to isolate test intervals. A high pressure regulator (1500 psi) is used on the nitrogen tank used for packer inflation to enable testing at greater depths. The packers are separated by 1¼" diameter perforated steel pipe and the through pipe in the packers is 1¼" in diameter. Compressed nitrogen is used to push the water table down (falling head slug test) and a 2" valve on the fitting is used to release the pressure (rising head slug test).

Three pressure transducers are used, one measuring pressure in the test interval, one measuring the water level in the open hole above and one measuring the pressure below the packed off interval (Figure 5-3). The transducer measuring the pressure in the test interval is attached with an elbow compression fitting to the riser pipe, measuring the pressure in the riser pipe just above the packed off interval. Measurement below the packed off interval is done through a ¼" flexible tubing that is run through the system and is fixed with a bored through compression fitting on the top of the top packer and on the end cap at the bottom of the bottom packer. Data resolution was very poor measuring the pressure in this fashion because it was inevitable that air would become entrapped in the ¼" throughput tube as the equipment is lowered into the borehole. A better design for measuring pressure in the test interval and below is outlined in Chapter 2. The transducer measuring the pressure in the open borehole above the test interval was fixed in the same location as the other transducers. Three types of transducers were used in the data collection in this study including vented Druck PDCR 1830 (0-100 mV output), and vented, current output PMC VL400 series (4-20 mA output). These transducers were periodically calibrated using a Druck DPI 603 portable pressure calibrator. Recovery tests and slug tests used Mini Divers (20 m, 50 m, and 100 m full scale) for pressure measurements because these transducers have a slightly higher resolution (± 0.5 cm). A barologger was used to correct for barometric fluctuations. (Chapter 2)

Both falling head slug tests and rising head slug tests were conducted in the same test interval when possible. However, the o ring seals on the well casing appeared to leak in the below freezing weather and the riser pipe had to be pressurized numerous times to achieve the desired initial displacements for the rising head tests, rendering the pressurization data unusable. The falling head tests were conducted by instantly pressurizing the 2 inch riser pipe with compressed nitrogen and monitoring the recovery. The rising head tests begin by opening a 2 inch valve after the falling head test achieves equilibrium which results in an immediate drop in interval pressure followed by recovery.

5.2 CONCEPTUAL FRAMEWORK FOR DATA ANALYSIS

A common method for analyzing slug tests in unconsolidated media is the Hvorslev (1951) method. Hvorslev identified two phenomenon typically observed in slug tests results. He defined he hydrostatic time lag i as the amount of time required for 63% recovery of the initial head displacement in the Hvorslev semi log plot. This time lag is directly proportional to the permeability of the formation. However, he also identified the stress adjustment time lag, which is caused by a change in the void ratio of the soil near the test hole, either through the process of drilling or by temporarily changing the effective stress near the borehole by pressurizing the pore water. This stress adjustment time lag can interfere with the test results.

Formulas are presented to calculate the hydraulic conductivity for cases of different well or piezometers geometries if the stress adjustment time lag is insignificant (ideal conditions). He supplements the discussion of these processes with test examples conducted in fractured and unfractured clay. Deviations from the ideal always occurred at early times but the slope of the semi log plot at late times usually became constant, so to avoid the interfering effects (compressibility) he used late time data for permeability determination when deviations from the ideal are observed.

In the Hvorslev model, flow in the riser pipe during recovery is given by:

$$Q = -Axs \frac{d(\Delta H)}{dt} \tag{1}$$

Where:

A_{xs} = cross sectional area of the riser pipe
ΔH(t) = the difference in the head at any time (t) and the static water level

The flow in this model is assumed to be a transient analogue of steady state flow:

$$Q(t) = FK\Delta H(t) \tag{2}$$

Where:

F = Shape Factor based on the well geometry
K = Hydraulic conductivity

Combining (1) and (2) and solving the resulting equation results in the governing equation for analyzing slug tests.

$$\ln\left(\frac{\Delta H}{\Delta H_o}\right) = \frac{FK}{Axs} t \tag{3}$$

A plot of $\ln\left(\frac{\Delta H}{\Delta H_o}\right)$ versus time will yield a straight line with a slope equal to $\frac{FK}{Axs}$ as long as the stress adjustment time lag is insignificant.

The shape factor for packer tests in which flow is dominated by horizontal fractures can be represented by radial flow of a fully penetrating well in a homogeneous confined aquifer (Figure 12 case 9 in Hvorslev 1951).

$$F = \frac{2\pi L}{\ln\left(\frac{r_o}{r_w}\right)} \tag{4}$$

Where: L = length of test interval
r_o = radius of influence of the test
r_w = well radius

The shape factor for packer tests in which flow is not dominated by horizontal fractures can be best represented by spherical flow in an infinite medium (Figure 12 case 1 in Hvorslev 1951). This would be appropriate for situations in intensely fractured rock with many sub vertical fractures and when no fractures are present.

$$F = 2\pi L \tag{5}$$

Maini (1971) independently developed a method for determining aperture values from slug test data in fractured rock assuming all flow is through the fractures. He essentially integrated the cubic law into the Thiem equation to derive the general equation of transient radial flow through a fracture.

$$dH(t) = \frac{6\mu Q(t)}{\pi\rho g(2b)^3}\log\left(\frac{r_o}{r_w}\right) \tag{6}$$

As the head changes the volume of water displaced in the borehole is $(dH)\pi r_w^{\ 2}$ and the water displaced in the fractures is $\pi\left(r_o^{\ 2} - r_w^{\ 2}\right)2b$ if the matrix flow is negligible, and equating these two volumes results in a relationship for the volumetric radius of influence:

$$\left(\frac{r_o}{r_w}\right) = \left[1 + \frac{dH}{2b}\right] \tag{7}$$

Also

$$Q = -\pi r_w^{\ 2}\,\frac{dH}{dt} \tag{8}$$

Substitution of (7) and (8) into (6) results in the final equation for aperture determination from a slug test.

$$\ln(dH) = \ln(2b) - \frac{2\rho g (2b)^3}{3\mu r_w^{\ 2}} \frac{H}{\left(\frac{dH}{dt}\right)} \tag{9}$$

A plot of H/(dH/dt) vs ln(Ho-H) results in a straight line with a slope equal to:

$$\frac{2\rho g (2b)^3}{3\mu r_w^{\ 2}}.$$

Reynolds Number to Represent Flow Conditions

It is useful to identify the flow regime in the test equipment when analyzing the test results. This can be done by expressing results in terms of a dimensionless number, the Reynolds number (Re). First defined in 1883 by Osborne Reynolds for flow through pipes, Re is often used to determine the similarity of two different flow systems, and by extension, the flow regime present. In order for two systems to be considered similar, all of the forces acting on a fluid particle must be present at equal ratios. These forces can include fluid compressibility, gravity, inertia, and friction (viscosity). Re is the ratio of the inertia forces to the viscous forces. In order for two flows to be similar, the Re must be equal (Schlichting, 1979).

$$\mathrm{Re} = \frac{\rho \bar{v} D}{\mu} \qquad (8)$$

Where:

ρ = water density
ῡ = average fracture velocity
μ = water viscosity
D = characteristic length based on system geometry

For flow in pipes the characteristic length is the pipe diameter. Flow can be considered fully turbulent if Re > 2300 (Fox and McDonald, 1992).

5.3 RESULTS AND DISCUSSION

Figure 5-4 shows the typical raw slug test data from intervals in both the low permeable matrix (A) and the high permeable matrix (B). Displacements ranged from 0.07 to 16 m. Representative data from thirty tests in five different test intervals in the low permeable matrix holes (City site) and one hundred and seventy six tests in 19 different test intervals in the high permeable matrix holes (rural site) are presented below. In both the falling head and rising head tests the earliest time data possible was used to calculate T because the point of greatest certainty is the initial displacement.

Hydraulic Short Circuiting and Packer Leakage

The open borehole above the test interval was affected more often in the tests conducted in the high matrix permeable holes (rural site), but the response was delayed indicating hydraulic short circuiting through the formation. Figure 5-5 illustrates this phenomenon observed during the 16 m initial displacement slug test in a 6 m test zone in BH-6. At large displacements a slug of much smaller magnitude (4 cm) was observed above the test interval compared to the displacement in the test interval of 16 m. Various magnitudes of this type of behavior was observed in over 50% of the tests conducted at the rural site and the resulting vertical flow violates the radial flow model typically used to analyze hydraulic tests in fractured rock.

A more immediate response was observed in the low matrix permeable holes (urban site) as illustrated in Figure 5-6. During the pressurization of the riser pipe (falling head test) an immediate, muted response is observed below the test interval at the higher pressures. Other data suggest that the borehole wall is rough in this area (e.g. acoustic televiewer log, core log) indicating likelihood of leakage between the packers and the borehole wall. The resulting increase in T at higher displacements could be misinterpreted as fracture dilation. Unless the pressure is monitored above and below the test interval, this effect will not be seen. This type of response was observed less frequently and only in rough areas of the borehole.

Non-linear Flow Effects

Figure 5-7 shows semi log analysis plots of the pressure release tests (rising head) in the high permeable matrix holes at increasing initial displacements. The semi log plots typically resulted in a concave upward curve for small initial displacements (exponential decrease) but as the initial displacement was increased the shape of the curve gradually changed, showing an early time concave downward portion and a late time concave upward portion. This trend was consistent for all of the tests conducted at the rural site and these plots illustrate the impact of non-linear flow on the slug test response. A Reynolds number analysis of the flow through the equipment reveals turbulent flow in the higher initial displacement tests as identified in Figure 8a. This indicates that the reduced slope and the initial concave downward shape of the larger displacements are partially due to non-linear flow in both the test equipment and the formation. Non-linear flow in the test equipment occurred most commonly in the larger test intervals because they have relatively larger T because of more flow paths causing faster recovery.

The Reynolds number (Re) is a convenient parameter to identify turbulent flow in pipes where fully turbulent flow is commonly observed at Re ≥ 2300 (Fox and McDonald 1992). Reynolds also determined 517 as the minimum Re below which turbulent flow can no longer exist. This implies that fully turbulent flow in a pipe can remain non-linear below 2300 as the flow rate is gradually decreased. Therefore, to ensure that data used to calculate T had no non-linear flow in the test equipment, the early time turbulent data was removed until the Re was below 517. The corrected data is shown in Figure 5-8B indicating that there is still non-linear flow occurring in the formation at the higher initial displacements.

Tables 5-1 through 5-3 summarize typical results from the rural site. The calculated T decreased with increasing initial displacement indicating that non-linear flow is occurring during large initial displacements. Sometimes the non-linearity in the formation begins before turbulent flow in the test equipment can be seen as illustrated in Tables 5-1 and 5-3. In other tests (Table 5-2), non-linearity is not seen until it exists in the test equipment. Based on the results of this study, non-linearity is a function of the initial displacement, and the interval transmissivity.

Fracture Dilation and Contraction Effects

The semi log plots for the pressure release (rising head) tests at the City site typically showed a concave downward curve that increased in magnitude with increasing initial displacements (Figure 5-9). These plots were also not nearly as smooth as the plots in the high permeable matrix holes. Slight non-linearity is observed and the rough behavior is very similar to the behavior observed by Choi et al. (2008) which was explained by formation compressibility.

Tables 5-4 through 5-6 summarize the results of the rising and falling head slug tests conducted in some of the City site test intervals. The early time data was used to calculate T and displacements ranged from 9 cm to 3 m. The calculated T values did not always uniformly decrease with increasing initial displacement as in the high permeable matrix holes. Instead the T values sometimes increase and then decrease ultimately ending with the smallest value of T for the largest initial displacement. In all cases the rising head test T was smaller than the falling head T, consistent with the findings of Schweisinger et al. (2009) in which fracture dilation during falling head tests and fracture constriction during rising head tests is proposed to explain the differences. In addition, some tests did not show non-linearity in the T values even though Re calculations show turbulent flow in the test equipment (Table 5-4). This can only be physically possible if the fractures enlarge to allow more flow thereby masking the effects of non-linear flow.

5.4 CONCLUSIONS AND IMPLICATIONS

Slug test equipment commonly used in contaminated site studies makes it easy to apply large pressure differentials to cause participation of a relatively large volume of rock in the full hydraulic response. However at early time during such high differential tests, there is commonly a strong propensity for other processes to interfere with the test results; nonlinear flow, fracture dilation/contraction, and short circuiting or leakage to the open borehole. Therefore when large differentials are used, the response data during the early time period are least suitable for obtaining T values most representative of the rock under ambient hydraulic conditions. Multiple slug tests conducted in each interval over a large range of initial applied pressures provides an improved framework for data interpretation and provide much improved prospects for discerning influences of non-ideal behavior. This study has shown that the initial displacement can affect the calculated T values obtained through slug tests in fractured rock in both high and low permeable matrix conditions. T generally decreases with increasing displacements and is caused by non-linear flow in both the formation and the test equipment. Non-linear flow through the test equipment can be eliminated if the pressure transducer is physically located in the test interval rather than the traditional location above the top packer. Slug tests in rock boreholes with low matrix permeability show more complicated trends typically involving increases as well as decreases in the calculated T as the initial displacement increases. This is due to the competing processes of fracture dilation, non-linear flow and leakage between the packer and the borehole wall. The Falling head tests consistently resulted in a higher value for T than the rising head tests implying that increases in effective stress can dilate fractures.

Tables

Table 5-1 Slug Test Results from BH-2 Zone 3. Non-linear flow is reflected in the decreasing T values. Non-linear flow in the test equipment is bolded and involves dP>2m. Non-linear T values begin at dP~75cm reflecting non-linear flow in the formation before turbulent flow in the test equipment.

BH-2 Zone 3 Slug Tests (10 m Interval)				
Initial Displacement (m)	Highest Equipment Re	Displaced Volume (L)	T (m2/s) radial	T (m2/s) spherical
0.25	319	0.50	4.1E-05	7.4E-06
0.38	523	0.78	4.1E-05	7.4E-06
0.51	694	1.04	4.1E-05	7.4E-06
0.73	876	1.47	3.7E-05	6.8E-06
1.06	1342	2.16	3.7E-05	6.8E-06
1.40	1536	2.84	3.2E-05	5.8E-06
2.12	**2116**	**4.30**	**2.7E-05**	**4.8E-06**
2.67	**2275**	**5.41**	**2.3E-05**	**4.2E-06**
6.65	**3458**	**13.48**	**1.6E-05**	**2.9E-06**
9.91	**4436**	**20.09**	**1.2E-05**	**2.3E-06**
12.58	**4732**	**25.50**	**1.2E-05**	**2.3E-06**

Table 5-2 Slug Test Results from BH-5 Zone 5. Non-linear flow is reflected in the decreasing T values. Non-linear flow in the test equipment is bolded and involves dP>1.4m. Non-linear T values begin at dP~ 60cm reflecting non-linear flow in the formation before turbulent flow in the test equipment.

BH-5 Zone 5 Slug Tests (6 m Interval)				
Initial Displacement (m)	Highest Equipment Re	Displaced Volume (L)	T (m2/s) radial	T (m2/s) spherical
0.17	455	0.35	1.1E-04	1.9E-05
0.27	796	0.55	1.1E-04	1.9E-05
0.62	1706	1.26	9.8E-05	1.8E-05
1.42	**3526**	**2.88**	**8.9E-05**	**1.6E-05**
5.56	**9783**	**11.27**	**7.5E-05**	**1.4E-05**
9.10	**14447**	**18.45**	**5.6E-05**	**1.0E-05**
12.75	**18314**	**25.84**	**5.0E-05**	**6.4E-05**
14.76	**21727**	**29.92**	**4.1E-06**	**7.4E-07**

Table 5-3 Slug Test Results from BH-6 Zone 1. Non-linear flow is reflected in the decreasing T values. Non-linear flow in the test equipment is bolded and involves dP>2.5m. Non-linear T values begin at dP~66cm reflecting non-linear flow in the formation before turbulent flow in the test equipment.

BH-6 Zone 1 Slug Tests (6 m Interval)				
Initial Displacement (m)	Highest Equipment Re	Displaced Volume (L)	T (m2/s) radial	T (m2/s) spherical
0.16	228	0.33	5.3E-05	9.6E-06
0.24	341	0.49	6.1E-05	1.1E-05
0.28	341	0.57	5.9E-05	1.1E-05
0.35	455	0.71	5.8E-05	1.1E-05
0.66	683	1.34	5.4E-05	9.8E-06
1.00	1251	2.03	5.2E-05	9.5E-06
1.31	1251	2.66	4.6E-05	8.3E-06
1.92	1706	3.89	4.4E-05	7.9E-06
2.61	**2161**	**5.29**	**2.4E-05**	**4.4E-06**
5.88	**3640**	**11.92**	**3.1E-05**	**5.7E-06**
9.70	**5233**	**19.66**	**2.7E-05**	**5.0E-06**
15.95	**6711**	**32.33**	**2.2E-05**	**4.0E-06**

Table 5-4 Slug test results from MW-26 Zone 9. Non-linear flow is reflected in the decreasing T values. Almost all tests involve turbulent flow in the test equipment.

MW-26 Zone 9 Slug Tests						
Initial Displacement (m) Pressurize	Highest Equipment Re	T Early (m2/s) Pressurize	Initial Displacement (m) Release	Highest Equipment Re	Displaced Volume (L) Release	T Early (m2/s) Release
0.33	1918	1.5E-04	0.13	264	0.26	5.8E-05
0.62	3588	1.5E-04	0.26	513	0.52	5.8E-05
0.91	5257	1.5E-04	0.41	937	0.83	5.8E-05
1.18	6473	1.5E-04	0.53	1230	1.08	5.8E-05
1.16	5535	1.4E-04	0.64	1245	1.29	5.8E-05
1.92	9826	1.4E-04	0.76	1420	1.53	5.7E-05
2.38	9621	1.4E-04	1.07	2065	2.16	5.7E-05
2.33	10339	1.3E-04	1.43	2343	2.90	5.1E-05
1.63	6912	1.3E-04	1.91	3280	3.88	5.2E-05
NA	NA	1.3E-04	2.67	4335	5.41	5.1E-05

Table 5-5 Slug test results from MW-26 Zone 10. Non-linear flow is reflected in the decreasing T values. There was no turbulent flow identified in the test equipment.

MW-26 Zone 10 Slug Tests						
Initial Displacement (m) Pressurize	Highest Re	T Early (m2/s) Pressurize	Initial Displacement (m) Release	Highest Re	Displaced Volume (L) Release	T Early (m2/s) Release
0.31	262	1.8E-05	0.09	68	0.17	5.8E-06
0.28	159	1.6E-05	0.12	34	0.25	5.8E-06
0.38	228	1.6E-05	0.17	34	0.35	5.6E-06
0.41	205	1.5E-05	0.19	23	0.39	5.8E-06
0.51	284	1.5E-05	0.21	34	0.42	5.8E-06
0.85	512	1.5E-05	0.36	91	0.73	5.6E-06
1.40	557	1.4E-05	0.60	102	1.21	5.2E-06

Table 5-6 Slug test results from MW-367-7 Zone 16. Non-linear flow is reflected in the decreasing T values. Non-linear flow in the test equipment is bolded. Non-linear T values begin at dP~ 1.5m.

MW-367-7 Zone 16 Slug Tests						
Initial Displacement (m) Pressurize	Highest Equipment Re	T Early (m2/s) Pressurize	Initial Displacement (m) Release	Displaced Volume (L) Release	Highest Equipment Re	T Early (m2/s) Release
0.17	621	1.0E-04	0.14	0.28	166	2.4E-05
0.40	1450	1.0E-04	0.19	0.39	166	2.4E-05
0.29	911	1.0E-04	0.23	0.47	228	2.6E-05
0.18	538	9.3E-05	0.43	0.87	290	2.4E-05
0.48	**2112**	**1.0E-04**	0.56	1.14	476	2.4E-05
1.56	**4266**	**8.3E-05**	0.87	1.76	746	2.4E-05
4.95	**7642**	**5.0E-05**	3.18	6.45	1781	1.9E-05

Figures

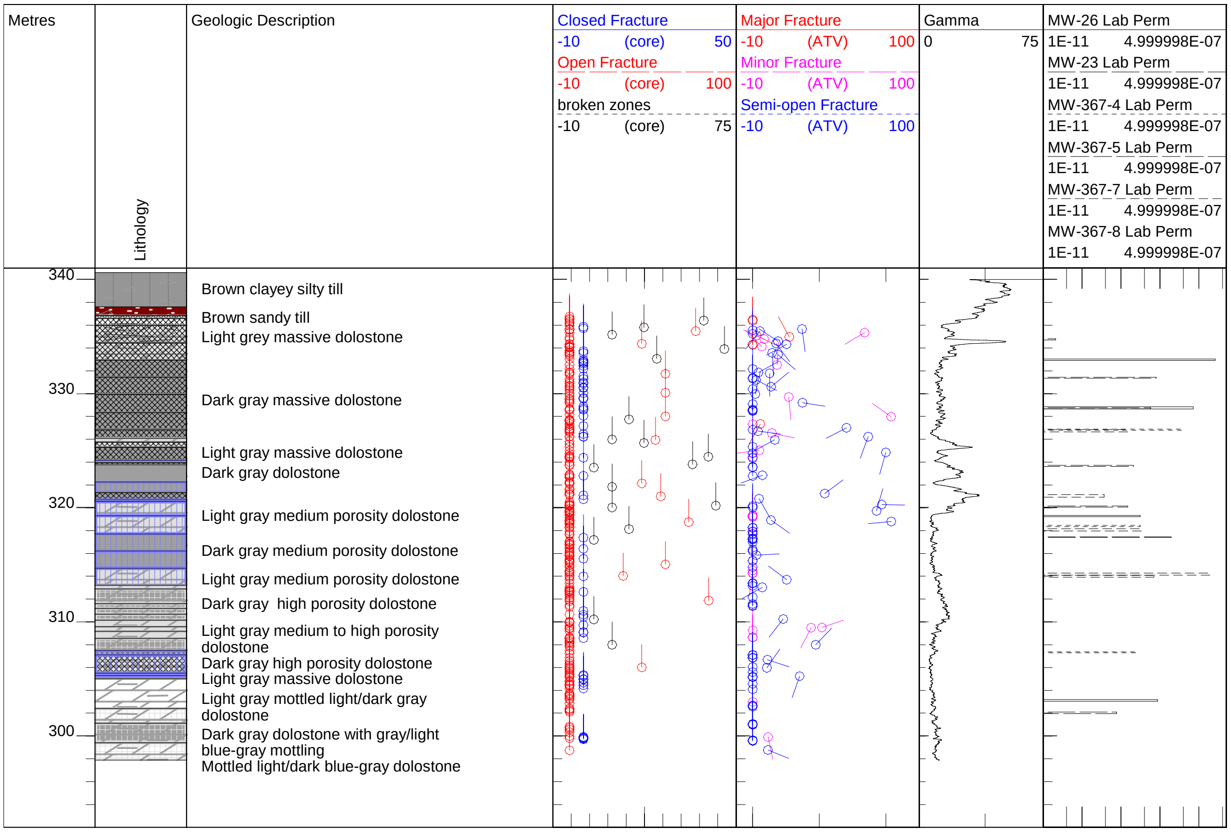


Figure 5-1 Core Logs, Geophysical Data, and Lab Permeability Tests from borehole MW-26 at the Guelph Tool Site.

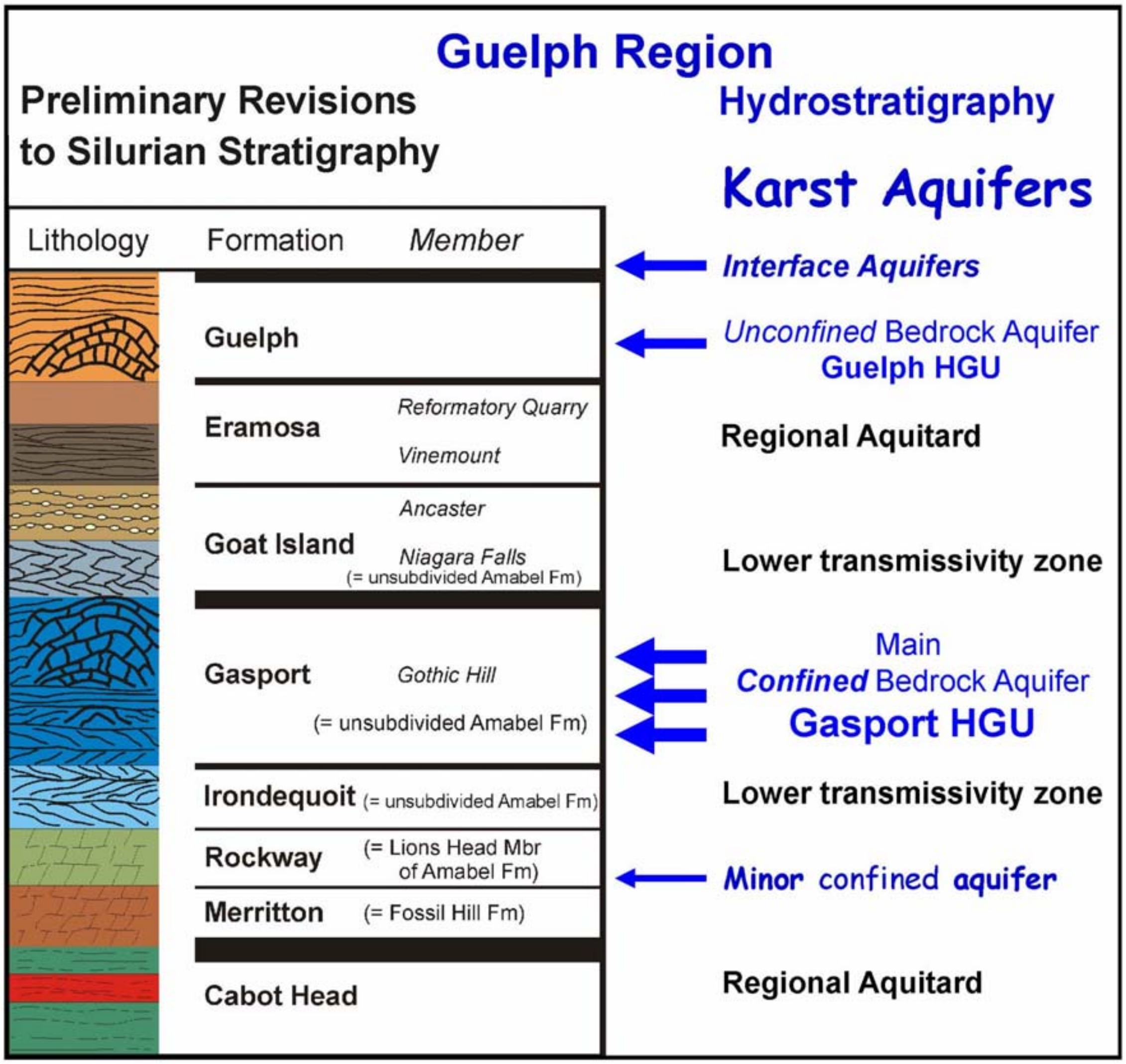


Figure 5-2 Guelph Region Stratigraphy as outlined by Brunton (2008)

(A)

(B)

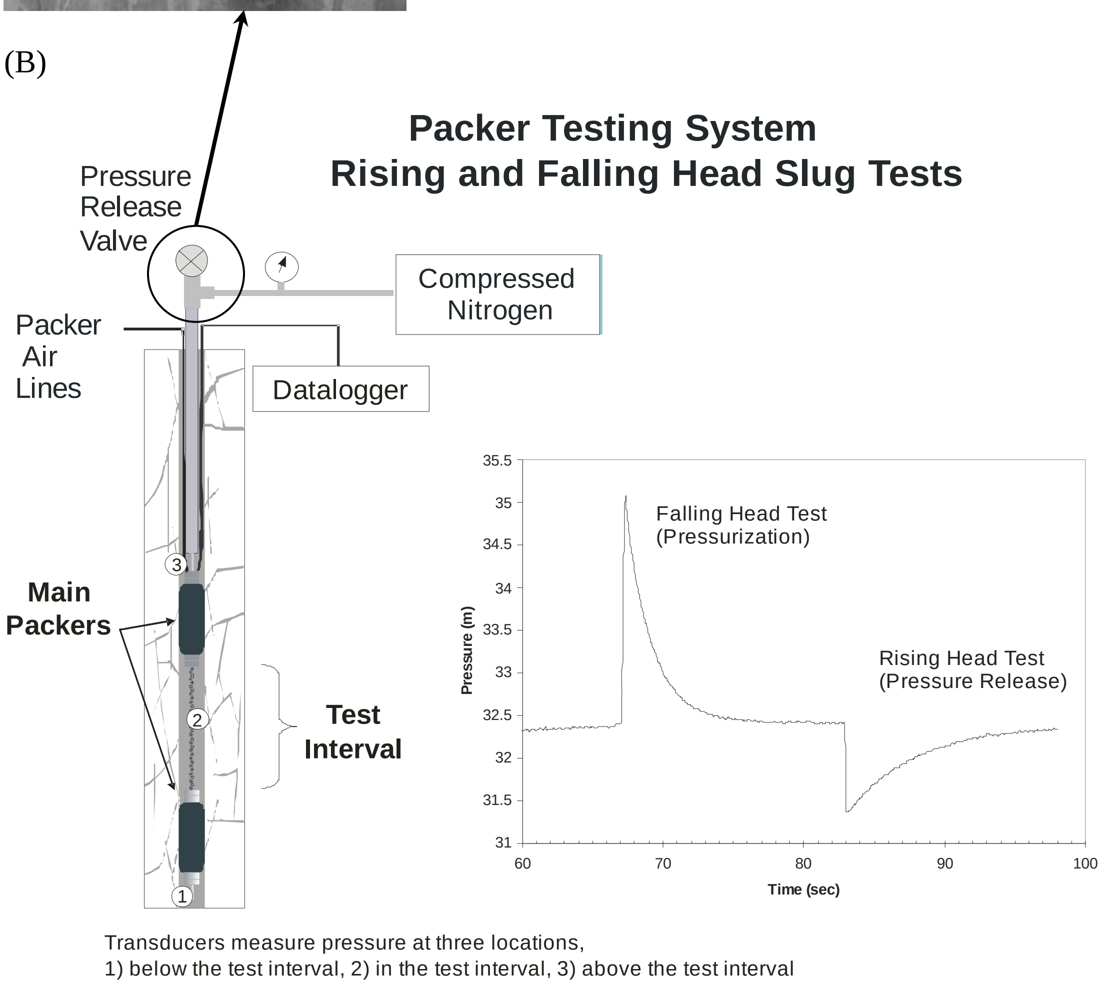
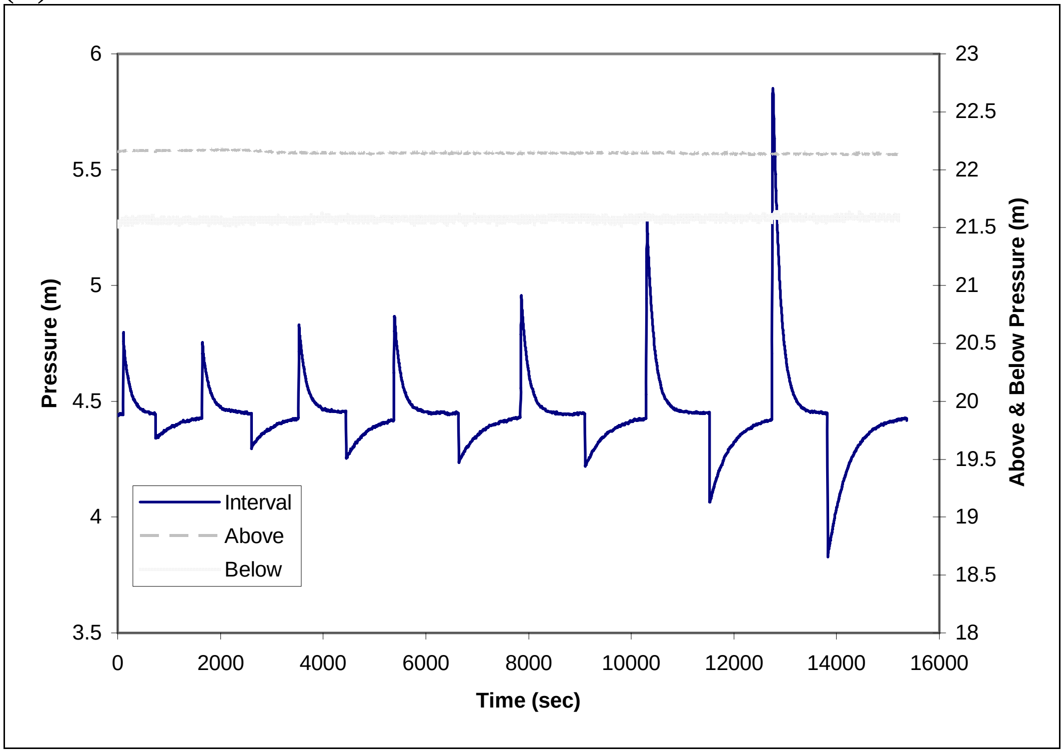


Figure 5-3 (A) Fitting for conducting pneumatic slug tests, (B) Schematic of Packer Testing System and resulting data.

(A)



B)

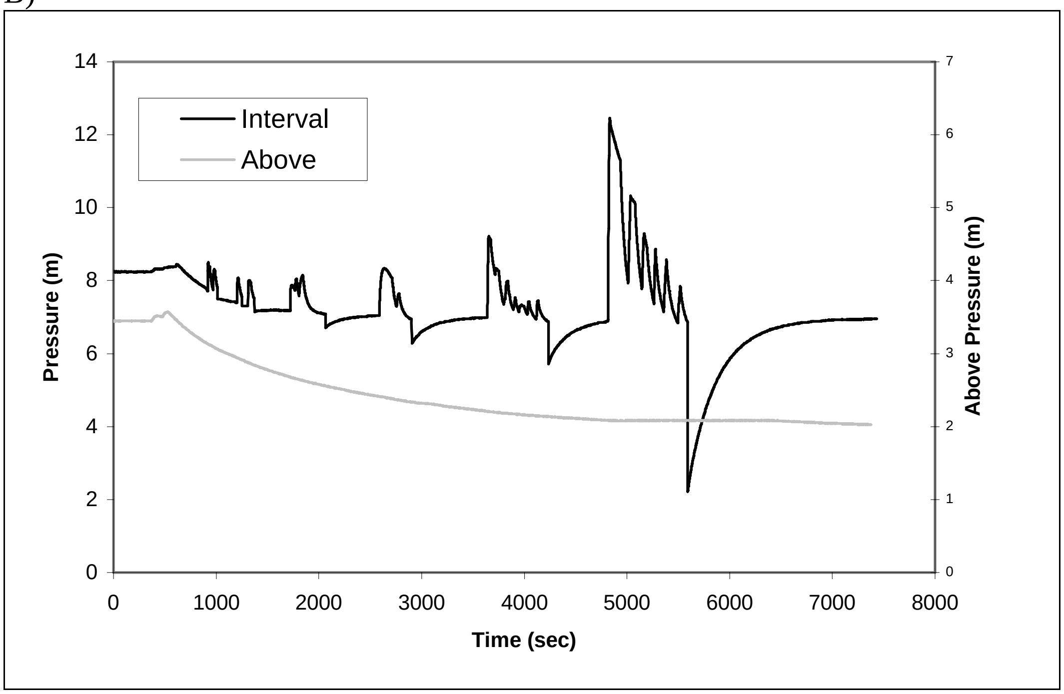


Figure 5-4 Typical raw slug test data from (A) Guelph Tool (low permeable rock matrix) intervals and (B) Tier 3 (high permeable rock matrix) intervals. The pressurized portion of the slug tests were only analyzed for the low permeable rock matrix tests (A) because of the multiple step pressurization required in the high permeable matrix holes to achieve larger displacements.

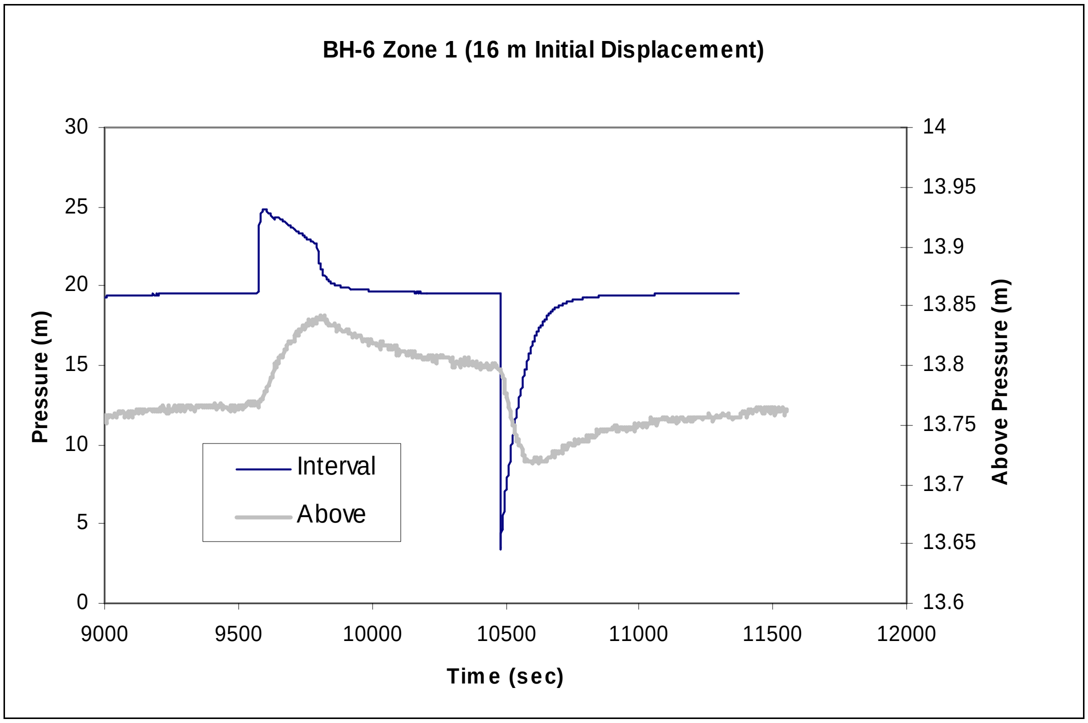


Figure 5-5 Slug caused by leakage to the open hole above the test interval in BH-6 Zone 1. The slug created above the test interval had a 4 cm initial displacement. The delayed response is indicative of short circuiting through the formation.

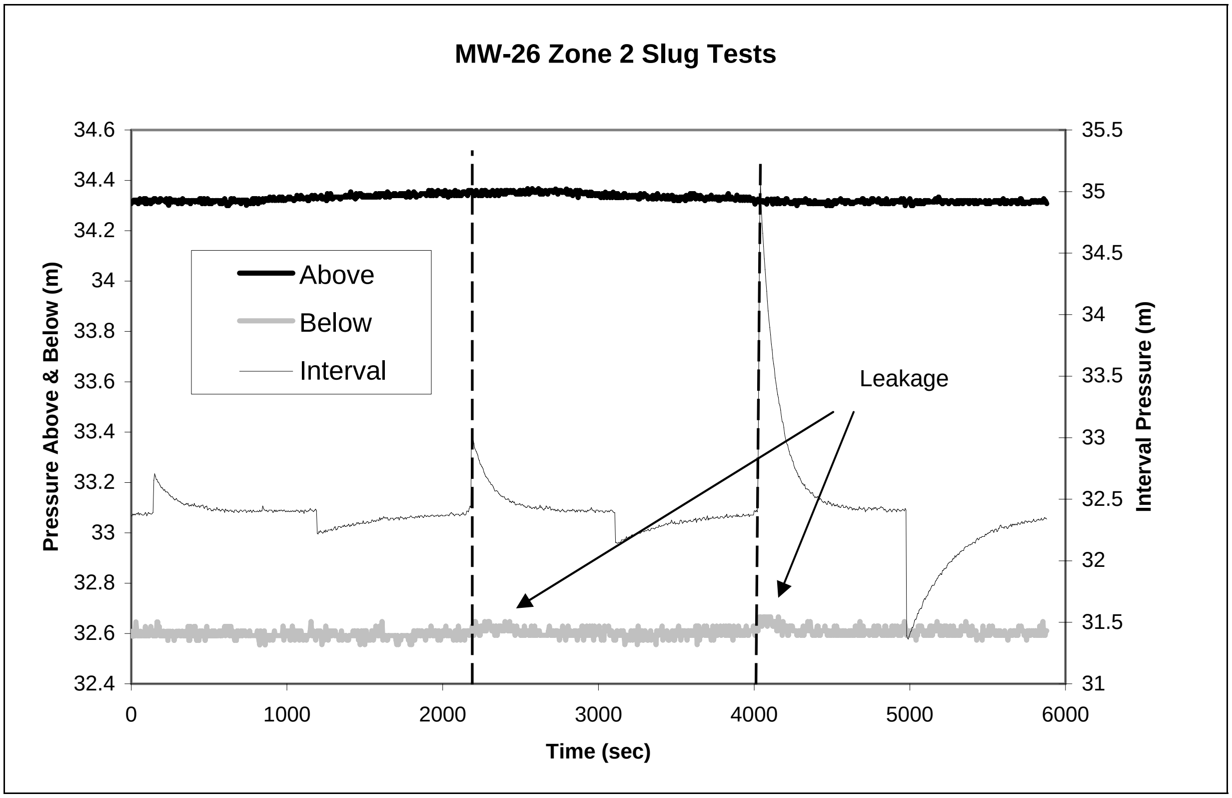


Figure 5-6 Raw data for slug tests conducted in a low matrix permeability test interval. Leakage can be seen below the test interval during the pressurization (falling head) test. This would result in a higher value for T.

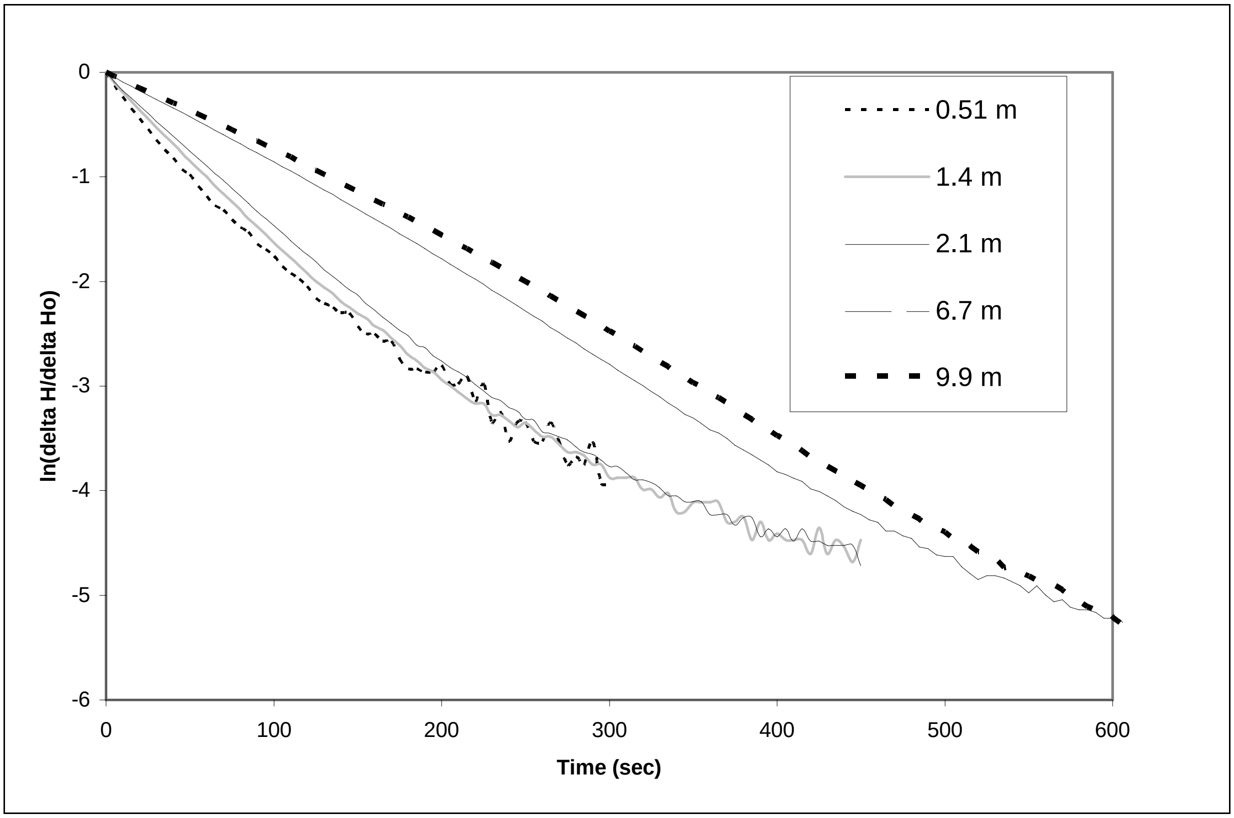
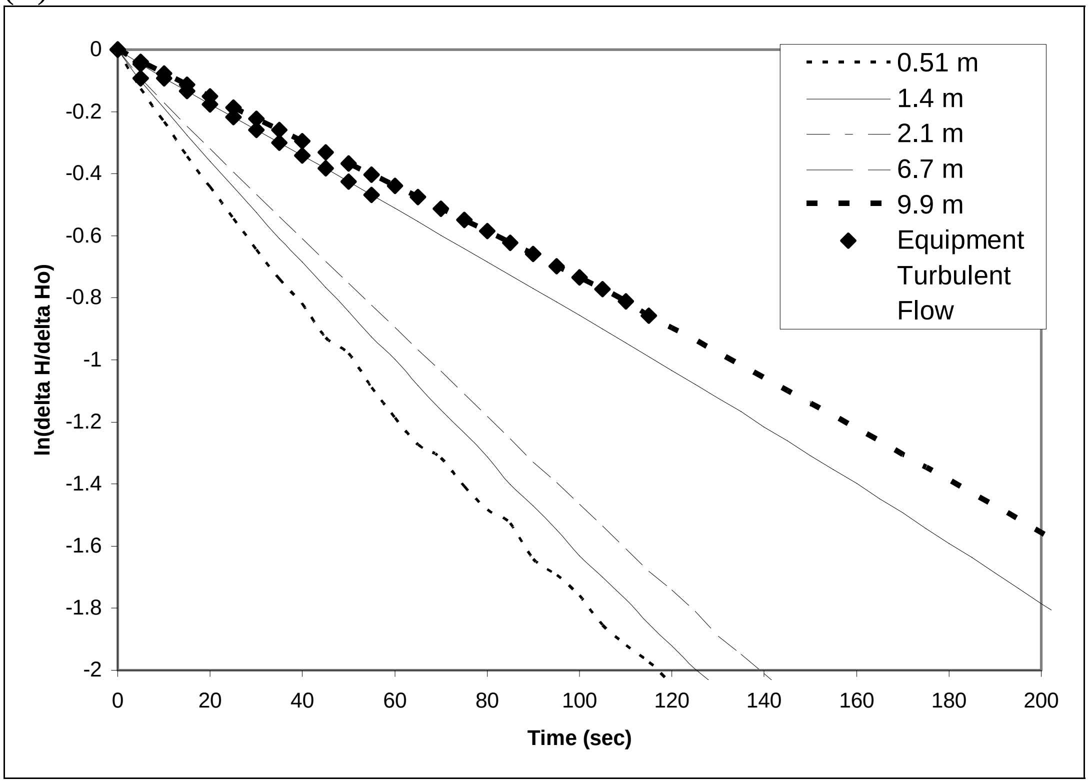


Figure 5-7 Hvorslev plot variations with increasing initial displacement in holes with a high permeable matrix.

(A)



(B)

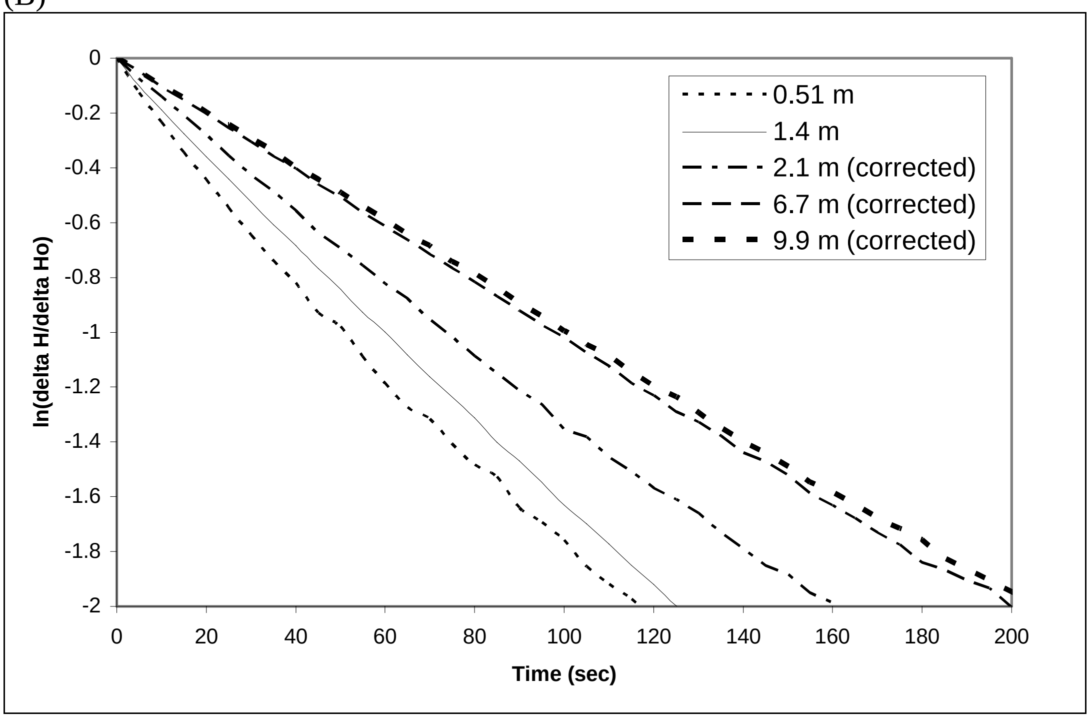


Figure 5-8 (A) Turbulent flow through the equipment during the slug tests was confirmed by Re at initial displacements of 2.1, 6.7, and 9.9 m and (B) Test results after removal of identified equipment non-linear data..

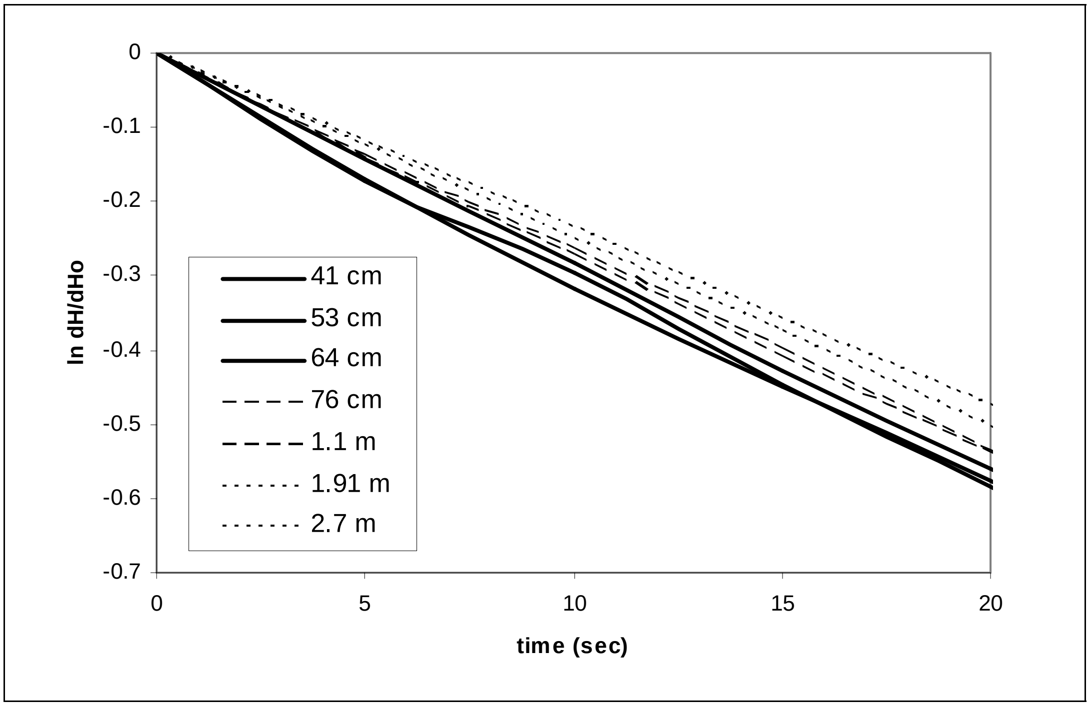


Figure 5-9 Hvorslev plot variations from low permeable rock matrix intervals for pressure release (rising head) tests at increasing initial displacements. Slope, and therefore permeability, decreases at large displacements indicating non-linear flow.

Chapter 6 Straddle packer pumping and recovery tests to determine transmissivity and examine dual permeability effects

6.1 INTRODUCTION

Hydraulic tests in fractured rock boreholes are commonly conducted using inflatable packers to isolate specific intervals where water is injected or withdrawn (i.e. straddle packer tests) to determine the transmissivity (T) of the test interval (e.g. NRC, 1996; Sara, 2005). These tests typically involve short time in which the head is maintained constant and the test run to achieve steady flow at a number of different applied head differentials (constant head step test), or an instantaneous pressure pulse is applied (slug test). T measurements by these tests are common in contaminated site characterization and waste isolation investigations in deep rock. Another approach to determining the T of fractured rock common in investigations pertaining to mine site water control and groundwater resource assessments involves pumping at constant rate to near steady state and monitoring the subsequent recovery when the pumping is instantaneously discontinued. This approach began with the Theis method of analysis (1935) for aquifer tests, a type curve method in which transmissivity (T) and storativity (S) can be determined from measurements of drawdown in observation wells (i.e. multiwell test data).

$$h_o - h = \frac{Q}{4\pi T}\int_u^{\infty}\frac{e^{-u}}{u}du \qquad\qquad u = \frac{r^2 S}{4Tt} \tag{1}$$

$$h_o - h = \frac{Q}{4\pi T}\left[-0.5772 - \ln u + u - \frac{u^2}{2\cdot 2!} + \frac{u^3}{3\cdot 3!} - \frac{u^4}{4\cdot 4!} + \ldots\right] \tag{2}$$

Cooper-Jacob (1946) showed that the infinite series can be approximated by the first two terms when u is small enough (i.e. long time and/or small r). This approximation is represented by a straight line on a semi log plot of drawdown vs log time. A quest to obtain T values from the pumping well using the recovery response soon began because in many field situations there are no monitoring wells and that the drawdown measurements in pumping wells can be quite inaccurate due to pumping disturbances particularly at early times. In contrast, the recovery response is generally cleaner without any of the pumping disturbances. Horner (1951) used the Cooper-Jacob approximate solution to develop a method to analyze recovery data from a shut in test, in which the pump is running for an unspecified period of time and the test hole is 'shut in', effectively turning off the pump instantaneously. Jacob independently developed the Theis recovery method with the only difference the requirement for the pumping portion of the test to be near steady state (Bentall,. 1963).

In fractured rock the flow system is composed of two parts, the rock matrix and the fracture network, making the traditional analysis methods, which assume homogeneity, less than ideal. Pollard (1959) developed a method for evaluating acid treatments in fractured limestone oil fields using a semi log plot of time vs log dP that had three exponential terms, representing flow from the system into the coarse fractures, flow from the coarse fractures to the well, and a skin effect between the coarse fractures and the well. In contrast, the Warren and Root (1962) double porosity model postulates that the early time data reflects the permeability of the fractures, the middle time data is transitional and the late time data reflects the permeability of the entire reservoir. This latter model results in two meaningful lines on the traditional Cooper-Jacob semi-log plot, the early time data reflecting fracture permeability and the late time data, which gives the permeability of the entire reservoir.

Although these methods are commonly used in the assessment of aquifer T using wells and open boreholes, it is rarely used in the context of straddle packer testing in fractured rock for contaminated site characterization or waste isolation investigations. This is likely due to the fact that pumping/recovery tests require more effort and time than the conventional methods (constant head and slug tests) and the desire to obtain high resolution of T with depth. In contrast, for full thickness aquifer T estimates pumping and recovery tests require the least effort and time.

One of the goals of this thesis is the development of improved accuracy of T and therefore hydraulic aperture values through the use of multiple test methods. Therefore the packer testing system was modified to allow pumping tests (injection or withdrawal) at constant rate followed by recovery. The literature suggests that possibilities exist for acquiring useful additional insights into the fracture system if pumping tests are conducted on a much smaller scale in straddle packer tests. In this study pumping/recovery tests were conducted in packed off intervals ranging from 1.5 to 10 m and both the pumping and recovery tests were analyzed using the Cooper-Jacob semi-log plot and the Theis recovery method. Tests were conducted in boreholes completed in a 100m thick, fractured dolostone aquifer in Guelph, Ontario overlain by Quaternary deposits and bounded by a shale aquitard below. The injection tests were conducted in three boreholes as part of a contaminated site investigation (city), and the withdrawal tests were conducted in three other boreholes as part of a groundwater resource evaluation (rural). Previously conducted constant head tests are also included as a comparison when possible.

Site Selection and Characteristics

The fractured rock selected for this study is located in and near the City of Guelph in southern Ontario , Canada where a fractured dolostone aquifer , 100 m thick , provides water to the City and farms in the area. The straddle packer hydraulic testing took place in three cored boreholes in the City and three cored holes in the outlying area. The boreholes were open and available for limited time for geophysical logging and the hydraulic testing after which multilevel monitoring devices were installed in most of the holes for hydraulic head monitoring and sampling. Therefore much is known about the hydrogeologic conditions in the holes to provide context for assessment of the slug test results.

The three boreholes in the City of Guelph are located at a contaminated site where numerous fractures were identified in rock core and by acoustic televiewing. Figure 6-1 shows typical data collected prior to the slug testing including a lithologic log, acoustic televiewer log with interpretations, core log fracture identification, gamma log, and results of laboratory permeability measurements on core samples in the holes tested. Laboratory permeability tests conducted on twenty cores from boreholes in the near vicinity of the test holes indicated low matrix permeability values ($2x10^{-7}$ to $2x10^{-11}$ m2/s; $6x10^{-9}$ m2/s geometric mean). Therefore, the bulk hydraulic conductivity of the dolostone aquifer is attributed to fractures and infrequent karst conduits and it is reasonable to expect that the slug tests involve flow exclusively or primarily in the fractures. The three holes subjected to slug testing at this site were also subjected to hydraulic testing using the constant head method along their entire length using 1.5 – 6 m intervals.

The three holes in agricultural areas have geologic characteristics different from those at the contaminated site. Brunton (2008) outlines the key regional hydrogeologic units based on core logs from more than 40 new boreholes in the Guelph region (Figure 6-2). One of these units identified in the boreholes was the Gasport Formation consisting of a basal cross-bedded crinoidal grainstone–packstone succession with incipient microbial-crinoidal reef mound lithofacies that change upward to bivalve coquinas and large-scale microbial reef mounds dominated by crinoidal holdfasts. This rock unit varies in thickness from 25 to more than 70 m and is the key hydrogeologic unit in the Guelph–Cambridge region used for well water supply. It has a characteristic white to dark blue-grey matrix (reef mound microbial matrix) and is known in the subsurface terminology of the Michigan Basin as the “White Niagaran” (Brunton, 2008). Unfortunately, no lab permeability or porosity tests have been conducted on the rock core to support the geologic findings.

6.2 EQUIPMENT AND TEST METHOD

This packer testing system (Figure 6-3) is an adaptation of the system first introduced by Gale (1982) and subsequently modified by Lapcevic (1988) & Novakowski. (1993). It consists of a trailer containing a series of tanks of different diameter with sight gauges used to measure flow rates by timing the rate of water level drop and knowing the tank inside diameter. Tank diameters range from 2.5 to 40 cm with the smaller tanks used for less permeable test intervals. All tanks are connected through a manifold system to a nitrogen tank used to pressurize the void space above the water in the tanks. This is the driving force for all constant head injection/recovery tests. A second nitrogen tank is used to inflate the packers. This equipment was modified further to improve flow control and measurement in the constant head tests and to allow for the conduction of injection/ withdrawal recovery tests as well as pneumatic slug tests. The pressure in the open borehole above and below the test interval was also monitored to identify leakage and/or short circuiting. (Chapter 2)

A 2” submersible Grundfos pump (Rediflo 2) is used for withdrawal recovery tests and flexible tubing is lowered into the 2” pipe for injection recovery tests. The flexible tubing allows for minimal interference in the 2” riser pipe for the falling head recovery period and because it was routed through the flow meters a wide range of flow rates can be used during the constant flow injection period. A check valve fitting was required to use the Grundfos for rising head recovery tests to prevent water in the outflow line from falling back into the test interval when the pump was turned off. A ¼” tubing is connected to this fitting to allow for the water in the line to be purges with compressed nitrogen before pump removal to lighten the hose weight and minimize leakage when transporting the pump. The outflow from withdrawal tests is routed through the largest flow meter (0.5-15 L/min) for accurate flow measurements. Higher flow rates must be measured manually (up to 20 L/min).

6.3 CONCEPTUAL FRAMEWORK FOR DATA ANALYSIS

The Cooper-Jacob straight line method (Cooper & Jacob, 1946) is commonly used to analyze pumping data and is an approximation of the Theis equation. The Theis equation assumes the aquifer is horizontal, confined, homogeneous and of infinite extent. Cooper and Jacob realized that for small values of u ($u < 0.01$) only the first two terms in the above equation need be used as the other terms become negligible assuming the storativity is constant. Traditionally for pumping tests in porous media using observation wells, u is considered small when t is large and/or r is small. $\frac{r^2}{t} <<< \frac{4T}{S}$

$$s = \frac{Q}{4\pi T} W(u) = \frac{Q}{4\pi T}\left(-0.5772 - \ln\frac{r^2 S}{4Tt}.\right) \qquad s = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2 S} \tag{3}$$

Where:

$u = \frac{r^2 S}{4Tt}$
s = drawdown (m)
Q = flow rate (m^3/s)
T = transmissivity (m^2/s)
S = storativity (-)
t = time since pumping began (s)
r = radial distance to the observation well (m)

A plot of log time vs drawdown will form a straight line and if this line is extended to the point of zero drawdown it will intersect the log time axis at t_o. Substitution in (4) gives us the governing equations for parameter determination.

$$S = \frac{2.25Tt_o}{r^2} \qquad T = \frac{2.3Q}{4\pi\Delta s} \tag{4}$$

Where:

Δs=the slope of the straight line in the semilog plot

This method was developed by Cooper and Jacob to simplify the interpretation of pumping test data and they note that this method is not always applicable and is meant to supplement not supersede traditional type curve methods. Traditional analysis commonly considers the middle time data, after u is small enough, most appropriate for T analysis in porous media.

The pumping portion of a well test can be influenced by well bore storage, and Cooper et al. (1967) presented a procedure to identify well bore storage effects on a log-time versus log drawdown plot. For pure well bore storage in which all of the discharged water comes from the well bore:

$$s_w = \frac{Q}{\pi r_c^{\,2}} t$$

Where: s_w = drawdown in the well
Q = flow rate
r_c = casing radius
t = time

Therefore, when the slope of the early time data on the log-log plot is equal one well bore storage is considered significant. These effects are commonly considered significant in large diameter wells, at high flow rates, and in low permeable test zones.

The Horner Shut in Test (1951) was developed to analyze recovery data of entire well pumping tests in the petroleum industry. The governing equation is:

$$Pw = Po - \frac{q\mu}{4\pi kb} \ln\left(\frac{to + \vartheta}{\vartheta}\right) \qquad (5)$$

Where: Pw = pressure at time t (atm)
Po = static pressure (atm)
q = constant rate of production (cm3 of subsurface volume/s)
k = permeability (darcies)
b = aquifer thickness (cm)
to = time pump turned off
ϑ = time since pump turned off

Divide both sides by ρg:

$$Ho - Hw = \frac{q}{4\pi T} \ln\left(\frac{to + \vartheta}{\vartheta}\right) \quad \text{and} \quad \left(\frac{to + \vartheta}{\vartheta}\right) = \frac{t}{t'}$$

Substitution arrives at an identical solution as Jacob (Theis recovery method)

$$s' = \frac{Q}{4\pi T} \ln\left(\frac{t}{t'}\right) \qquad (6)$$

The Theis recovery method was developed independently by Jacob (Bentall, 1963). A graph of log t/t' vs s' will result in a straight line passing through the origin and if the pumping rate is known T can be calculated from the slope of that line over one log cycle.

$$s' = \frac{2.3Q}{4\pi T} \qquad (7)$$

Where:

s' = residual drawdown over 1 log cycle of log(t/t')
Q = flow rate
T = transmissivity of the test interval

However, in his 1963 publication Jacob acknowledges that for many tests this method does not produce a straight line through zero. He postulates that this is due to the variability of the storativity in the aquifer noting that this variability appears to be greater in unconfined aquifers than confined. Figure 4 illustrates the three cases of recovery curves he discusses.

6.4 RESULTS AND DISCUSSION

Most of the tests conducted at both sites showed the same type of s-curve response described in the petroleum literature. In both the pumping and recovery tests T is calculated from the early time data and middle time data as illustrated in Figure 6-5. Test flow rates ranged from 0.05 to 15 L/min and representative data is presented from the twenty-two tests conducted in five different test intervals in the low permeable matrix holes (City site) and the thirty tests conducted in ten different test intervals in the high permeable matrix holes (rural site). Figure 6-6 shows typical raw data for injection and withdrawal tests from intervals in both the City site (A) and the rural site (B).

Hydraulic Short Circuiting and Packer Leakage

The open borehole above the test interval was affected more often and to a greater degree in the tests conducted at the rural site and the response was delayed indicating hydraulic short circuiting through the formation. Figure 6-6B illustrates this phenomenon observed during the tests in a 6 m interval zone in BH-6. At large flow rates a drawdown of much smaller magnitude was observed above the test interval. Various magnitudes of this type of behavior was observed in over 50% of the tests conducted at the rural site and the resulting vertical flow illustrates the inadequacy of a complete radial flow model when matrix flow is significant.. This phenomenon occurred less often at the City site at a much lower magnitude as seen in Figure 6-6A.

Well bore Storage Effects

Figure 6-7 shows log-log plots of two injection tests conducted in the same test interval at the City site. Well bore storage effects appear to be significant at the (A) higher flow rate of 500 ml/min, but the early time data in (B) the lower flow test of 72 ml/min is affected to a much lesser degree. However, this method only indicates whether or not well bore storage is significant and there is no easy way to separate the well bore storage effects from drawdown caused by water entering or leaving the formation. Historically there has been no interest in doing this because T values are typically calculated from later time data where well bore storage effects are absent (this is considered middle time data in this study). However, since both pumping and recovery tests are analyzed in this study, and both tests show linear early time data there is a desire to use the early time pumping data free from well bore storage effects to compare with the recovery data.

Another way to understand well bore storage influences on the pumping test results is to compare the early time change in drawdown from both the pumping test and the recovery test, because well bore storage effects are caused by the pump removing water from the well casing instead of from the formation and this process is absent in recovery data. The early time data from the tests shown in Figure 7 are summarized in Table 6-1. The linear early time data lasts for approximately 20 seconds, so the change in drawdown for the first 20 seconds for the pumping and recovery portions of the test are compared. In all tests in this interval the change in drawdown is basically the same for the pumping and recovery tests but the change in drawdown increases with each increase in flow rate. This indicates that well bore storage effects are negligible even though the traditional analysis identifies significant well contributions. Table 6-2 shows this same type of analysis on a different test interval. In this case the early time data lasts for 7 seconds and the drawdown from the pumping data is 2 times the drawdown in the recovery data which indicates significant well bore storage effects.

Withdrawal/Recovery Tests

All of the withdrawal recovery tests were conducted at the rural site. The conceptual model for the fractured dolostone in this area is predominately horizontal fractures along bedding planes with a substantially permeable rock matrix. The permeability of the matrix may be due to numerous channels owing to the reef mound geologic setting in this part of the aquifer. Most of the tests conducted in these boreholes (>90%) resulted in an s curve response in the semi-log plot (Figure 6-8). Both the pumping and the recovery plots are very similar and all of the s curve semi log plots have three linear portions at early time, middle time and late time. Because the late time data involve very small changes in pressure it is not considered in this study. However, T values are determined for the early and middle times for a comparison.

Table 6-3 outlines the typical data for recovery tests in a test interval. In all cases of recovery in the rural wells, the early time data results in a larger value for T than the middle time data and the value for T decreases with increasing flow rates.

Table 6-4 shows a comparison of the pumping test and recovery test analysis for the early time data. The T determined by pumping tests is consistently smaller than the recovery value at all flow rates. A comparison of the early drawdown indicates no well bore storage interference to account for this difference. However, this type of behavior is consistent with previous studies (Schweisinger et al., 2009) in which fractures close during pumping and open during recovery in a hysteretic fashion.

Injection/Recovery Tests

All of the injection recovery tests were conducted at the city site. The conceptual model for the fractured dolostone in this area is predominately horizontal fractures along bedding planes with fewer sub vertical fractures set in a low permeable rock matrix. Many of the tests conducted in these boreholes resulted in an s curve response in the semi-log plot (Figure 6-9). Both the pumping and the recovery plots are very similar and all of the s curve semi log plots have three linear portions at early time, middle time and late time consistent with the rural holes. T values are determined for the early and middle times for a comparison. Consistent with the tests in the rural site all of the early time data results in a higher value for T than the middle time data. However, a comparison of the pumping test T with the recovery T (Table 6-5) shows a different trend. In this test the injection T is slightly larger than the recovery T. This trend is consistent with fractures opening during injection and closing during recovery as the pressure is dissipated.

A preliminary comparison of slug tests, constant head step tests, pumping tests and recovery tests conducted in the same test interval is shown in Table 6 for an interval at the City site and in Table 6-7 from the rural site. Constant head step tests and slug tests are shorter term tests that are representative of fracture permeability. T from these tests are most similar to the early time recovery test T.

Double Permeability Conceptual Model

The conceptual model for analyzing pumping tests in fractured rock begins with an evaluation of the impact of a pumping test on the different components of the entire fractured rock system. Figure 6-10 illustrates the pressure pulse at steady state injection during the pumping portion of the test. The left hand side of the figure shows that flow is spherical when no fractures are present and radial in the fractures that intersect the test interval. The right hand side of the figure illustrates the combined effect caused by fractures present in the test interval, with the effect of high matrix permeability resulting in a more spherical influence near the test interval while flow in the horizontal fractures will always be radial. However, because of the permeability differences between these two portions of the fractured rock system, steady state is reached at different times. The fractures that intersect the borehole in the test interval reach equilibrium first, followed by the peripheral fracture network and the rock matrix. The fractures rapidly achieve equilibrium because of their low storativity, but it will take longer for the pressure pulse to move within the smaller fractures and rock matrix.

The straight line method for analyzing pumping test data is an approximation of the Theis method and data from a homogeneous confined aquifer of infinite extent will plot as a straight line on a semi-log plot. Therefore it follows that any straight line on a semi-log plot will represent a Theissian portion of the aquifer and a double porosity model could be represented as two or three straight lines on the plot. Early time would represent the permeability of the major fractures that intersect the test interval and using the same condition described by Cooper Jacob, $\frac{r^2}{t} <<< \frac{4T}{S}$ will always be true at early time because the storativity of the large fractures will be extremely small. Late time data represents the entire system supplying water for further recovery (similar to the Warren and Root model) after the effects of large fracture and the near portion of the system recovery is complete. Middle time data is more variable and complex and is representative of the environment within the influence of the test. This environment can be described as three basic cases.

1.) In a test in which the rock matrix is relatively permeable, the middle time data would represent recovery through the large fractures that is completely dependent on the matrix to supply the water (i.e. fractures have recovered at early time).

2.) In a test in which the rock matrix is relatively impermeable, the middle time data would represent recovery through the large fractures that is completely dependent on the peripheral fracture network to supply the water (i.e. smaller sub-vertical fractures).

3.) When the matrix permeability is similar to the peripheral fracture network permeability the middle time data will be due to both the peripheral fractures network and the rock matrix supplying water.

6.5 CONCLUSIONS

Hydraulic tests in fractured rock are more difficult to analyze than tests in unconsolidated media. This is because fractured rock is a true dual permeability medium in which most of the short term flow is through the fractures yet long term perturbations will affect the surrounding matrix/fracture network. After the fractures have mostly recovered (early time data), the remaining recovery will be dominated by the release of water from the formation (matrix and/or the peripheral fracture network) resulting in a lower value for T for the middle time data. This model is supported by the data collected in this thesis. T determined from constant head step tests and slug tests agree well with the T derived from the early time pumping or recovery data. The middle time T is lower than the early time T consistent with initial fracture response gradually transitioning to the response of the formation at middle times. In addition, recovery T values are commonly bounded by slug test values that are analyzed as radial flow and spherical flow models.

The traditional test for the influence of well bore storage at early times is not adequate to conclusively determine good early time data that free from this influence. The only way early time data can be validated for use in T calculations is to separate the drawdown caused by the formation from the drawdown caused by well bore storage. This can be accomplished by measuring flow in/out of the two inch pipe into the interval and compare it to the measured flow of the injected/withdrawn water. The difference between these flow rates is the flow of water from the well bore.

Tables

Table 6-1 Comparison of early drawdown from pumping and recovery tests in a highly permeable test interval at the City site. The similar values indicate minimal wellbore storage.

test	dP (m)	Q (L/min)	Pump dP 20 sec	Rec dP 20 sec
1	0.14	0.031	4 mm	1 cm
2	0.26	0.072	7 mm	1 cm
3	0.58	0.150	1 cm	3 cm
4	2.06	0.500	7 cm	9 cm

Table 6-2 Comparison of early drawdown from pumping and recovery tests in a lower permeable test interval at the City site. This illustrates that wellbore storage can cause the drawdown to double.

dP (m)	Q (L/min)	Pump dP 7 sec	Rec dP 7 sec
5.9	1.0	18 cm	8 cm
12.6	2.2	40 cm	20 cm

Table 6-3 Transmissivity values for early and middle time recovery data at the rural site. Early time T is approximately ½ an order of magnitude greater than middle time.

dP (m)	Q (L/min)	Pumping Time (min)	Pumping V (L)	Early T Recovery (m2/s)	Middle T Recovery (m2/s)
3.3	4.5	31	139	1.7E-05	5.0E-06
8.0	8.9	31	277	1.5E-05	3.9E-06
13.0	12.1	41	491	1.5E-05	3.3E-06

Table 6-4 Comparison of withdrawal pumping data with recovery data at the rural site. Well bore storage is assumed to be negligible in the pumping tests after a comparison of the early pumping drawdown with the early recovery drawdown. The early recovery T is somewhat larger than the pumping withdrawal T.

test	dP (m)	Q (L/min)	Pumping Time (min)	Pumping V (L)	Early Pump T (m2/s)	Early Recovery T (m2/s)	Pump dP 10 sec	Rec dP 10 sec
1	0.22	0.5	20	10	2.3E-05	2.7E-05	5 cm	4 cm
2	1.29	2.8	25	71	2.2E-05	3.0E-05	31 cm	29 cm
3	2.58	4.9	30	149	2.5E-05	2.8E-05	50 cm	53 cm

Table 6-5 Comparison of injection pumping data with recovery data at the city site. Well bore storage is assumed to be negligible in the injection tests after a comparison of the early injection drawdown with the early recovery drawdown. The early injection T is larger than the early recovery T.

Test	dP (m)	Q (L/min)	Pumping Time (min)	Pumping V (L)	Early T Injection (m2/s)	Early T Recovery (m2/s)	Pump dP 20 sec	Rec dP 20 sec
1	0.10	0.035	30	1.071	2.3E-05	1.2E-05	5 mm	1 cm
2	1.27	0.484	30	14.636	1.8E-05	1.3E-05	9 cm	8 cm

Table 6-6 Comparison of all four hydraulic tests in the same interval at the City site. Constant head T is very similar to the slug test T and the early recovery T.

dP (m)	Q (L/min)	Pumping Time (min)	Pumping V (L)	Early T Recovery (m2/s)	Middle T Recovery (m2/s)	Constant Head T (m2/s) ro = 30 m	Slug Test T (m2/s) ro = 30 m
0.14	0.031	31	1	2.2E-05	1.3E-06	1.7E-05	1.6E-05
0.26	0.072	32	2	2.0E-05	9.6E-07		
0.58	0.150	43	6	1.5E-05	8.4E-07		
2.06	0.500	51	25	1.4E-05	7.3E-07		

Table 6-7 Comparison of three hydraulic tests in the same interval at the rural site. Slug test T is similar to early recovery T.

s max (m)	Q (L/min)	Pumping Time (min)	Pumping V (L)	Early T Recovery (m2/s)	Middle T Recovery (m2/s)	Slug Test T (m2/s)
1.13	1.04	21	22	5.5E-05	7.9E-06	1.4E-05
5.83	3.76	31	115	3.1E-05	5.0E-06	
10.91	6.08	31	191	1.9E-05	4.5E-06	
14.84	7.72	31	238	3.2E-05	3.8E-06	

Figures

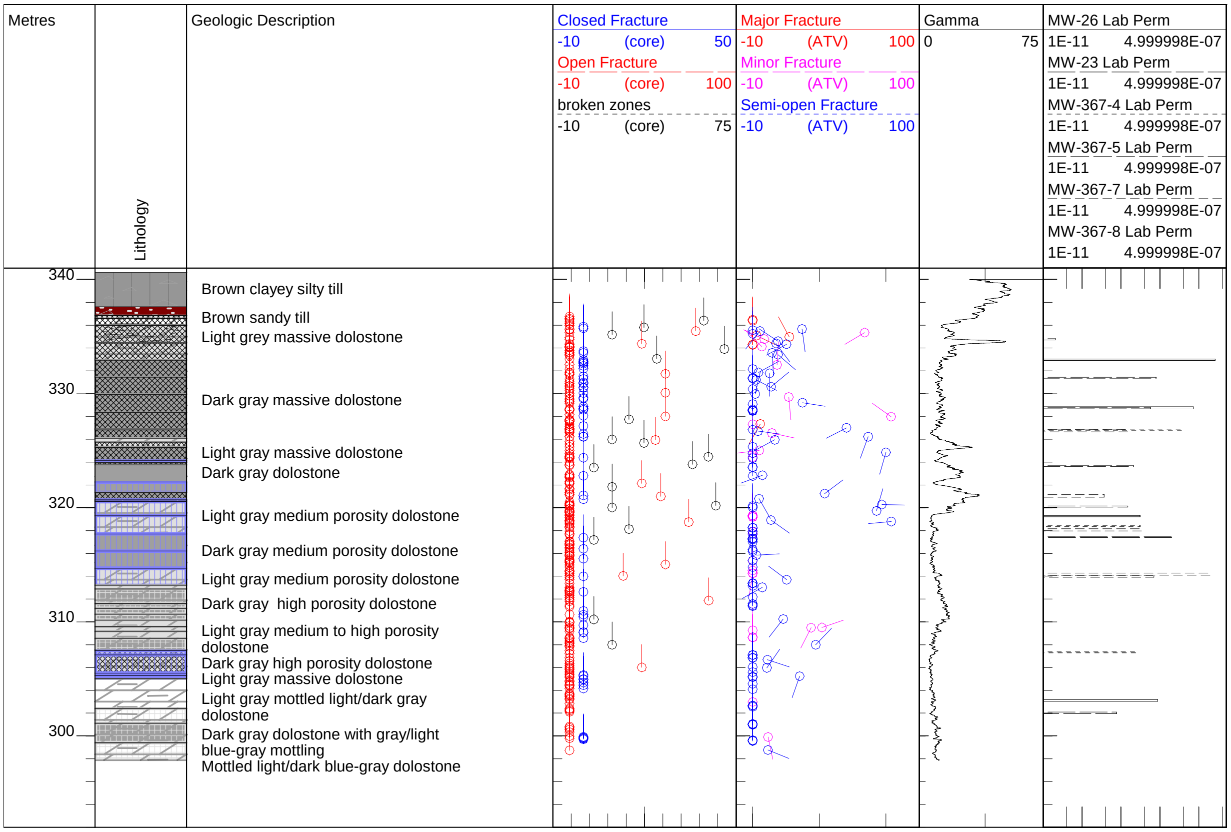


Figure 6-1 Core Logs, Geophysical Data, and Lab Permeability Tests in borehole MW -26 at the Guelph Tool site.

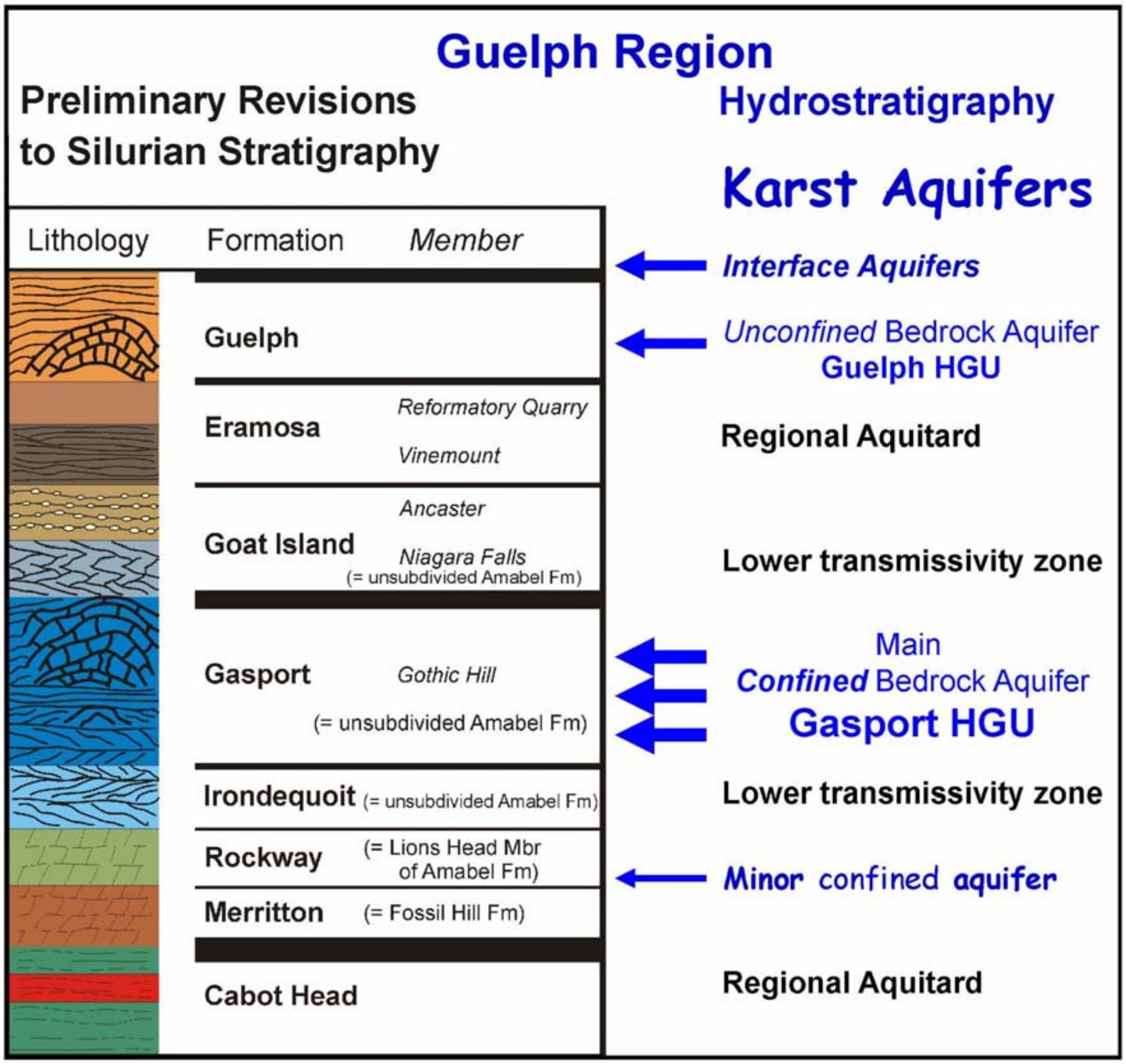


Figure 6-2 Guelph Region Stratigraphy as outlined by Brunton (2008)

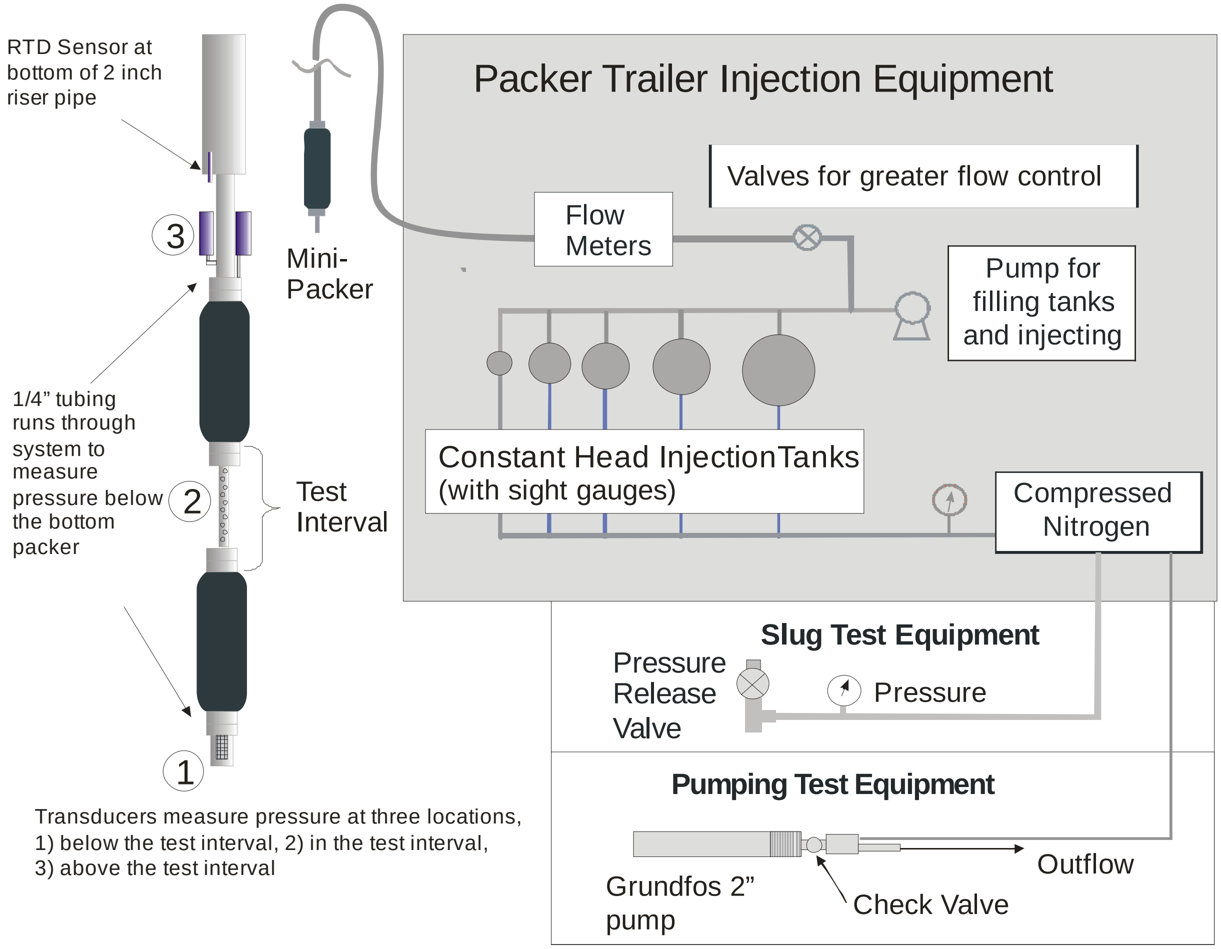


Figure 6-3 Schematic of Packer Testing System

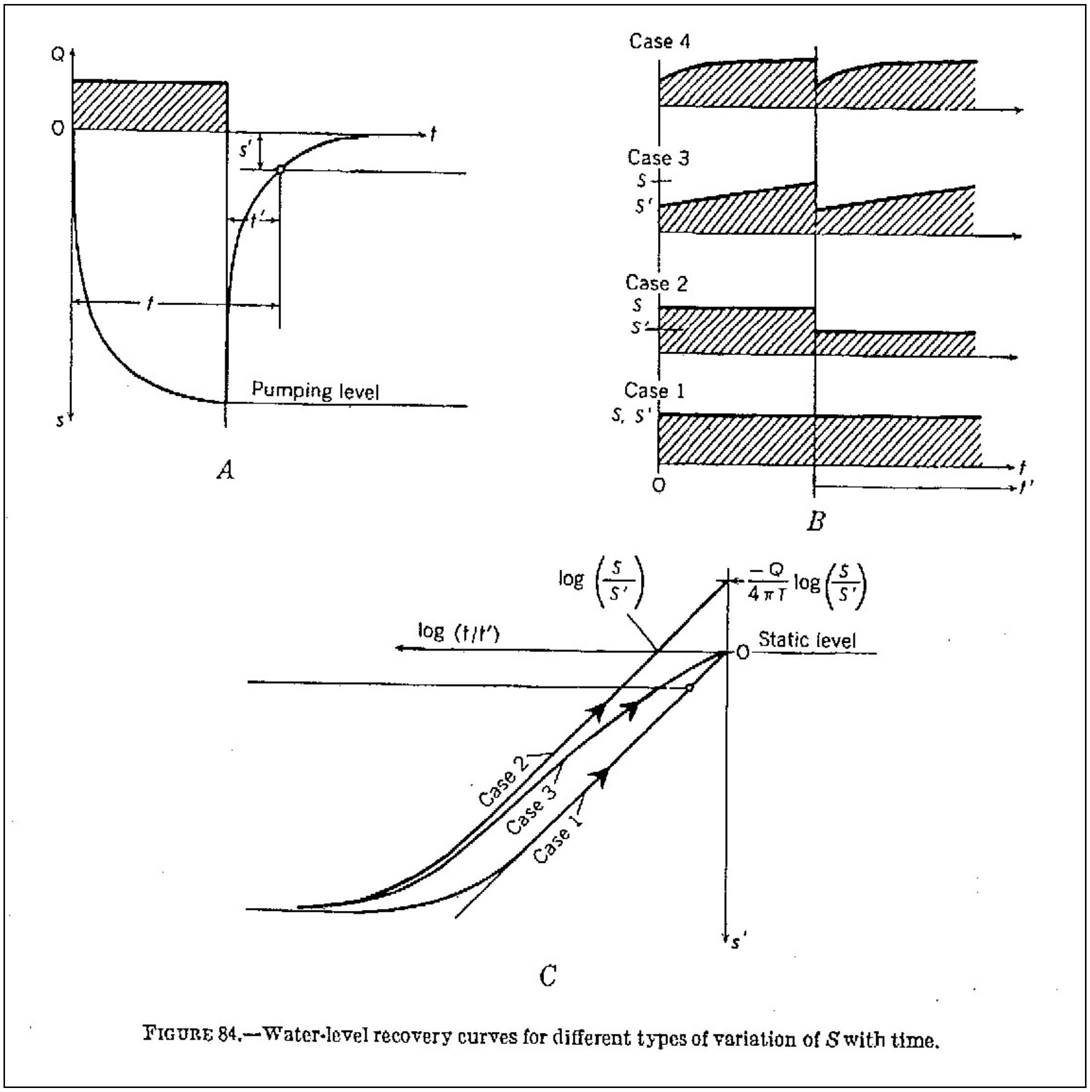
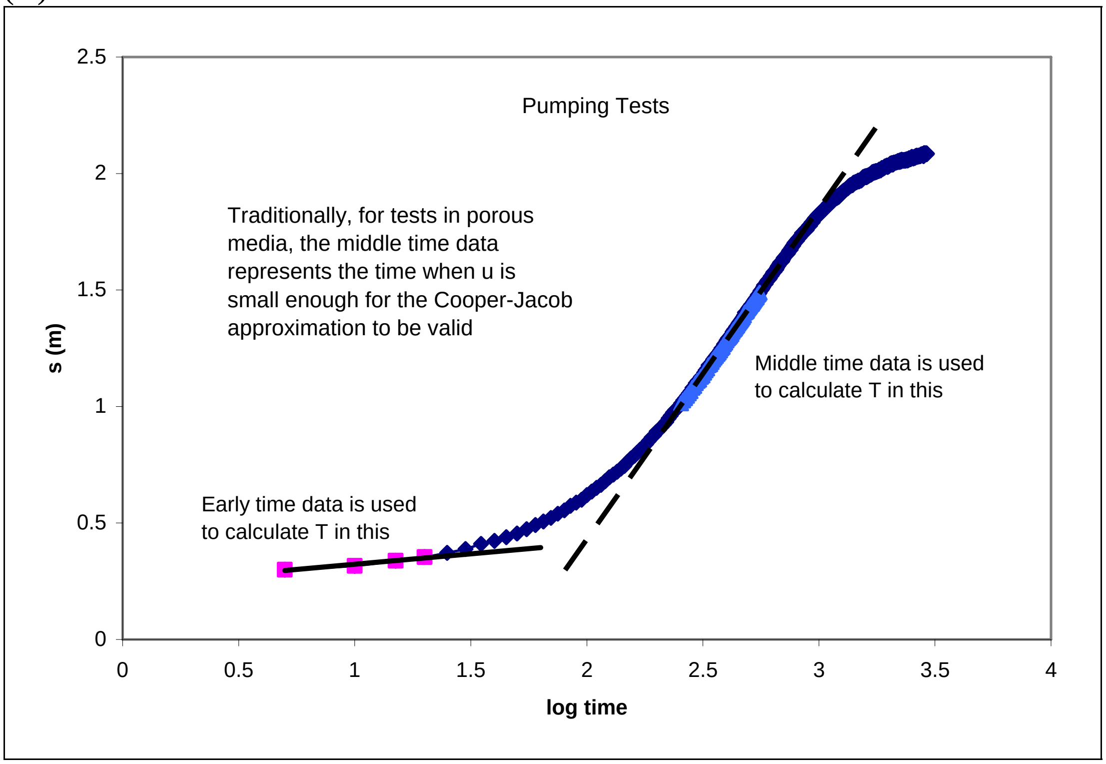


Figure 6-4 Jacob's reasoning for anomalous recovery curves (Bentall 1963). Case 1 and three are very similar to the typical recovery results observed in fractured rock.

(A)



(B)

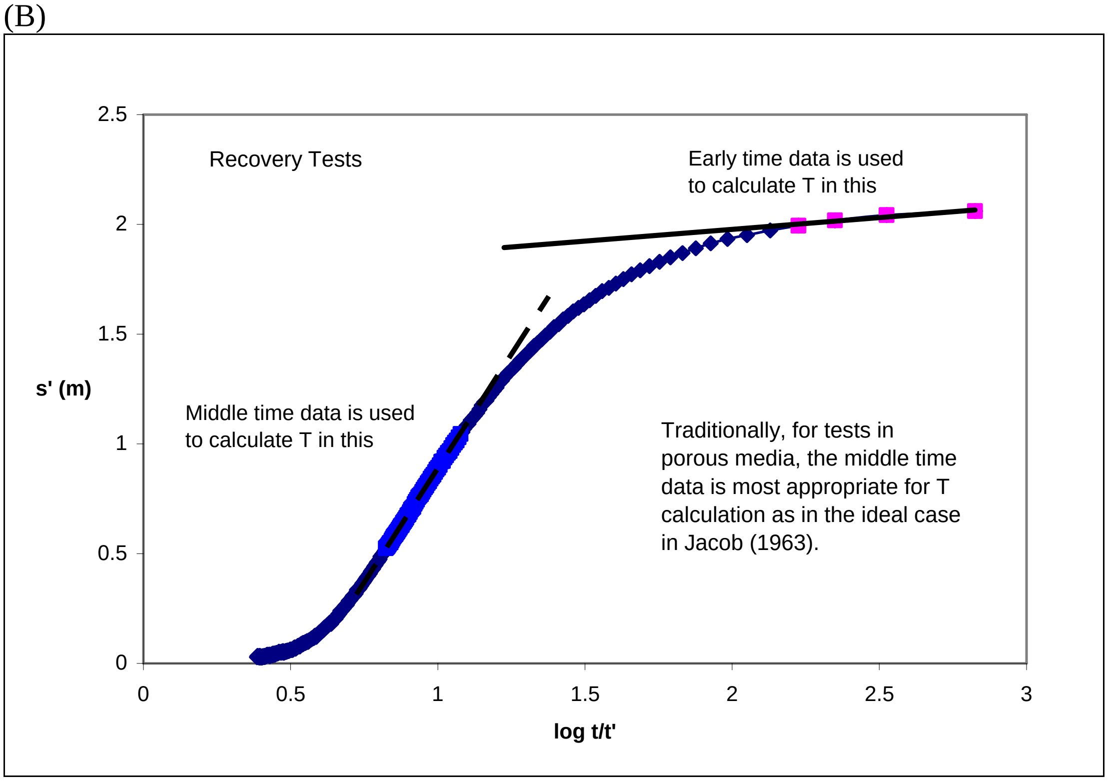
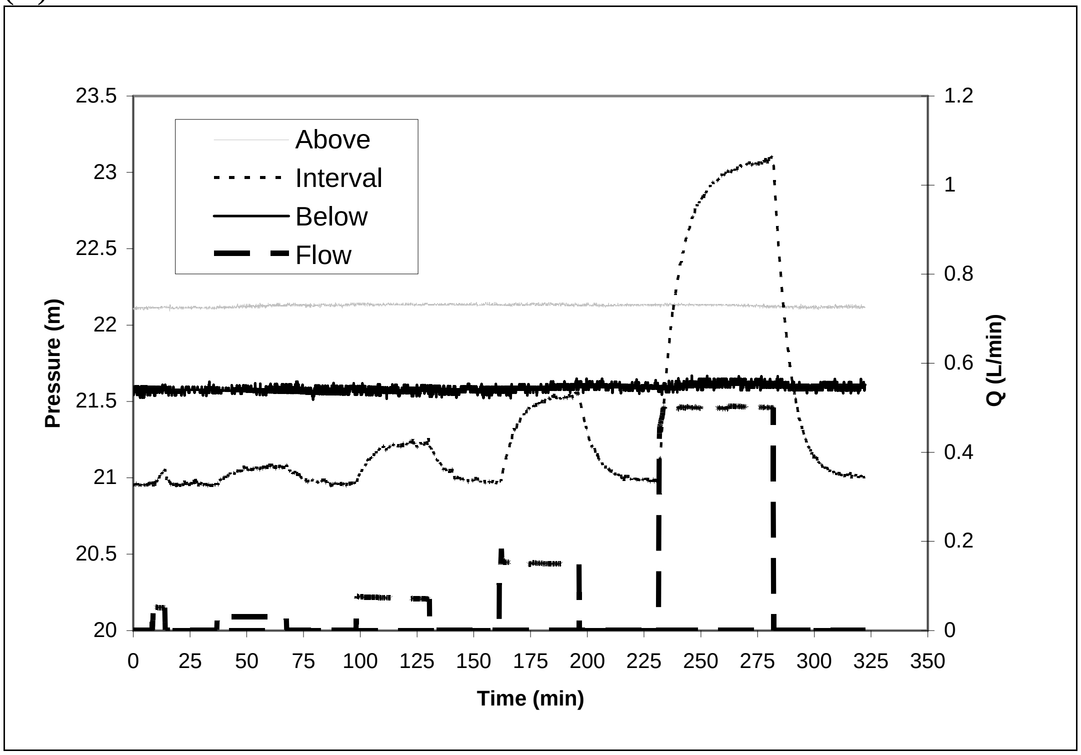


Figure 6-5 T calculation from semi-log plots for (A) pumping tests and (B) recovery tests. Two values for T can be calculated, one for the early time data and one for the middle time data.

(A)



(B)

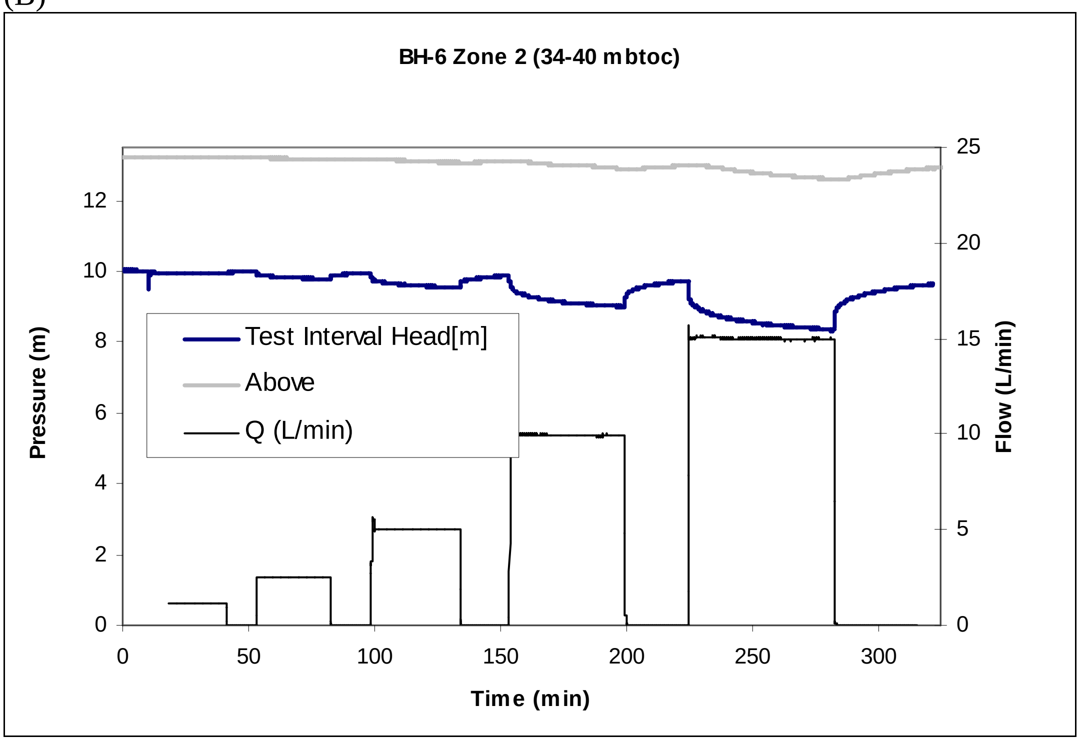
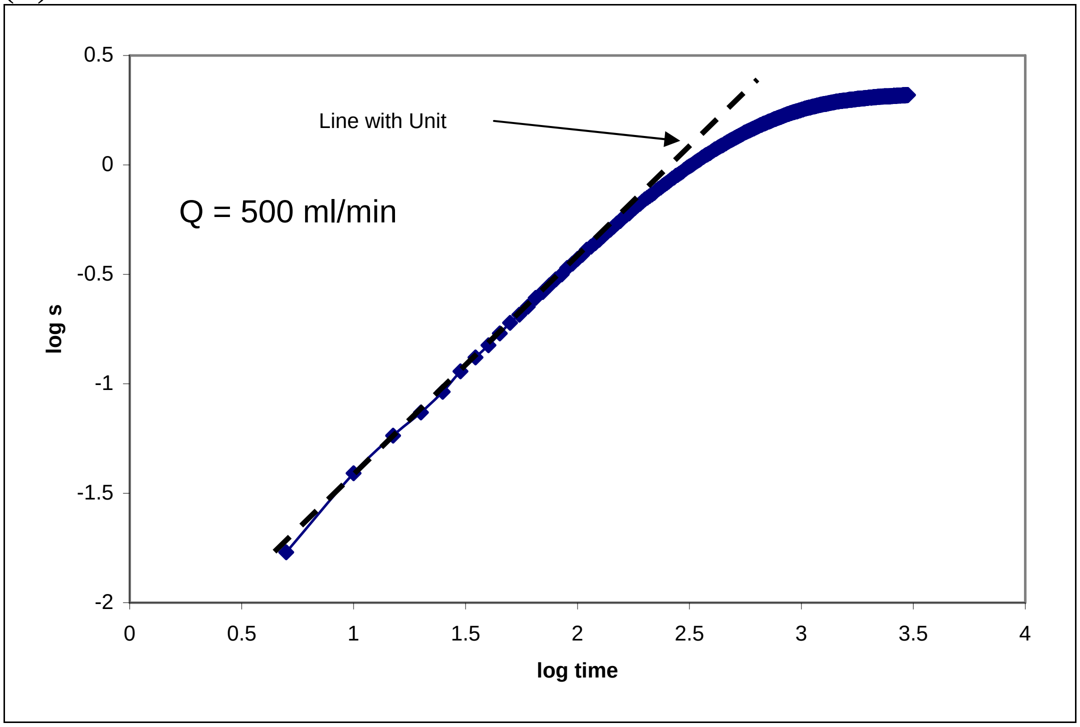


Figure 6-6 Typical Pumping and Recovery data for (A) 1.5 m interval injection tests and (B) 6 m interval withdrawal tests. Short circuiting was observed in many of the tests at the rural site and to a much lower degree at the City site.

(A)



(B)

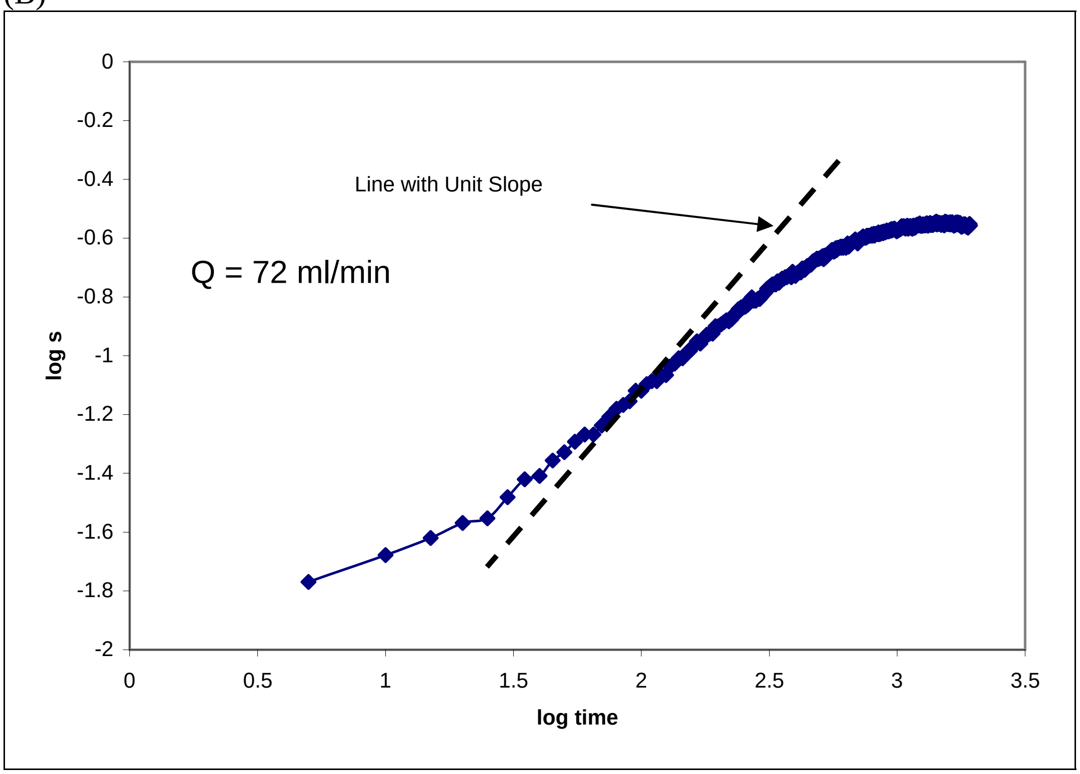
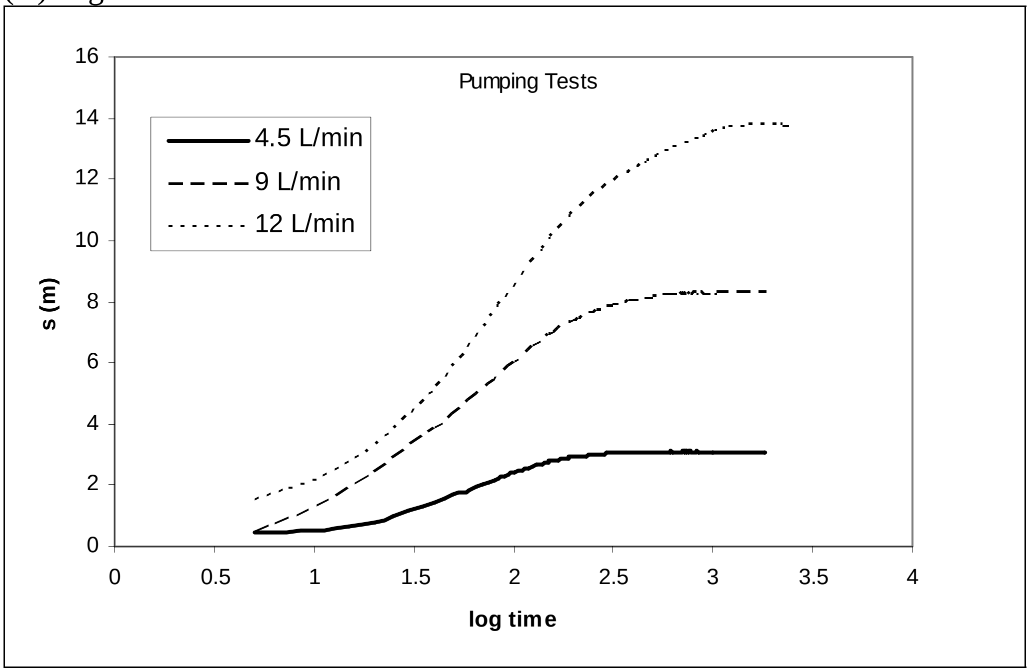


Figure 6-7 Well bore storage effects at two different flow rates in the same 1.5 m test interval (A) 500 ml/min and (B) 72 ml/min. Early time data with a unit slope is indicative of significant well bore storage.

(A) High Matrix K



(B)High Matrix K

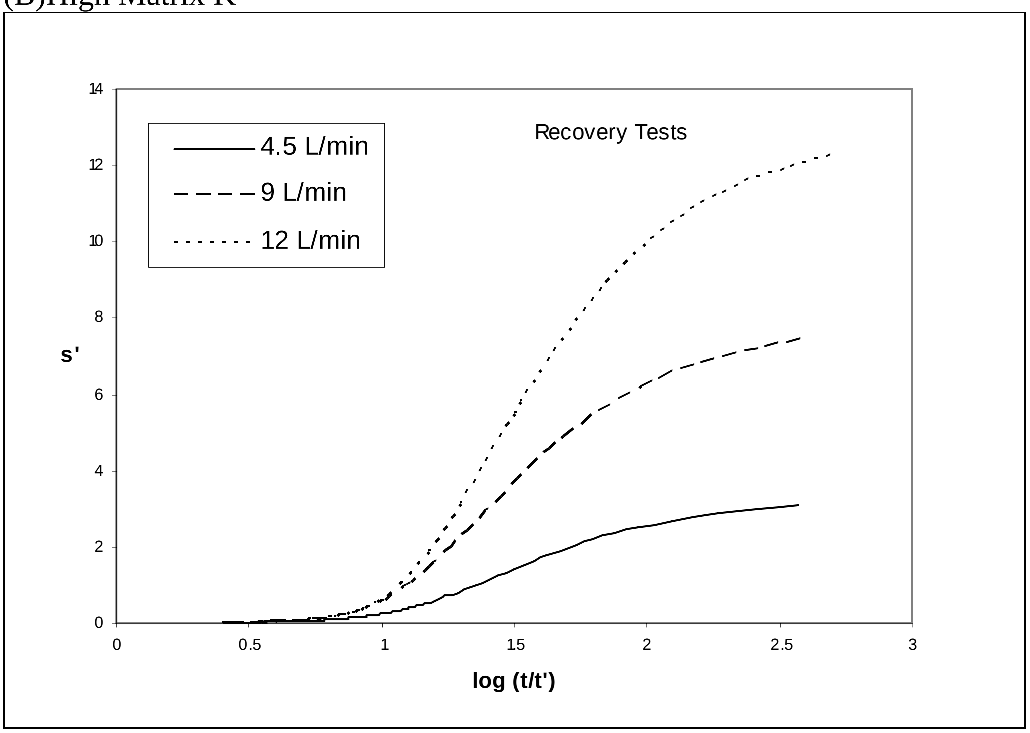
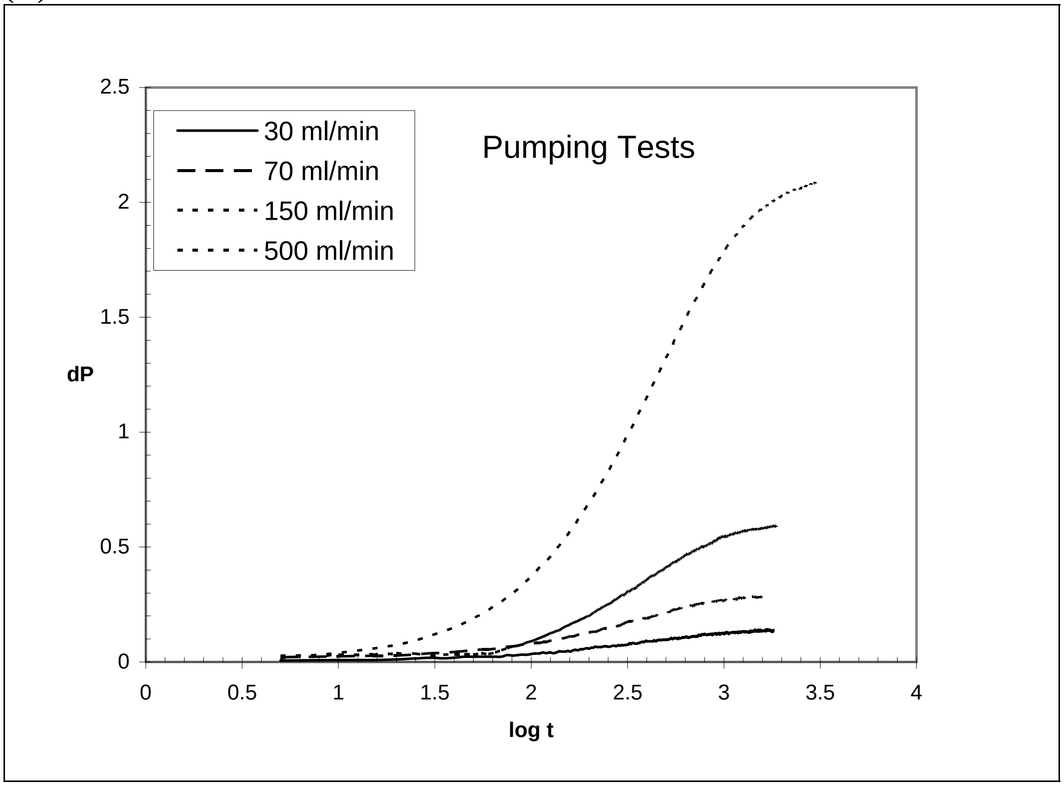


Figure 6-8 Semilog plots of a 10 m interval (A) pumping withdrawal tests and (B) recovery tests at the rural site.

(A) Low Matrix K



(B) Low Matrix K

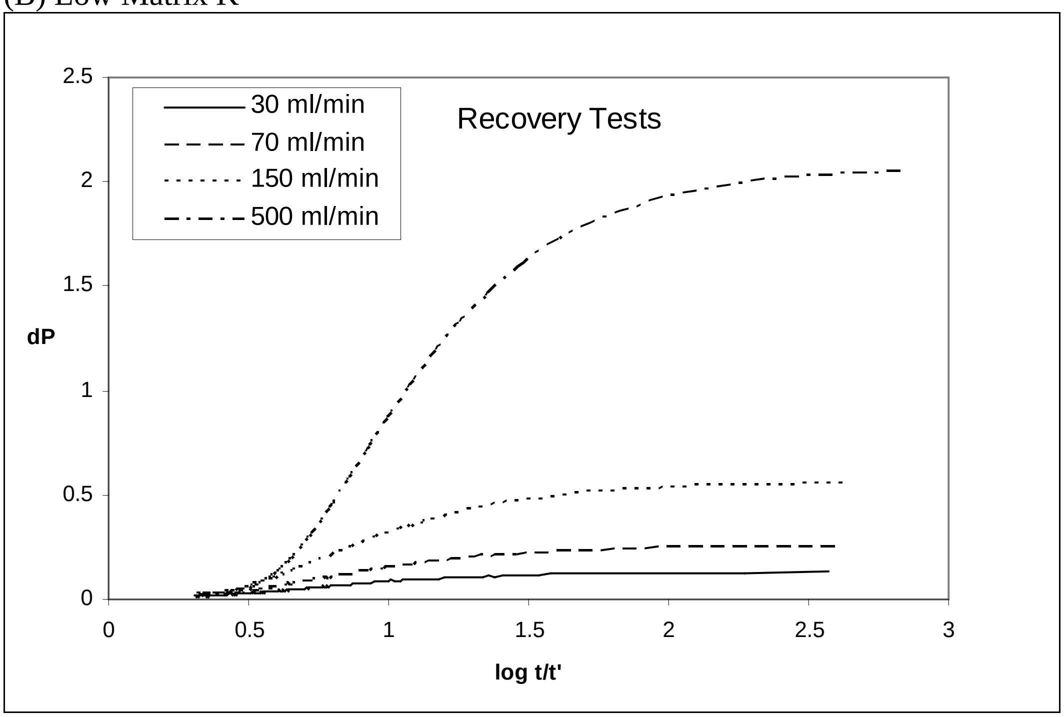


Figure 6-9 Semilog plots of a 1.5 m interval (A) pumping injection tests and (B) recovery tests at the city site.

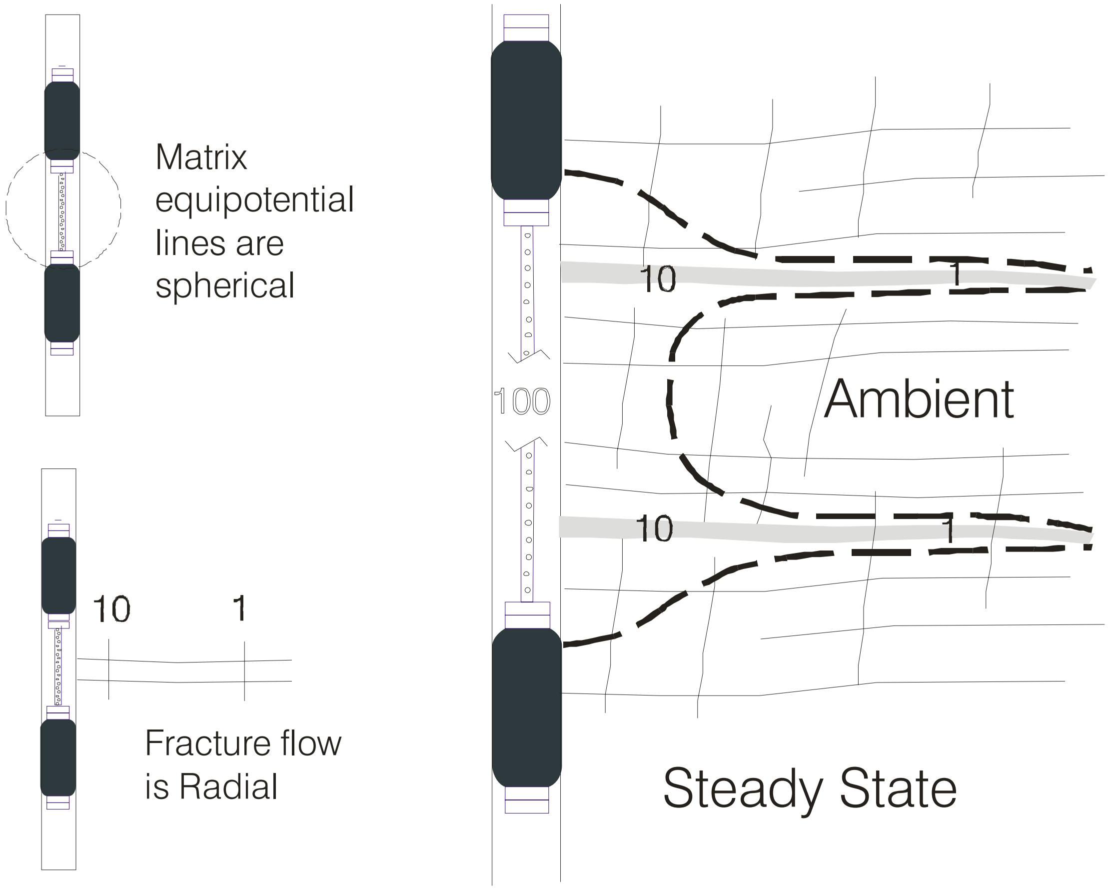


Figure 6-10 Conceptual model of the pressure at steady state in the major fractures that intersect the borehole in the packed off interval, the fracture network that is connected to those major fractures, and the rock matrix connected to both. Flow through the rock matrix is slower and spherical, while flow through the fractures is radial.

Chapter 7 Conclusions and Recommendations

7.1 SUMMARY AND CONCLUSIONS

This thesis is based on the following hypothesis resulting from a comprehensive review of the packer testing literature:

Packer tests in fractured rock aquifers have been conducted without use of rigorous procedures aimed at acquiring test data suitable for assessment of non-ideal conditions such as non-linear flow, short circuiting or leakage, and fracture dilation that can cause the T values calculated from the test data to be substantially different from the actual T of the formation. Rigorous packer testing whereby all four types of tests are done in each test interval under a broad range of imposed conditions will provide T values with minimal influences of these non-ideal effects.

This thesis has two main goals. One of the goals is to develop a packer testing system involving improved equipment and procedures, capable of efficiently conducting four different types of hydraulic tests in rock boreholes: constant head step tests (steady state), instantaneous pulse (slug tests), constant flow pumping tests to near steady state conditions and the subsequent recovery (recovery test). These four types of tests were established many decades ago for determining T by hydraulic tests in piezometers or wells in unconsolidated deposits (i.e. porous media). The most basic mathematical models used to calculate the T values from the field data for all four methods assume homogeneous permeable media with radial horizontal Darcian flow occurring during each test. For these ideal conditions in the test interval, these tests would produce the same value of T. However in fractured rock there are several common possibilities for one or more of these assumed idealities to be invalid, so that the T values calculated using the models for the ideal cases would deviate from the reality.

The second goal of this thesis is to apply the system in fractured rock boreholes to develop improved understanding of the effects influencing packer test results from the four methods and thereby provide new insights concerning the differences and similarities and relative advantages and disadvantages of the methods. The pursuit of this goal required extensive packer testing, involving all four tests in the same interval in fractured rock boreholes without moving or deflating the packers.

In the initial phase of the thesis research, conventional straddle packer testing equipment for constant head tests was tried out in boreholes in fractured dolostone at the Guelph Tool site. Standard procedures were followed and the Q vs dP plots typically showed a linear relationship that did not pass through the origin (0,0). Because theory predicts the linear relationship to pass through the origin, this was an unexpected and puzzling result. Conversations with persons experienced in packer testing in fractured rock indicated that Q vs dP graphs of packer tests in fractured rock typically do not pass through the origin. The conclusion drawn from this was that there was a fundamental flaw in the conventional method of packer testing because the mathematical models used to calculate T from packer test data are based on the assumption that Darcy's Law is applicable (i.e. there is a linear relationship between Q and dP). Therefore, in the conventional procedures for packer testing in fractured rock as recommended in manuals and guidance documents, the applied head and flow rate can be expected, based on the results of this thesis, to produce transmissivity values biased low because of nonlinear (non-Darcian) flow.

In the next phase of this research the equipment was modified to conduct tests at much lower flow rates to determine if linear data can be collected showing the Q vs dP graph passing through the origin. Once it was shown that linear data at very low flow rates can be collected that passes very nearly through the origin indicating Darcian flow, data were collected in both the linear and non-linear flow regimes to determine the effect of non-linear flow on calculated T values and to quantify the degree of non-linearity attained in the test. A method was subsequently developed using a Darcy-Missbach conceptual model to identify the linear data with a high degree of precision by accounting for the observed non-linearity.

In this thesis a major effort was directed at use of Reynolds number to identify and describe the flow regime in constant head tests so that insights from the literature concerning the fluid mechanics of flow in smooth and rough fractures can be used to advance the understanding of the field test data. It was discovered that Re calculated from constant head step tests appears to provide guidance concerning the number of hydraulically active fractures in the test interval. This is important because in the calculation of hydraulic aperture from the T values the number of hydraulically active fractures must be specified.

A major uncertainty in the T values obtained from constant head tests (Theim analysis) and slug tests (Hvorslev radial flow analysis) is the unavoidable use of an assumed value for the radius of influence. In the literature assumed values for the radius of influence varied between 2 feet and 160 m, making the range of calculated T from linear data fivefold. Because of this uncertainty, it was decided to also conduct slug tests and pumping tests with recovery monitoring in each test interval, providing independent data for calculation of T. Therefore, more equipment modifications were necessary, and the literature was re-examined regarding pneumatic slug tests and pumping/recovery tests.

A comparison of the three different hydraulic tests conducted in the same test interval gives insights into each tests' perspective regarding interfering processes that can be identified. In constant head injection step tests non-linear flow can be most clearly identified and quantified resulting in a high degree of certainty that the calculated T value is from the Darcian flow regime. In addition, the onset of non-linear flow can supplement data on fracture locations such as core descriptions and geophysical logs in the selection of the hydraulically active fractures present in the test interval. Slug tests are a much quicker test, but nonlinear behavior can result from the test equipment in addition to the formation at large initial displacements. There was evidence of fracture dilation in the slug tests results, but they are influenced by non-linear flow in the test equipment. Each type of test contributes unique information regarding the fractured rock system being tested thereby increasing the validity of the apertures calculated from the hydraulic data. Pumping/recovery tests were shown to give insight into both the major fractures intersecting the borehole and the large scale matrix and fracture network properties in a double porosity medium. A preliminary comparison of the results of hydraulic tests conducted in the same test interval reveals that T values from the constant head step tests and slug tests are most similar to the early time recovery test T supporting the dual permeability model.

The discrete -fracture approach for characterizing fractured rock involves application of several independent methods for identifying fractures of various types, including those that are hydraulically active. In the conventional use of straddle packer tests in intensive investigations of contaminated sites, packer tests using short intervals covering the entire length of the open hole are important. This is very time consuming even when only one type of test is done in each interval using a very limited range of repetitions. Therefore, to test entire holes using the entire group of tests over the wide range of repetitions described in this thesis would be generally impractical. However new methods have become available for efficiently identifying hydraulically active fractures by temperature logging inside holes with temporary seals and for measuring the approximate hydraulic conductivity of most fractures in the holes (the K profiling method of Keller et al, in submittal). The major role of packer testing using the comprehensive method described in this thesis should be application of the method at only a few intervals in each hole and these particular intervals should be selected based on priority assigned by examining many types of borehole information including the temperature logging and K profiling mentioned above. In this framework then, comprehensive packer testing can be expected to provide important information not otherwise obtainable.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

It would be interesting to see the effect of pumping time on the results from recovery tests. If a valid measurement of permeability can be obtained from a recovery test from a lesser period of pumping time, money can be saved in hydrologic investigations.

Because flow regimes are identified by the Q vs dP relationship, both of these parameters are necessary for flow regime identification. Both flow and applied pressure are measured during constant head step tests and non-linear flow can be easily identified. However, in transient tests it is common to only measure pressure changes and this makes it more difficult to quantify non-linear flow. The accurate measurement of both flow and pressure independently during transient tests will likely allow for flow regime identification which will be useful in fracture deformation models. In addition, if the flow was measured in the system at the top of the packer, it may be possible to separate well bore storage effects from drawdown in the formation.

Hydraulic short circuiting between the test interval and the open hole was identified during many of the slug tests conducted in the high rock matrix permeable holes. The pressure response above the test interval responded slower than the response in the test interval indicating that this short circuiting occurred through the formation. Short circuiting in the low matrix permeability holes occurred less often and the immediate pressure response above or below the test interval indicates leakage between the packers and the borehole wall. This would most likely occur at locations in the borehole where the borehole wall is rough or grooved vertically thereby preventing complete seals of the packer against the wall. For these cases, disposable packer sleeves made from a closed cell foam material similar to that used for wetsuits could be fitted over the conventional packer gland. The compressibility of the foam should create a better seal at locations of poor borehole wall conditions without requiring excessive packer inflation pressures.

APPENDICES

APPENDIX A

Missbach Equation for Radial Flow

$$\left(\frac{dh}{dr}\right)^{\alpha} = \left(\frac{1}{2\pi T}\right)Q$$

$$\left(\frac{dh}{dr}\right) = \left(\frac{1}{2\pi T}\right)^{n} Q^{n} \quad \text{where: } n = \frac{1}{\alpha}$$

Missbach Equation Constants

This is the solution for linear (n=1) radial flow at steady state (Thiem).

$$\Delta h = \int_{r_w}^{r_o} \frac{dr}{r}\left(\frac{1}{2\pi T}\right)Q \qquad C_1 = \frac{\ln\left(\frac{r_o}{r_w}\right)}{2\pi T}$$

Where: r_o = radius of influence
r_w = radius of well

When non-linear flow is present, the value of the constant does not change, but the mathematical representation of the constant does change.

Linear portion (n=1) away from the well when non-linear flow is present.

$$\Delta h = \int_{r_c}^{r_o} \frac{dr}{r}\left(\frac{1}{2\pi T}\right)Q \qquad C_2 = \frac{\ln\left(\frac{r_o}{r_c}\right)}{2\pi T}$$

Where: r_o = radius of influence
r_c = critical radius of well where flow returns to linearity

Non-linear portion of the flow

$$\Delta h = \int_{r_w}^{r_c} \frac{dr}{r^{n}}\left(\frac{1}{2\pi T}\right)^{n} Q^{n}$$

$$\Delta h = \frac{r_c^{\,-n+1} - r_w^{\,-n+1}}{(-n+1)(2\pi T)^{n}} Q^{n} \qquad C_3 = \frac{r_c^{\,-n+1} - r_w^{\,-n+1}}{(-n+1)(2\pi T)^{n}}$$

However, the exponent will change with radial distance from the well as the velocity decreases away from the hole.

APPENDIX B

Rational for using 2b as the characteristic length in the Reynolds number for parallel plate flow as proposed by Bird, Stewart and Lightfoot (1960)

Friction factor calculations : Pipe Flow

$$F_k = AKf$$

Where:

F_k = Kinetic force on the fluid
A = Wetted surface area of flow
f = friction factor

For flow in pipes:

$$F_k = (2\pi rL)(1/2\rho v^2)f$$

Another relation can be obtained based on head changes:

$$F_k = \Delta h(\pi r^2)$$

Solving for f results in the following:

$$f = \left(\frac{\Delta h \pi r^2}{2\pi r L \frac{1}{2}\rho v^2} \right) = \frac{1}{2}\left(\frac{r}{L}\right)\left(\frac{\Delta h}{\frac{1}{2}\rho v^2}\right) = \frac{1}{4}\left(\frac{D}{L}\right)\left(\frac{\Delta h}{\frac{1}{2}\rho v^2}\right)$$

Now the average velocity for flow in pipes can be expressed as:

$$\bar{v} = \frac{\Delta h r^2}{8\mu L}$$

Substituting this for one of the velocities in the denominator results in:

$$f = \frac{1}{4}\left(\frac{D}{L}\right)\left(\frac{\Delta h}{\frac{1}{2}\rho v}\right)\left(\frac{1}{\frac{\Delta h r^2}{8\mu L}}\right) = \frac{1}{4}\left(\frac{2r}{L}\right)\left(\frac{\Delta h}{\frac{1}{2}\rho v}\right)\left(\frac{1}{\frac{\Delta h r^2}{8\mu L}}\right) = \left(\frac{2}{\frac{4\rho v r}{16\mu}}\right) = \left(\frac{16}{\frac{\rho v D}{\mu}}\right) = \left(\frac{16}{\mathrm{Re}}\right)$$

This is identical to the friction factor described by the Hagen-Poiseuille Law for laminar flow in pipes.

Friction factor calculations : Parallel Plate Flow

$$F_k = AKf$$

Where:

F_k = Kinetic force on the fluid
A = Wetted surface area of flow
f = friction factor

For flow in parallel plates:

$$F_k = (2(2b)+2w)(L)(1/2\rho v^2)f$$

Another relation can be obtained based on head changes:

$$F_k = \Delta h(2b)(w)$$

Solving for f results in the following:

$$f = \left(\frac{\Delta h(2b)(w)}{(2(2b)+2w)(L)\frac{1}{2}\rho v^2} \right) \text{ since 2b<<<w } = \frac{1}{2}\left(\frac{2b}{L}\right)\left(\frac{\Delta h}{\frac{1}{2}\rho v^2}\right)$$

Now the average velocity for flow in parallel plates can be expressed as:

$$\bar{v} = \frac{\Delta h(2b)^2}{12\mu L}$$

Substituting this for one of the velocities in the denominator results in:

$$f = \frac{1}{2}\left(\frac{2b}{L}\right)\left(\frac{\Delta h}{\frac{1}{2}\rho v}\right)\left(\frac{1}{\frac{\Delta h(2b)^2}{12\mu L}}\right) = \frac{1}{2}\left(\frac{1}{\frac{1}{2}\rho v}\right)\left(\frac{1}{\frac{2b}{12\mu}}\right) = \left(\frac{12}{\frac{\rho v(2b)}{\mu}}\right) = \left(\frac{12}{\text{Re}}\right) \text{ if D=2b}$$

If 2(2b) is used for the characteristic length $f = \frac{24}{\text{Re}}$. Parallel plate flow has a greater surface area for friction than pipe flow and therefore the friction factor should decrease at a rate lower than for pipe flow.

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