Groundwater

New Method for Continuous Transmissivity Profiling in Fractured Rock

by Carl E. Keller[1], John A. Cherry[2], and Beth L. Parker[3]

Abstract

A new method is presented to search for hydraulically transmissive features in open boreholes in bedrock. A flexible borehole liner made of a watertight, nylon fabric is filled with water to create a constant driving head to evert (reverse of invert) the liner down the hole so that the liner pushes the borehole water out into transmissive fractures or other permeable features. The descent rate is governed by the bulk transmissivity of the remaining permeable features below the liner. Initially, the liner descent rate or velocity is a measure of transmissivity (T) of the entire hole. As the everting liner passes and seals each permeable feature, changes in the liner velocity indicate the position of each feature and an estimate of T using the Thiem equation for steady radial flow. This method has been performed in boreholes with diameters ranging from 96 to 330 mm. Profiling commonly takes a few hours in holes 200- to 300-m long. After arrival of the liner at the bottom of the hole, the liner acts as a seal preventing borehole cross connection between transmissive features at different depths. Liner removal allows the hole to be used for other purposes. The T values determined using this method in a dolostone aquifer were found to be similar to the values from injection tests using conventional straddle packers. This method is not a replacement for straddle-packer hydraulic testing of specific zones where greater accuracy is desired; however, it is effective and efficient for scanning entire holes for transmissive features.

Introduction

Understanding the flow in fracture networks in bedrock is needed for assessments of contaminant transport and fate, groundwater resource management, groundwater control at mine sites, and other purposes. In most types of rock, groundwater flow occurs primarily in interconnected fractures where the rock matrix blocks between fractures have much lower permeability. For the purpose of contaminant transport assessment, Neuman (2005) draws attention to the importance of identifying all the fractures in each borehole potentially involved in groundwater flow, rather than just the few features that may appear to dominate flow. Parker et al. (2012) provide an overall framework and approach for acquisition of data for individual fractures and fracture networks, referred to as the discrete fracture network (DFN) approach with emphasis on the importance for contaminant transport in all the fractures in the network, and Parker et al. (2011) show the importance of DFN characteristics on contaminant transport and attenuation at a site situated on fractured sandstone. The method described in this article is a new option available for use in the search for hydraulically transmissive features in boreholes. This method is typically used in conjunction with other methods of borehole data acquisition including borehole geophysics, borehole imaging, and in some cases also used in conjunction with hydraulic tests using packers with focus on particular fractures.

The limitations of existing methods used in the search for permeable features in fractured rock boreholes are substantial. Borehole televiewing (optical, acoustic, or electrical) commonly shows many fractures in each borehole but does not discern the transmissive fractures from those that are closed or filled with cement and therefore not transmissive. In open boreholes, the water column commonly has vertical flow because of cross connection between transmissive fractures with different hydraulic heads in the formation (e.g., Price and Williams 1993; Sterling et al. 2005), and therefore fluid electrical resistivity or temperature measurements within the open-hole water column typically discern a few major features with flow but not the many intermediate and lesser features (Pehme et al. 2010, 2013). Conceptual fracture networks based only on a few major fractures present in each hole and excluding many other transmissive fractures are unrealistic and produce inaccurate contaminant plumes in transport simulations. Hydraulic tests involving water injection into, or withdrawal out

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of, permeable intervals isolated with inflated packers measure the transmissivity of these intervals. When such tests are done throughout the entire borehole length using short test intervals (e.g., 1 to 2 m), the locations and transmissivities of all substantial transmissive zones become known; however, testing an entire borehole using short test intervals typically takes several days, and therefore is rarely done except in research-intensive projects (e.g., Novakowski et al. 2006; West et al. 2006). Therefore, efficient methods capable of identifying and measuring the transmissivity of all or nearly all potential permeable fractures in each borehole are needed.

This article describes a method recently developed for conducting hydraulic tests in open boreholes in fractured rock. The purpose of this method, referred to here as transmissivity profiling, is to: (1) quickly identify along the entire length of open hole the permeable fractures or other permeable features; (2) estimate the transmissivity and also in some cases the hydraulic conductivity; and (3) determine the bulk transmissivity of the entire length of open hole. This method is also known more simply as liner profiling or the drop liner method. The method is suitable for use in holes in rock that have a casing sealed through the overburden and/or through the weathered zone into the intact rock. The open hole below the casing must have no obstructions or substantial restrictions. This method uses a tubular length of impermeable urethane-coated nylon fabric, closed at the bottom, which is very flexible so that it can be rolled onto a reel and positioned at the hole to begin the profiling procedure. The liner is about the same length and diameter as the borehole. The liner is slightly elastic and about 10% larger than the nominal borehole diameter so it can conform to the borehole wall. To initiate the profiling procedure, the liner is filled with water to inflate it and to create a hydraulic head differential between the inside and outside of the liner. This head differential causes the liner to descend down the hole acting as a piston. As this piston descends, water below is forced out of the hole and into the formation through transmissive features. The descent rate of the piston at each depth in the hole is a function of the transmissivity of the remaining length of open hole below the piston. Hence, with measurement of the descent rate and other factors, a transmissivity (T) profile is obtained from the top to the bottom of the hole. Changes in descent velocity of this piston along the hole indicate the presence of the transmissive features.

The impetus for the use of flexible liners to seal holes came from our recognition of the need to minimize cross contamination at sites on fractured rock with chlorinated solvent contamination, an example of which is described by Sterling et al. (2005). In such cross contamination, the borehole acts as a conduit to connect fractures with higher hydraulic head to fractures with lower head in the same hole. This induces vertical cross flow between fractures. These cross connections can worsen the degree of contamination at the site and confuse the hydrochemical conditions being investigated. Price and Williams (1993) describe a fractured rock hole where such cross connection changed the natural hydrochemistry of the formation. Pehme et al. (2010, 2013) used high-resolution temperature profiling in lined and unlined holes to show that cross connections are a common feature of holes in fractured rock and that open holes severely hinder the ability to characterize the natural system. Minimization of cross contamination because of vertical flow in holes drilled in contaminated site investigations on bedrock has become desirable in many jurisdictions. For example, it is required in the state of New Jersey that all annular space between well casings and annular space between casing and borehole be sealed within 24 hours (NJ Reg. 7:9D–2.2 (a) 10) and that “there shall be no more than 25 feet of total open borehole” (NJ Reg. 7:9D–2.4 (a) 4) (NJDEP 2012). The use of flexible liners to seal boreholes to temporarily prevent cross contamination was initiated in 2001 and since then many hundreds of holes have had flexible liners installed for this purpose.

The transmissivity profiling method introduced in this article was invented by the first author, as described in patents (C.E.K., US patent nos. 6910374 and 7281422 and foreign patents). The seals installed by this method are temporary because the intended use of the liner is to create a seal until such a time as the borehole is needed for geophysics, hydraulic testing, and/or installation of a monitoring well, after which the liner can be removed with relative ease. Profiling measurements are conducted during liner installation with the intent that the liner will seal the hole once the profiling procedure has been completed.

Although this article only reports results from a field study area in a dolostone aquifer, the method has been applied in more than 300 rock boreholes at more than 60 sites across North America and in Europe. The shallowest hole profiled so far is 18 m and the deepest is 450 m in a sandstone borehole in California. Borehole diameters have spanned the range from 96 mm (3.8 inches) to 330 mm (13 inches). The depth to standing water in the holes has ranged from artesian conditions to more than 100 m. In nearly all cases where this profiling method has been applied, the liner has been left as a seal in the holes for a period of several weeks to many months before using the holes for other purposes. Our general conclusions concerning applicability and limitations of the profiling method presented in this article are based on the broad experience from all of these boreholes tested in many types of fractured rock.

To demonstrate the nature of results from the liner measurements and interpretive issues, we present results from three core holes in a 100-m-thick fractured dolostone aquifer. This aquifer provides the water supply for the city of Guelph, Ontario, Canada. Results from this field area were selected because these holes have been used for many other types of data acquisition for fracture identification and hydraulic conductivity determinations, including core logging, borehole geophysics with acoustic televiewing, flow metering, high-resolution temperature profiling (Pehme et al. 2010, 2013), and hydraulic tests using straddle packers and pumping tests (Quinn et al. 2011a). The comprehensive data collected from these holes allow comparison of liner profiles to other indications of fracture presence and transmissivity. Overall, development of the liner profiling is still in the early stage of application in contaminated site investigations. This article introduces the method as well as initial results and considers hydrogeologic and other factors that influence the performance and limitations of the method.

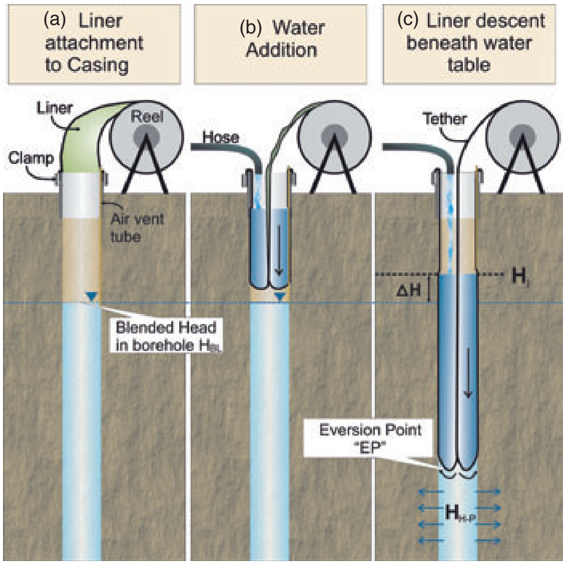


Figure 1. The stages in installation of blank FLUTe™ liner: (a) top of liner from the reel is clamped onto the top of borehole casing; (b) the liner is pushed by hand down into the casing so that water can then be added to cause the liner to descend by eversion; and (c) the liner descends below the static water level in the borehole and water is added to maintain a positive hydraulic head differential between the inside of the liner and the initial static water level, referred to as the blended head.

Approach

The details of the liner design and parameter values for the profiling procedure are specific to each hole; however, the generalities, as described here, are common to nearly all holes. The liner fabric (the urethane-coated material) is selected to have the combination of strength and flexibility suitable for the borehole diameter and the site-specific hydrogeological conditions. An essential objective is to select a fabric that will not rupture but have good flexibility for the profiling and also the strength to accommodate the necessary applied head differential established on arrival of the bottom of the liner at the bottom of the hole where the liner function is to form a seal along the entire hole. Previous experience related to the site conditions guides the selection of the characteristics of the liner material for each hole. If the fabric is too stiff and inflexible, it will create too much friction while descending down the hole. If the fabric is too thin and extremely flexible, it is more prone to rupture. Rupture occurs when the head of the water column inside the liner excessively exceeds the head in the fractures outside the liner. We expect that profiling of holes with diameters as small as 75 mm or even 51 mm will become feasible in the future with the use of very thin, extremely flexible liners made of strong enough material. Each liner is custom made and shipped from the FLUTe Ltd. manufacturing facility in Santa Fe, New Mexico to the field site on a reel. The outer diameter of reel plus the liner ranges between 0.6 and 1.0 m.

The profiling procedure evolves in stages. First, as shown in Figure 1a, the reel loaded with the liner is positioned at the hole and the open end, which is the top of the liner, is pulled off the reel and attached with a clamp around the top of the steel casing that protrudes above-ground surface. This casing extends through the overburden or weathered rock downward into the intact, stable rock mass. After clamping of the liner top to the casing head, the liner is pushed by hand at an arm's length downward into the casing to form an annular pocket. The second stage begins when water is added, usually from a hose connected to a water tank, into this pocket to create weight that drives the liner down the casing into the open rock hole below, as shown in Figure 1b. The process by which the liner goes down the hole is known as eversion such that, as the liner descends, the fabric initially on the inside of the liner while it was on the reel becomes the outside of the liner pressing first against the casing and then deeper against the rock wall. However, while the liner is descending through the air-filled segment of casing above the static water level, the air must be allowed to escape through a slotted tube extending to the water level.

Once the liner reaches the static water level in the hole, the third stage begins, which is the start of the controlled *T* profiling measurements. Initially, when the liner goes below the water level, the liner is temporarily restrained to create tension and then the liner is released to descend. The rate of water addition to the liner in this stage is carefully controlled to create a nearly constant applied head differential between the inside of the liner and the water level in the formation outside the liner. The rate at which water is added to the liner is governed mostly by the rate at which the water can escape into the permeable features in the open hole below the descending liner as it forces the water out into the permeable zones in the formation. The rate of water addition from the hose typically ranges between 0.5 and 100 L/min. Occasionally, the rate has to be larger when the transmissivity of the hole is exceptionally large. In such circumstances, the rate may reach hundreds of liters per minute. However, above such large rates, the current equipment cannot achieve the desired accuracy of measurement. If the transmissivity of the entire hole is exceptionally small, then the liner descent rate is so slow that the profiling effort is rendered impractical. However, in this case, what is learned for the profiling attempt is nevertheless valuable. An impractically slow liner descent indicates that there are no zones in the entire length of hole that have transmissivity above the detection limit, which establishes an upper bound on the bulk transmissivity of the hole. For this information to be most useful, the borehole must be well developed to clear all fractures of drill cuttings.

The static water level measured in the open hole just prior to the onset of profiling is referred to as the blended head or static water level and this is an important feature of the open-hole hydraulic system. The blended head is the equilibrium head that is achieved as a result of water flowing into the hole from those fractures that have relatively high head in the formation and water leaving the hole from those fractures with lower formation head. The inflows and outflows adjust through these vertical cross connections to produce the static blended head. In the formation away from the hole, the head distribution is governed by the groundwater flow system within the larger spatial domain. The blended head condition is a local hydraulic equilibrium and some distance away from the hole this disturbance caused by these open-hole cross connections is negligible.

To start the profiling, the water level in the liner is raised a few meters, generally between 3 and 6 m above this initial open-hole blended head to drive the liner downward. This applied head differential is referred to as the driving head. The driving head is set based on the knowledge of the initial blended head to create the necessary head differential to drive the liner down the hole. All flow of water from the hole under this condition is outward into the formation. During this period when the liner is descending down the hole, all cross connections in the hole have been eradicated. However, as the liner passes the first permeable fracture and seals it, the head in the water column below the liner may change to reflect the new condition and some change can occur continually until the liner reaches the bottom of the hole. The head below the descending liner is measured by a pressure transducer situated at the bottom of the hole. Therefore, the head in the hole below the liner is always known and is governed primarily by the applied head differential. However, extreme conditions are possible and are mentioned here to help illustrate the difference between a simple situation where the formation heads all along the hole are not greatly different and the more complex scenario of highly variable head. For example, if the bottom part of the formation around the bottom part of the hole is strongly artesian, then it would be possible that the driving head, which is set according to the initial blended head, would become so small that the liner would stop its descent. Another extreme condition could be that the formation head toward the bottom of the hole is exceptionally low and therefore in this part of the hole the effective head differential becomes too extreme that the liner ruptures. For such ruptures to occur there must be cavities or large aperture fractures into which the liner expands excessively. The actual head distribution in the formation around the open hole is not known before profiling begins; only the blended static head is known. However, insights about the head conditions are commonly obtained during the profiling procedure from system behavior and from the transducer record. Field experience with profiling many different sites shows that the two contrasting extreme conditions outlined above are not common.

To allow the data records acquired during liner descent to serve for calculation of the T profile, it is essential that the following measurements be made using the equipment setup shown in Figure 2: elapsed liner descent time, depth of the liner in the hole below top of casing at each time step, liner tension, and the head inside the liner that is measured using a bubbler tube system. This bubbler system is located in an internal sleeve in the liner to minimize disturbance by the water fed into the liner from the hose. The bubbler tube receives a constant airflow from an air tank and the system is adjusted so that the air pressure in this tube is a measure of the head inside the liner. These bubbler head measurements, along with the blended head value, allow the driving

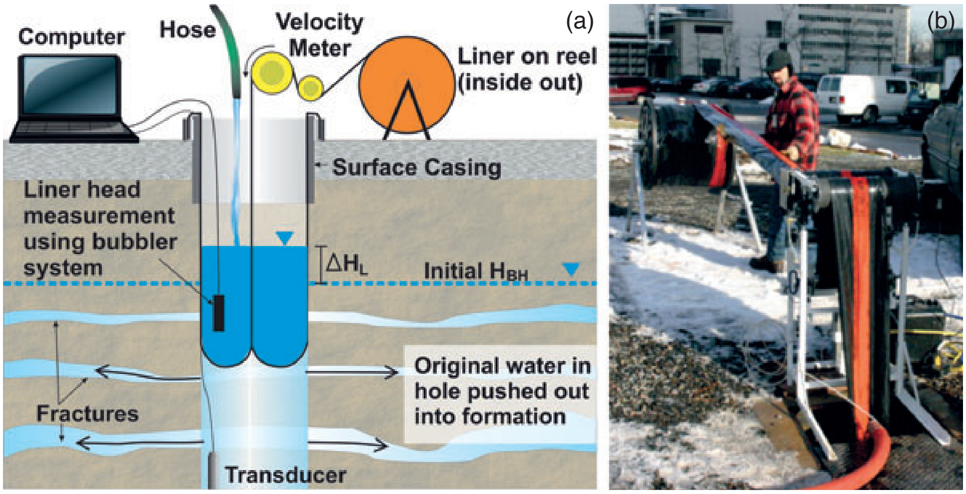
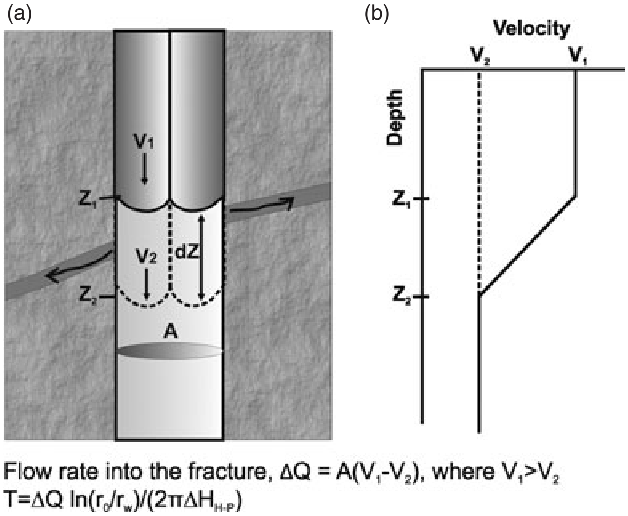


Figure 2. System components for the profiling method (a) (not to scale, vertically compressed). As water is added to maintain a constant head differential (ΔH_L) between inside the liner and the initial blended head, the liner descent rate (velocity) is measured as the head below the liner is measured (by the transducer) and (b) photograph showing the liner deployed from the shipping reel in the background and extending through the profiler positioned above the hole (foreground).

head to be calculated. The measurements of each of these quantities are made electronically at 0.5- or 1-s intervals. Other critical information that is not time dependent is also recorded including hole depth, hole diameter, casing depth, and casing height aboveground. The head in the liner is maintained constant during liner descent by adjusting the flow from the hose. The rate of descent, referred to as the liner velocity, is measured using a pair of encoders on a meter roller that accurately measures across a large velocity range. The velocity of the liner coming off the reel is measured by the roller for each time step (0.5 or 1 s), and therefore the velocity of the "eversion point" (EP) at the bottom of the liner (Figure 1c) is known because it is exactly half of the velocity of the liner entering the hole. The velocity is greatest at the beginning of the profiling when the length of open hole is longest and all permeable features along the hole are available for water escape in response to the driving head. As transmissive features are sealed off by the descending liner, the velocity slows at each transmissive feature as is explained in more detail in the next section. When the velocity slows to about 1 m/h, it is commonly decided to stop profiling measurements because of minimal continuing benefit. The T at this velocity for the remaining length of open hole is about 0.012 cm^2/s for a 15-cm diameter hole. The tension in the liner during the descent is measured using a monitoring roller equipped with a braking system. This tension measurement is performed using a pair of load cells with analog data converted to digital data recorded on a laptop with each recording event. A spread sheet is used as the liner descends to calculate the depth, velocity, driving head, pressure below the liner, and the other parameters needed for data analysis.



Flow rate into the fracture, $\Delta Q = A(V_1 - V_2)$, where $V_1 > V_2$
$T = \Delta Q \ln(r_0/r_w)/(2\pi \Delta H_{H-P})$

Figure 3. Schematic illustration showing the parameters involved in the measurement of transmissivity of a single permeable feature (e.g., fracture). The liner velocity changes from V_1 to V_2 as the liner passes (shuts off) a fracture over depth increment Z_1 to Z_2.

Identification of Transmissive Features

The capability of the liner method to provide information concerning transmissive features is based on the fact that, as the liner acting as a piston goes down the hole, the water column is pushed out into the formation through transmissive zones (transmissive fractures and other permeable features). As this happens, the rate of descent (liner velocity) changes by an amount proportional to the transmissivity of each permeable feature passed and therefore closed off by the liner. The water flow rate out of the open borehole into the formation beneath the liner is simply the velocity of the bottom of the liner (EP) multiplied by the horizontal cross-sectional area of the hole. At the beginning of the profile, the initial rate of flow is a direct measure of the transmissivity of the entire hole. Because of the constant driving head imposed inside the liner, the liner velocity must decrease each time it passes a transmissive feature because the remainder of the hole then has lower T. When the liner passes a transmissive fracture receiving flow at a rate of ΔQ (Figure 3a), the liner velocity drops by an increment equal to $\Delta Q/A$ when the EP passes the fracture, where A is the horizontal cross-sectional area of the hole. The precision of the location of transmissive zones is dependent on the time record intervals (e.g., recordings made 0.5 or 1 s apart). Figure 3b illustrates the ideal case for a single fracture. The EP depth over which the drop in liner velocity occurs identifies the location of the transmissive zone. Therefore, the entire descent velocity history is governed by the distribution of the transmissive features along the borehole.

The obtained velocity profile typically shows several types of changes in shape and those commonly observed are illustrated in the hypothetical velocity profile shown in Figure 4, in which the first interval has a slope of

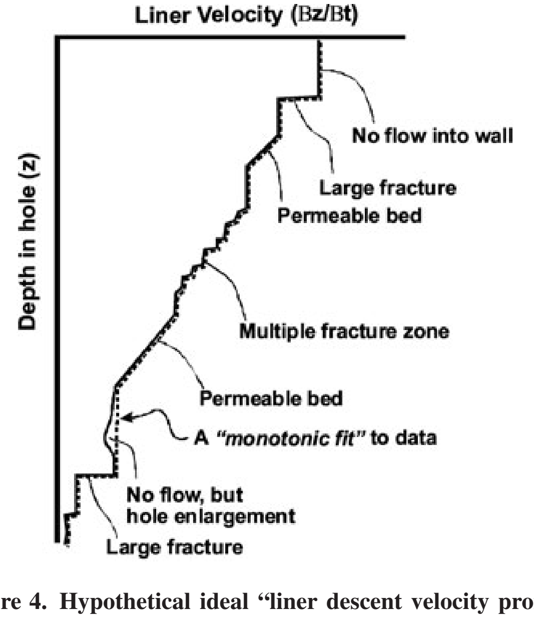


Figure 4. Hypothetical ideal "liner descent velocity profile" showing changes caused by several types of borehole features. The monotonic fitted line ignores temporary drops in liner velocity such as caused by a borehole enlargement where the liner velocity decreased but then increased upon exiting the enlargement.

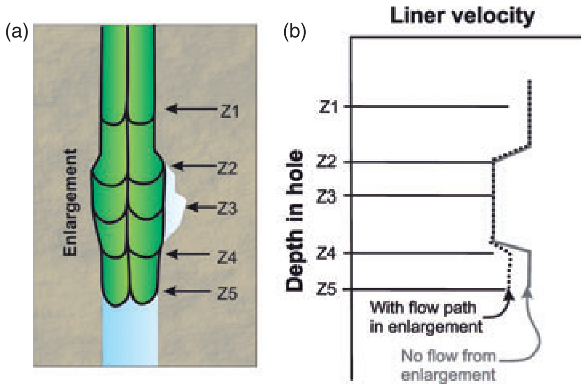


Figure 5. Hypothetical illustration of effects of borehole enlargement: (a) borehole conditions with blank line expanding where borehole is enlarged with five points along the liner, above (Z_1), within (Z_2, Z_3), and below (Z_4, Z_5) the enlargement interval, and (b) liner descent velocity profile showing an apparent temporary decrease in liner descent velocity followed by an increase after the liner passes the enlargement. In the absence of a permeable feature within the enlargement area, the liner velocity returns to the pre-enlargement rate.

zero, representing no detectable permeability and thus no flow features in this interval being sealed by the liner. The initial abrupt step change in velocity is typical of the liner passing a thin, discrete, nearly horizontal, permeable fracture intersecting the hole. The less abrupt, sloped portions of the velocity profile indicate transmissive intervals of substantial vertical thickness. These features can have various characteristics such as a uniform permeable bed (a smooth slope) or a zone with multiple fractures (a slope composed of numerous small steps) or a fracture intersecting the borehole wall at an angle.

In addition to the transmissivity of the borehole and the driving head in the liner, other factors can influence the velocity of the liner descent. Recognition of these factors is necessary to avoid them being incorrectly interpreted as transmissive features. For example, some boreholes have intervals where the hole diameter is enlarged, known as breakout or washout zones. As the liner passes through an enlarged segment, the liner expands slightly to fill the larger cross-sectional area (i.e., a larger volume displacement per unit length of travel) causing a corresponding drop in the liner velocity (Figure 5). This drop in velocity is not caused by formation transmissivity, but could be falsely interpreted as such. In field trials, the presence of this borehole enlargement effect is usually recognized because, when the liner passes out of the enlarged zone, the liner cross section is smaller relative to the nominal borehole dimension and the velocity then increases proportionally. The decrease followed by increase in velocity is diagnostic evidence for borehole enlargement. Figure 5 shows a sequence of a liner passing through an enlarged borehole segment where the liner may not be able to expand enough to press against the enlarged borehole wall and therefore the liner in effect is a balloon in this interval of the hole. If the liner exit velocity from the enlargement is less than the entrance velocity, the velocity change, and the associated transmissivity, is assigned to the upper portion of the enlargement. Therefore, the effect of a washout or solution cavity or other enlargement of the borehole on the profile is taken into account by the fit of a monotonically decreasing curve to the data that ignores the temporary drops in velocity. In some cases, the borehole diameter is determined independently by geophysical logging (mechanical caliper or virtual caliper from acoustic televiewer [ATV] logs) before conducting the profile so that borehole diameter variations are anticipated in the profile interpretation.

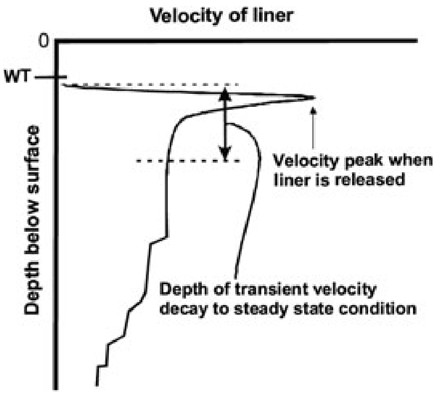


Figure 6. Transient velocity decay to steady-state conditions during early stage of liner eversion. Upon release of the liner, the liner velocity immediately peaks and then drops to the nominal steady-state flow rate. Thereafter, the velocity changes are governed by the sealing of transmissive features.

In the calculation of T values from the velocity profiles, steady-state flow is assumed. However, at the start of profiling when the liner is released to propagate down the hole, a short period exists when the flow out of the borehole is clearly not steady state (Figure 6). The velocity data obtained during this transient period are not used for fracture T determinations. In this transient period, the hydraulic gradient from the borehole wall into the formation is imposed instantaneously at the beginning of a profile and is initially extremely steep as the liner descent accelerates to a peak velocity (Figure 6). As the transient flow field propagates outward in the formation, the gradient at the borehole wall becomes much less steep and both the flow rate out of the hole beneath the liner and the associated liner velocity approach a nominal steady state. Fortunately, the transition interval in the hole is usually only about 2 to 6 m long, depending upon the liner velocity, and therefore the lack of useful T data from such a short section of the hole is usually not substantial and commonly some of this interval is in the casing, not in the open hole being tested.

Framework for Calculation of Transmissivity

The Thiem method (Wenzel 1936) for radial steady flow is used to obtain T values from the profiling data for the open borehole segment remaining below the liner as the flow paths are sealed from the top downward. As the liner is driven down the hole and the velocity decreases

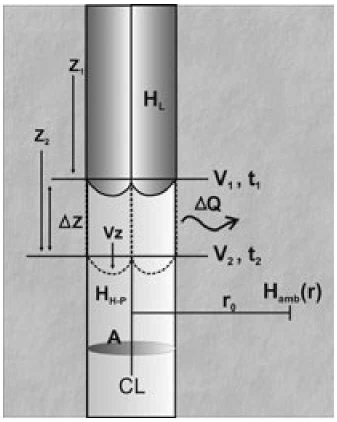


Figure 7. Diagram illustrating the parameters and concepts used for the mathematical framework of the transmissivity measurement.

as each permeable feature is sealed off, ideally, the flow rate into each fracture below the EP is nearly constant such that the flow regime in all fractures receiving water is at quasi-steady state at and near the borehole wall. The parameters used in the application of the Thiem equation for T calculation are indicated in Figure 7. The flow out of the borehole interval sealed by the liner in one time step is assumed to be steady-state Darcian radial flow represented by ΔQ. The steady-state radial condition represented in cylindrical coordinates is assumed to begin once the liner descends below the aforementioned transient interval early in the profiling. Therefore, there has been substantial time available for a steady-state flow to be achieved. This use of the Thiem equation presented here has general similarities to its use for calculating T values from constant-head packer test results in fractured rock holes as described by Maini (1971), Haimson and Doe (1983), Braester and Thunvik (1984), Lapcevic (1988), Novakowski and Bickerton (1997), and others. Quinn et al. (2012) provide a summary of the Thiem method applied to straddle-packer tests. For both liner profiling and packer testing applications, the Thiem equation is expressed as

$$T = \frac{\Delta Q}{2\pi \Delta H_{\text{H-P}}} \ln\left(\frac{r_0}{r_\text{w}}\right) \tag{1}$$

where ΔQ [L^3/t] is the flow rate reduction due to sealing an interval of the borehole, T [L^2/t] is the transmissivity of the portion of the borehole measured ($K\Delta z$), $\Delta H_{\text{H-P}}$ [L] is the applied head difference in the borehole above the open-hole blended head, r_0 [L] is the radius of influence of the test, and r_w [L] is the radius of the borehole.

As with all single-well tests, the r_0 cannot be measured and therefore an assumed value is used. In packer testing literature for fractured rock, assumptions of r_0 ranging from 10 to 60 m have been justified (e.g., Maini 1971; Haimson and Doe 1983; Bliss and Rushton 1984). However, because the T may vary over several orders of magnitude, the uncertainty caused by the r_0 value selection is small as it is contained in the natural log term. This uncertainty is generally not viewed as important when the Thiem equation is applied to straddle-packer test results because the T values from such tests are generally referred to as "order of magnitude" estimates (e.g., Maini 1971; Ziegler 1976; Haimson and Doe 1983; Bliss and Rushton 1984; Lapcevic et al. 1999). For this study, $\ln(r_0/r_\text{w})$ is set to a value of ln(600) representing a 30-m radius of influence in a 100-mm (4-inch) borehole, which is the value recommended by Haimson and Doe (1983) and used by Quinn et al. (2011a, 2011b, 2012) for calculation of T values from constant-head packer tests in the Guelph dolostone aquifer. In application of the Thiem equation to straddle-packer test results, the r_0 value is generally fixed at the same value for all tests in each hole and for many holes at the same site, even though the extent of radial influence must vary in some unknown amount from interval to interval because of different injection rates and fracture apertures.

The preferred method for obtaining the actual head in the water column in the hole below the descending liner, $\Delta H_{\text{H-P}}$, relies on a transducer, such as a Solinst Levelogger model 3001 or a Schlumberger Diver positioned at the bottom of the hole with on-board recording and transmission of the pressure history to the surface via a slender cable (Figure 2). This downhole transducer allows continuous recording during profiling of the head driving the water into the formation. For lower cost and/or to avoid the potential of any leakage along the cable, a self-contained version of these recording pressure transducers attached to a thin string (e.g., fishing line) can be used. However, when a transducer attached to a string is used rather than a transducer attached to a data transmission cable, the data are only available when the transducer is retrieved after the liner is removed. This is not ideal when the plan is to leave the liner in place to seal the borehole for longer periods.

This method of using the FLUTe liner as a piston to obtain velocity profiles is referred to as a transmissivity (T) profiling method rather than a hydraulic conductivity (K) profiling method because conversion from T to K requires exact knowledge of the vertical interval across which the flow has occurred. The interval of measurement depends on the measurement recording frequency. Because the velocity decreases as profiling proceeds, the interval of measurement decreases with depth. Therefore, because the velocity is measured and time intervals are known, which provide the interval for each T calculation, K can be calculated as an average for each interval.

Estimation of Head Below the Liner

For avoidance of transducer use, borehole pressure beneath the liner is estimated using an empirical equation derived from laboratory tests of liner tension vs. driving pressure during liner eversion and inversion:

$$H_{\text{H-P}} = \Delta H_\text{L} - H_\text{MIN} - \frac{2\left(\Theta_\text{w} + \Theta_\text{D}\right)}{A} \tag{2}$$

where ΔH_L is the driving head in the liner, H_{MIN} is the minimum head needed to evert the liner against the resistance due to the fabric stiffness, Θ_W is the recorded tension on the liner at the wellhead, Θ_D is the total drag force on the liner within the borehole (friction), and A is the borehole cross-sectional area. The factor 2 is an empirical coefficient determined from many eversion tests in a laboratory apparatus using different liner materials. The tension at the wellhead (Θ_W) and the head inside the liner (H_L) are precisely measured in the field while profiling using load cells selected for the desired load range and a pressure transducer mounted in the profiler, respectively. The total drag on the liner (Θ_D) is not measured, but is intentionally reduced to as near zero as possible. The drag term becomes important when the water table is very deep or when profiling a borehole with extremely high transmissivity. For profiling in boreholes with deep water tables, the use of a tremie hose inside the liner to introduce the water at the water table depth without wetting the inverted liner helps to minimize the drag. In extremely high-permeability boreholes, the driving head in the liner (ΔH_L) is kept as large as possible to reduce the significance of drag on the liner. Uncertainties in Θ_W, Θ_D, and the "factor 2" are only significant to $\Delta H_{H\text{-}P}$, and therefore T, to the extent that the uncertainties are large relative to ΔH_L. For that reason, it is important that ΔH_L be relatively large, but not so large as to rupture the liner. It is also important that the head in the hole beneath the descending liner, $H_{H\text{-}P}$ in Figure 7, exceeds the head everywhere in the formation so that all flows are out of the borehole and that there is no cross flow occurring in the borehole between transmissive intervals. Significant inflow is easily recognized in that it causes an increase in the velocity, violating the expectation of a monotonically decreasing liner velocity. Comparison of the calculated head from surface measured parameters with the directly measured head beneath the liner generally shows excellent agreement as indicated by the example shown in Figure 8, which is typical for the many holes where this comparison has been made.

The velocity per unit driving pressure ($v_i/\Delta H_{H\text{-}P}$) for each time step is plotted vs. depth to create a velocity profile of the borehole. Because the depth increments for each time step vary with the liner velocity, the hydraulic conductivity obtained from the transmissivity calculation has variable depth resolution. The largest intervals (Δz_i) are located at the top of the borehole where the velocity is highest. Changes in the velocity per unit driving pressure are then calculated throughout the borehole and multiplied by the borehole cross-sectional area to obtain $\Delta Q/\Delta H_{H\text{-}P}$ for use in the Thiem equation.

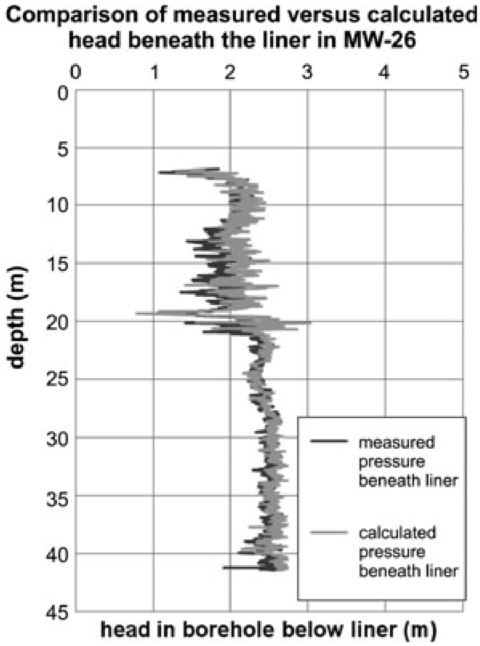


Figure 8. Comparison of measured pressure history from the transducer at the bottom of the hole beneath the liner with the calculated pressure history using the measurements of the liner at the surface for MW-26. In this case, the agreement is very good and the transmissivity results are essentially the same using either history for this borehole. Boreholes with higher vertical flow rates (>38 L/min [10 gpm]) generally do not show such good agreement.

Insights from the Velocity Profile

Profiling results from three holes in the Guelph fractured dolostone aquifer are used here to illustrate insights derived from the liner profiling method. The overburden at the site is between 3 and 5 m thick. Boreholes were continuously cored (HQ, 96-mm diameter) from the top of rock to the bottom of the boreholes up to 100 m below-ground surface (bgs). The water level in the open boreholes varies seasonally between 3 and 5 m bgs. This dolostone aquifer supplies most of the municipal water supply for the City of Guelph. Borehole flow metering in open unpumped holes shows that some boreholes in this formation have downward vertical flows greater than 400 L/min. This flow condition is caused by the pumping of municipal wells that draw most of their water from the deep part of the aquifer. The three boreholes were selected to show the nature of velocity profiles. In 2006, the liner method was applied twice in 1 d in borehole MW-24, which extends through the full depth of the 100-m-thick dolostone aquifer into the underlying shale aquitard. Each profiling episode took about 2 h. In the first step of liner profiling data processing, the data from each run were smoothed, as shown in Figure 9a, to produce a velocity profile used for hydrogeological interpretation. The profile smoothing process removes the small oscillations in the profile reasonably attributed to noise caused by the measurement and recording devices. Figure 9a shows both the raw velocity profile and smoothing results for MW-24, with the profile smoothed over three successive time steps and the monotonic fit of the smoothed curve. The degree of smoothing needed is judged by the amount of deviation from the raw data. For this example, the excellent match of the three profiles is typical of what is deemed to be a "good data set."

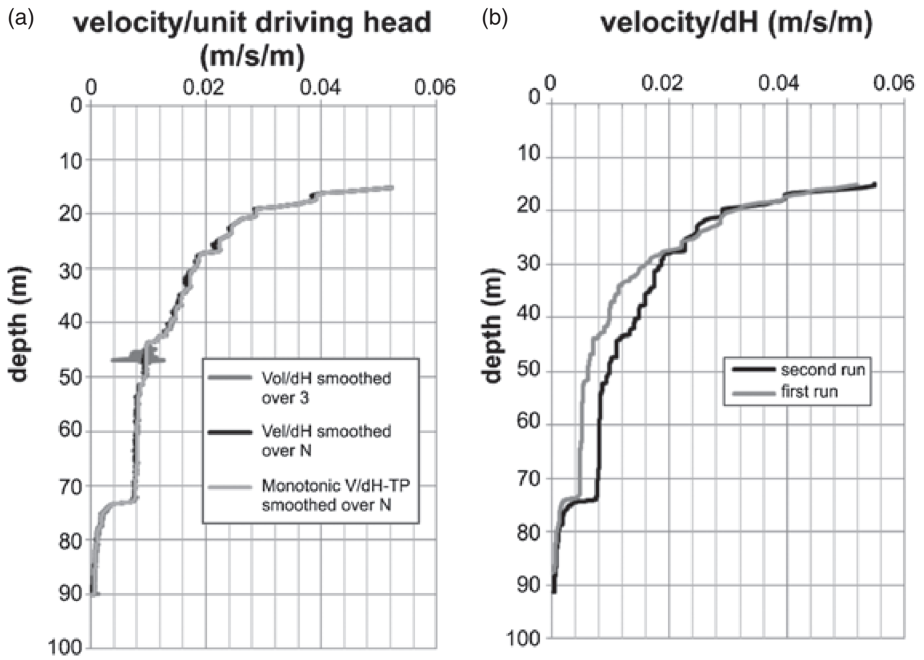


Figure 9. Plots showing (a) data from MW-24 liner profiling showing raw and smoothed velocity profiles over three time steps (6 s) and monotonic fit used for hydrogeological interpretation, and (b) monotonic fit for two profiling events done on the same day, showing generally similar results but with the *T* obtained in the zone of the most prominent permeable feature at 73 m bgs greater from the second run, which is attributed to "well-development" effects caused by liner removal after the first run.

An unexpected benefit of the liner method is its use for removing sediment clogging from fractures. Figure 9b shows the monotonic fit for the two profiling events done on the same day. The two profiles are generally similar, but the *T* obtained from the second run was greater than the first by about 60% at the most prominent fracture at 73.1 m bgs. This difference is likely owing to "well-development" effects caused by the removal of the liner after the first run. A specially designed machine referred to as a "linear capstan" is used to remove the liners as quickly as possible by applying strong tension to the tether that is attached to the bottom of the liner causing the liner to invert back up through the borehole. This tension creates a strong low pressure beneath the liner that draws water from the formation into the borehole. The tension typically applied produces a pressure drawdown estimated at up to 30 m of head difference between the water column in the hole and the formation pressure represented by the open-hole blended head. This large inward hydraulic gradient promotes removal of sediment clogging fractures. This increased transmissivity (and corresponding decrease in liner profiling time) has been observed in other boreholes where a blank liner was removed and installed a second time.

In boreholes that penetrate through an aquifer into an aquitard, the liner method provides insights about the nature of the contact or transition between the aquifer and the aquitard. This is illustrated by the liner profiles in MW-24 (Figure 9b), which show strongly decreasing velocity in the first 35 m gradually becoming slower with an abrupt velocity drop at 75 m bgs. The profiling was discontinued at 93 m when the velocity became so slow that there was no further benefit to continuing the measurement. The point at which the liner descent velocity became markedly slower indicates that the horizontal transmissivity below this elevation is much smaller than above. However, the contact with the aquitard is at 102 m bgs, where the shale begins as indicated by core and gamma logs. Figure 10 shows the *T* profiles in this hole alongside other types of borehole information. The depth (~93 m bgs) at which liner descent velocity detected minimal transmissivity, and therefore only slightly permeable fractures, coincides with the depth (~92 m bgs) below which no active groundwater flow was detected by Pehme et al. (2010) using high-resolution temperature profiling in the water column in this lined hole.

The liner profile expressed as *T* (Figure 10e) shows numerous transmissive features. It is reasonable to attribute each drop in velocity to a permeable fracture or fracture zone because the rock matrix permeability, as indicated by laboratory tests of representative core samples is small, about 5×10^{-9} m/s. This is a factor of 100 lower than the practical limit of liner measurements; therefore, the features identified by this profiling method are due to individual fractures. However, one must be wary of inferring too much about the transmissivity ascribed to each small interval traversed in a time step as an individual fracture. An obvious example is that near the bottom of the hole the liner is moving at less than a centimeter per half second time step. If a high angle fracture intersects the

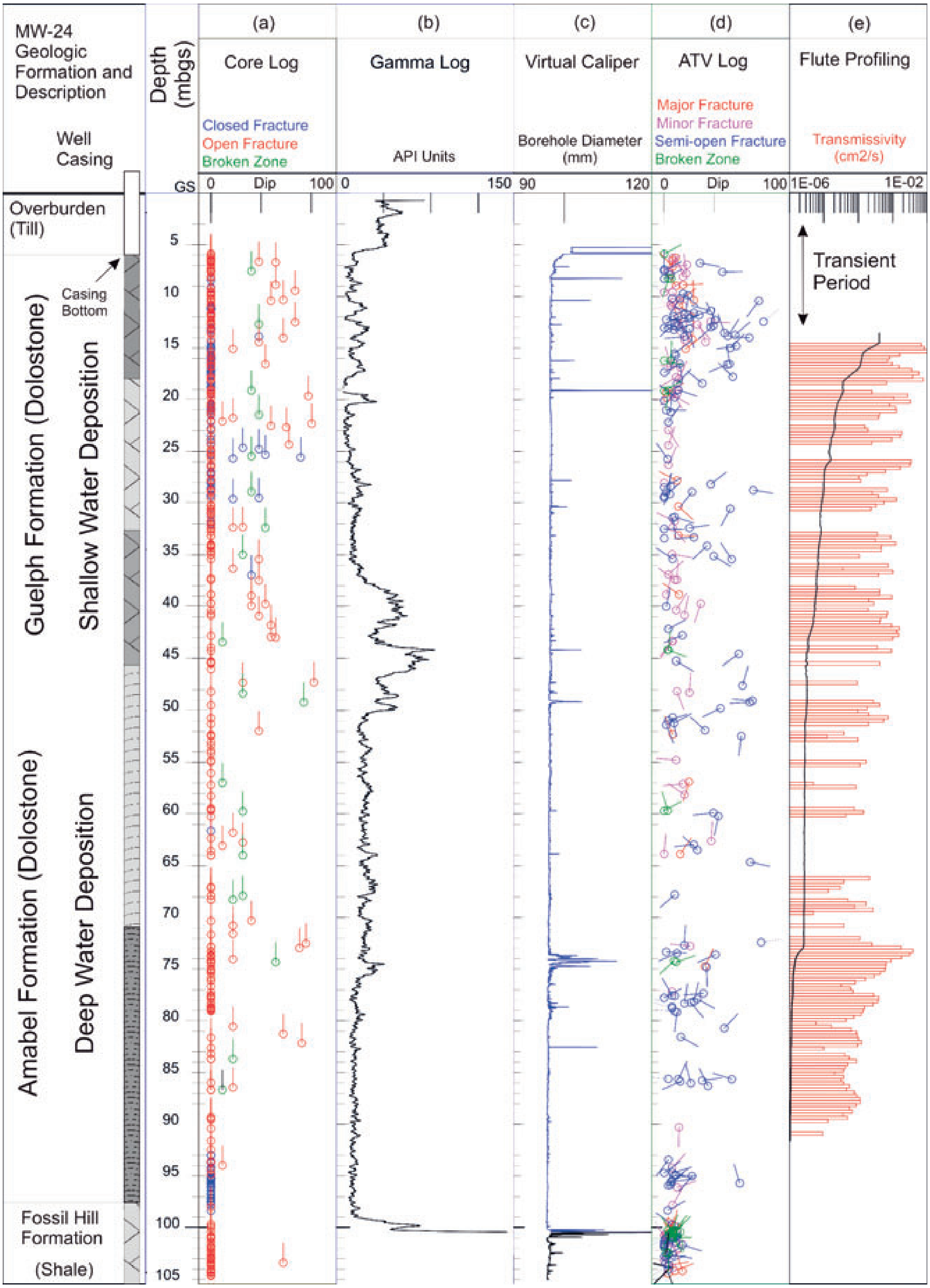


Figure 10. Geological and geophysical features in MW-24 displayed along the liner *T* profile. The core log, caliper, and ATV logs all indicate the presence of numerous fractures, which is consistent with the liner profile where the *T* values are integrated over 1-foot intervals.

borehole over a vertical distance of 20 cm, the liner measurement will divide the sealing of that fracture into about 40 time steps corresponding to 40 velocity increments which sum to the total velocity change as the liner seals the single fracture. Likewise, at the top of the hole, the liner may pass several fractures in a single time interval at a higher velocity. The continuous curve of Figure 10e is the integral of the transmissivity from the bottom of the hole to the top. The step changes in the curve are visually correct for the relative magnitude of each flow zone. The bar graph of Figure 10 is the integral of the discrete transmissive intervals over a fixed interval of 0.30 m. This would be comparable to a continuous series of 0.3 m straddle-packer tests. Such a short interval allows the easy identification of the prominent transmissive features. A shorter interval of integration would perhaps define the individual fractures more clearly. However, at some small scale, the inherent noise in the measurement would lead to very small false fractures.

Figure 10 shows that the liner profiling indicating numerous transmissive features is consistent with the occurrence of large numbers of fractures in this hole inferred from inspection of continuous rock core and acoustic televiewing. It is also consistent with the high-resolution temperature profiling inside the lined hole by Pehme et al. (2010), which showed a total of 18 hydraulically active fractures between depths of 34 and 91 m bgs. Above 34 m, the temperature profiling method did not provide data suitable for fracture identification. The core log and ATV identified fractures, but provide no indication of whether these fractures are permeable or not. It is reasonable to expect that the total number of significant fractures identified by the liner profiling method can be larger than the number identified by high-resolution temperature profiling (Pehme et al. 2010) because not all permeable fractures would have the degree of active groundwater flow needed for identification using only temperature profiles. For some fractures, the sensitivity for identification of fracture position or presence using the profiler method will be lower than the temperature method.

Comparison to Straddle-Packer Results

Packer testing was done at 1.5-m intervals throughout the full length of two holes (MW-26 and MW-367-7) in the Guelph dolostone aquifer using the constant-head injection step method. Quinn et al. (2011a, 2011b) describe the equipment and test procedures applied in these holes. Figures 11 and 12 show comparisons of T profiles from the liner method with measurements from straddle-packer tests. The liner profiles provide T values due to permeability offered by individual fractures or specific intervals with multiple fractures or solution channels. It was necessary to integrate the liner measurements for comparison to the packer results by summing the liner T values over the same 1.5 m intervals as the packer test profile.

The depth-integrated (1.5 m interval) T profiles from the liner profiling of holes MW-26 (Figure 11) and MW-367-7 (Figure 12) are very similar to the packer testing results, except for the uppermost part of the hole where, as expected, the transient period prevented determination of T values from liner measurements. In the part of the hole where both methods gave T values, most intervals have similar values. The liner profile does not resolve transmissive features less than approximately 1% of the remaining transmissivity beneath the liner. For that reason, some of the lowest packer test values correspond to no measured transmissivity for the liner profile. There is a small tendency for packer testing T values to exceed liner T values in the bottom half of the hole, which is consistent with the expectation that the liner method has best accuracy toward the bottom of the hole, and the expectation that the liner method is prone to underestimate T values because of the effect of non-Darcian flow. The packer testing method used in these holes (Quinn et al. 2011a) was directed at avoiding errors as a result of non-Darcian flow, as discussed in the next section.

The liner profiling method provides the T for the entire hole below the point at which the transient condition ceases, which comes from the velocity measured at this point. For MW-26 and MW-367-7, these liner T values were 1.1 and 1.3 cm^2/s, respectively, which are close to the T values obtained for the same sections of these holes by totaling the packer testing values, which provided 1.0 and 1.5 cm^2/s, respectively. The closeness of these "entire hole" T values illustrates use of the liner profiling method as a rapid means for determining entire hole T values. The closeness of these values suggests that although the two methods have different sources of error and uncertainty, these are not so large as to cause the T values to differ substantially from total aquifer thickness or hydrogeologic unit perspective.

The liner profile in MW-26 (Figure 11) has two gaps where the intervals are below detection, and one gap in MW-367-7 (Figure 12) where the packer testing also showed relatively low T values. These below-detection gaps occur in the upper part of the hole above the highest T intervals, which occur in the middle of these holes. This is also consistent with lesser liner method sensitivity in the upper part of holes. Nonetheless, the overall assessment through comparison of the two methods in these holes provides confidence that liner method T profiles provide good estimates compared with carefully performed straddle-packer tests, and that the profiles are a reasonable representation of the hydrogeologic conditions in the holes based on multiple lines of evidence.

Difficult Conditions, Limitations, and Uncertainties

The liner profiling method is aimed at providing two types of information: (1) positions of permeable features along the borehole and (2) transmissivity estimates of permeable features along the borehole wall. A permeable feature may be a single fracture, a solution channel, an interval with numerous closely spaced fractures, or in some cases a zone where there is substantial rock matrix permeability. There are reasons for evident errors or uncertainties associated with the liner results for each of the two types of information. As the liner descends into the hole, the descent rate is measured at set time intervals (e.g., every half second). The applied head inside the liner is maintained by adjusting the rate at which water is added to achieve a constant positive differential between the head inside the liner and the head outside the liner in the formation. The liner descent rate (velocity) decreases each time a permeable feature is sealed by the passing liner. Because the descent rate is measured at a set time interval and the descent rate diminishes down the hole, the resolution based on the

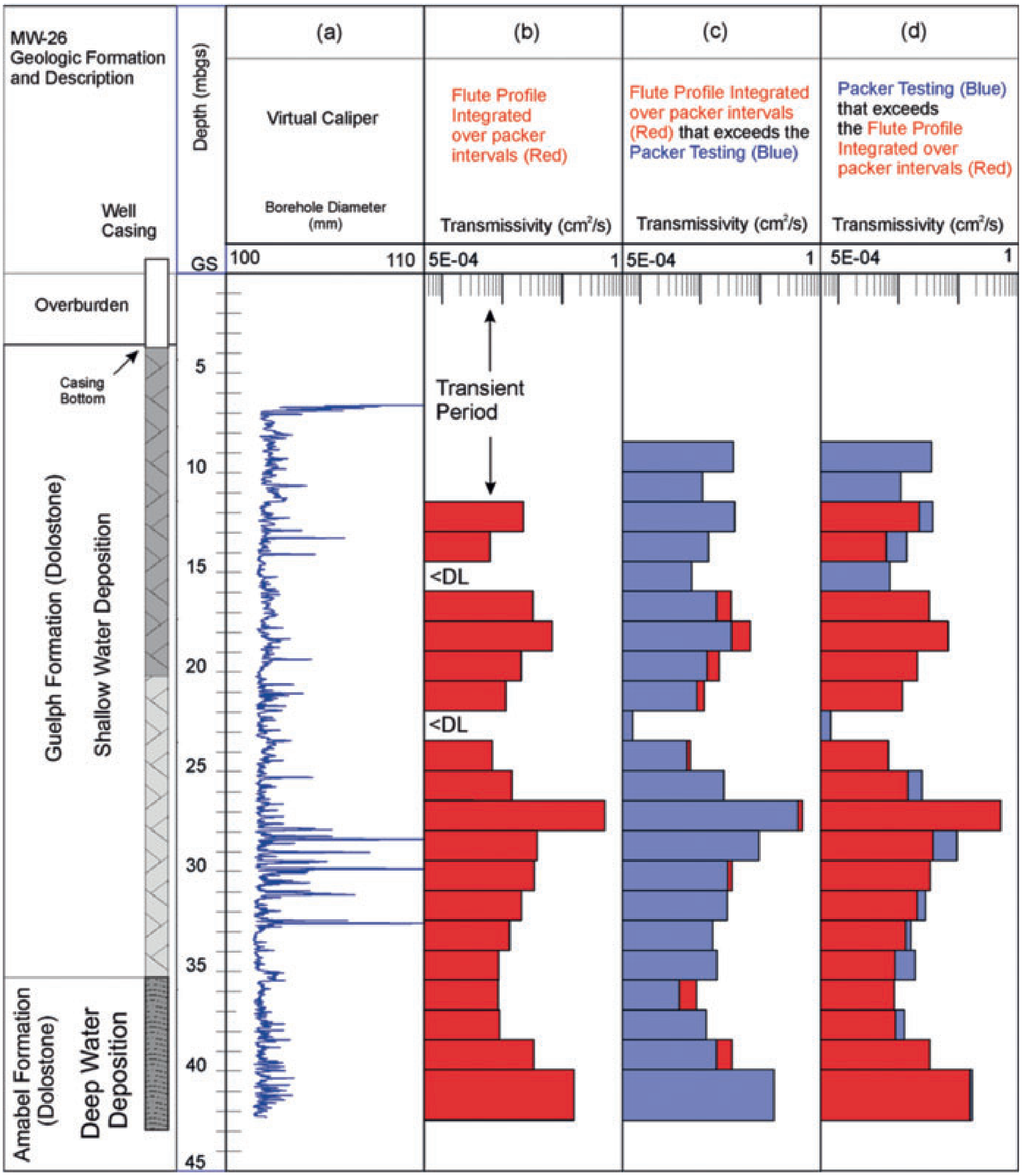


Figure 11. Comparison of liner T profile with packer test T values in MW-26. The raw FLUTe profile integrated over the packer intervals is shown in column (b). The integrated FLUTe profile is compared to the packer testing values in columns (c)-(d). Column (c) shows the intervals in which the FLUTe had a larger value for T, and column (d) shows the intervals where the packer testing had a larger value for T. Geology and well construction are shown to the left of the diagram, and column (a) shows the virtual caliper log of borehole diameter.

descent rate measurements increases with depth down the hole; and therefore the sensitivity of the liner profile to detect permeable features increases down the hole. The highest resolution of transmissive feature identification is achieved in holes where the highest transmissive zones are nearest to the top of the hole rather than at the bottom of the hole. Fortunately, at many sites the highest T zones occur at or near the top of rock where there has been more weathering or structural disturbance. In holes where the highest T is at or near the bottom of the hole, features with relatively much lower T go undetected.

Regardless of the distribution of permeable features along the borehole, the liner profile is normally expected to provide a reliable measurement of the total transmissivity in the open hole beneath the initial transient interval and it is generally very unlikely that the liner profiling method will miss identification of any major transmissive features. Cumulative experience obtained from profiling many different hydrogeologic settings indicates that the only holes where the velocity was too fast to obtain useful T was in karst with large solution channels near the bottom of the hole. The fastest profile to date was to 71-m

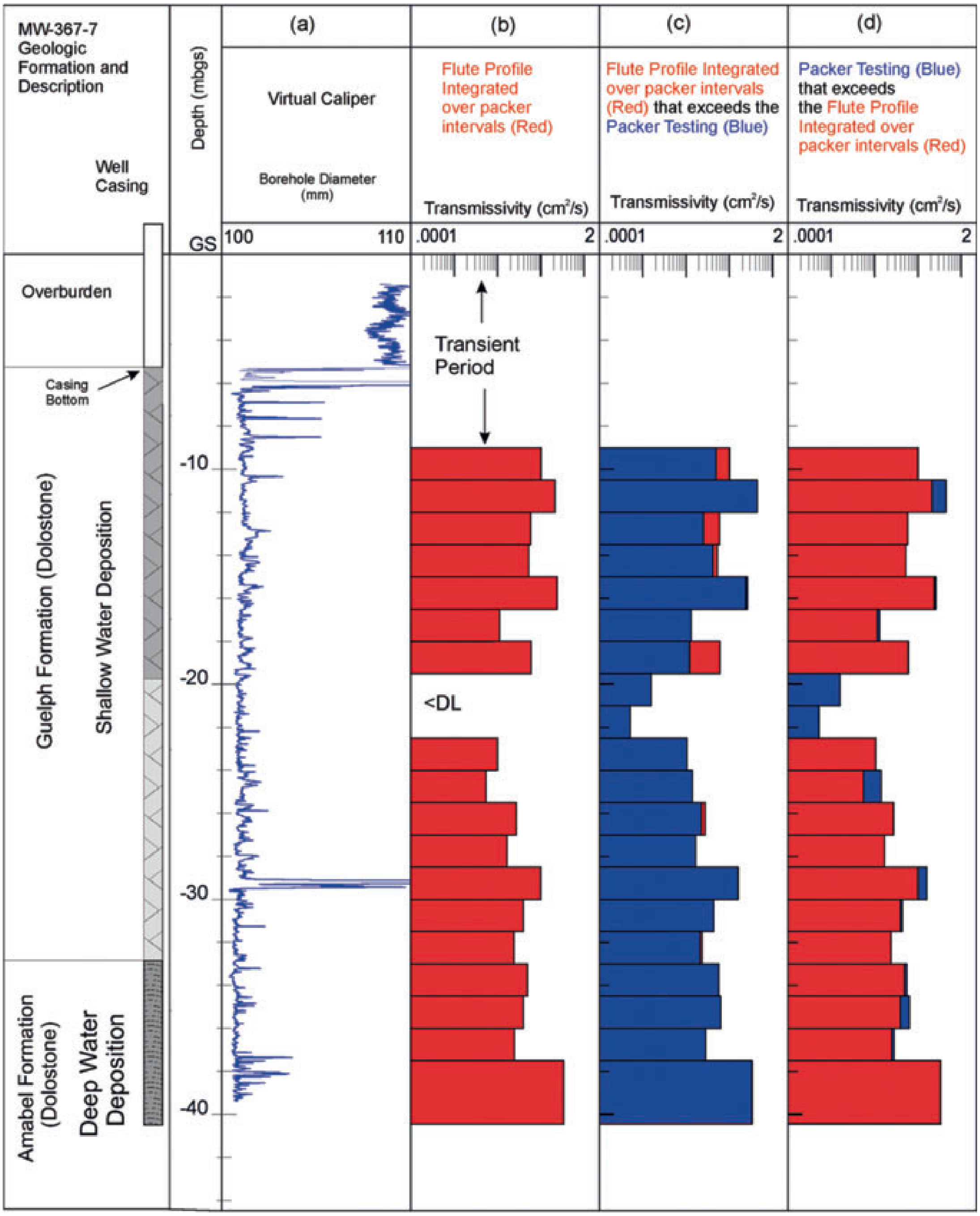


Figure 12. Comparison of liner T profile with packer test T values in MW-367-7. The raw FLUTe profile integrated over the packer intervals is shown in column (b). The integrated FLUTe profile is compared to the packer testing values in columns (c)-(d). Column (c) shows the intervals in which the FLUTe had a larger value for T, and column (d) shows the intervals where the packer testing had a larger value for T. Geology and well construction are shown to the left of the diagram, and column (a) shows the virtual caliper log of borehole diameter.

depth in 12.5 min and the spatial resolution of this profile was poor. However, profiling has also provided many useful profiles in karstic rock environments.

Artesian conditions present a particular but not insurmountable challenge. In a few cases where liner measurements were desired and the static head in the hole was above-ground surface (i.e., flowing artesian hole), the liner method was difficult but found to be feasible when a temporary structure (e.g., scaffolding) was used to allow application of the head differential necessary to drive the liner down the hole. Recently, a more sophisticated approach for artesian holes has been applied that uses an attachment to the top of the wellhead to enable pressurization.

A much different problem arises in boreholes where a large inflow of cascading water occurs from a shallow fracture located in the exposed borehole segment above the blended head. This condition can exist only where there is a high-T, low-head zone deeper in the hole. Profiling in these holes can be difficult or impossible. The cascading water has a tendency to pull the liner into the borehole without applied head, and the high flow along the borehole wall may prevent proper sealing. In one hole, this problem was avoided by feeding an extremely large flow rate (e.g., 400 L/min) into the liner to keep the driving head large enough to seal the shallow inflow zone. Excessively high head may occur at some depth in the hole even though the blended head is not exceptionally high. In such cases, the liner profile may show no apparent transmissivity at this excessively high head zone, but when the liner passes the inflow zone and seals it, the liner descent velocity increases to compensate for the lost inflow. To confirm this excessive head condition, once the liner is in place, the water level can be lowered inside the liner in successive steps. When the water level no longer drops with the water removal, the head in the liner is at the highest head in the formation, because that highest head interval is starting to collapse the liner. Identification of these artesian intervals in this manner is very useful to the design of multilevel liner systems. Flowmeter measurements can also be useful evidence of this condition.

Although application of the Thiem equation for calculation of the T values is most appropriate, this can be a source of T value uncertainty because of differences between the actual field conditions and those assumed in the derivation of this equation. The Thiem equation is based on the assumption of steady-state horizontal flow in a fully confined horizontal layer (Todd 1980). The steady-state assumption is most appropriate because, typically, the borehole has been open for many hours or days before liner profiling begins. Because of cross connection caused by the open hole, water flows into the hole from one or more fractures and out of the hole from others to establish a local open-hole, quasi-steady-state flow condition. Then liner profiling quickly imposes a new quasi-steady-state condition on the borehole. Once the liner is below the transient interval, the applied head pushing the water out of the hole into the formation is maintained as a constant differential relative to the initial blended head. This condition ensures that the flow rate (ΔQ) out of the hole at each permeable feature is constant until the liner passes and seals the feature at which point the ΔQ into the fracture goes nearly instantaneously to zero. Therefore, at each instant as the liner travels down the hole, the flow regime in the fractures above the liner bottom becomes transient as groundwater flow in the fracture network adjusts to the imposition of the borehole seal. However, below the descending liner, there is quasi-steady-state flow into each fracture because the constant applied head differential initiated when profiling begins. If the fractures are primarily horizontal with minimal vertical hydraulic conductivity, then it is reasonable to expect that the descending interface (transition zone) between the transient- and steady-state flow regimes does not influence the accuracy of the values calculated from the Thiem equation. However, in systems where there are numerous vertical or angled fractures allowing substantial vertical flow, the transient regime adjacent to the sealed hole rather than the assumed steady flow can introduce a source of error until that flow path has been sealed, at which time the total change in flow out of the borehole due to that flow path is correct. The complication of vertical flow for use of the Thiem equation also exists for straddle-packer tests where it can lead to connection of the straddled interval to the segment of open hole above and or the segment below the packers. This effect caused by vertical fractures is a form of local short circuiting. However, in profiling, this source of error is less, because the connection to the open hole above the bottom of the liner is not possible as the entire hole is sealed above the end of the liner.

There are other sources of error related to assumptions in the Thiem equation. The assumption that the initial blended head in the borehole is the same as the formation head has some uncertainty associated with it. However, this profiling method does allow the estimation of the actual formation pressure using a stepwise procedure for the liner when it is to be removed. This new technique of performing a vertical head profile during the liner removal is currently being tested to be reported in a future article. For holes where a multilevel monitoring system is installed later, the head data then obtained can be used to refine the profiling T results. Quinn et al. (2011a, 2011b) show that straddle-packer testing in these and other boreholes in the Guelph dolostone conducted at excessively large injection rates produces "non-Darcian" flow and therefore the T values are underestimated. The packer test T values in columns (c) and (d) in Figures 11 and 12 were obtained for "Darcian" flow regimes because the injection rates were controlled to achieve Darcian flow in each test interval (Quinn et al. 2011a, 2011b). However, in liner profiling, it is not feasible to control injection rates to achieve "Darcian" flow; thus, "non-Darcian" flow can be a source of error in the T values. However, based on the comparison between liner profiling and packer testing results for MW-26 and MW-367-7 shown in Figures 11 and 12, this source of error in these holes is very small. The errors in the values attributable to non-Darcian flow and the r_0 assumption are expected to generally be less than an order of magnitude.

Conclusions and Implications

Generally, the most important reason for installing liners in rock boreholes at contaminated sites is to minimize hydraulic cross connection and the associated cross contamination that is difficult to remove. However, only minimal additional effort, time, and expense are required during the liner installations to perform measurements to discern positions of permeable features and to obtain T estimates for these features. Therefore, since the introduction of this liner profiling method in 2003, it has rapidly become recognized as a useful addition to many fractured rock investigations. Testing the method in hundreds of boreholes in different hydrogeologic conditions has produced many refinements in the equipment and procedures and there is continual improvement to the method. In cases where the borehole penetrates through an aquifer into an aquitard, this method provides insights concerning the position and nature of the aquifer/aquitard contact.

Prior to the development of the liner profiling method, hydraulic testing using straddle packers was the primary method available to obtain such depth-discrete, T profiles in boreholes. However, except at research sites, high cost generally prevents application of comprehensive packer testing using short intervals along the entire borehole length. Therefore, in conventional contaminated site investigations, straddle-packer tests are typically done in only a few intervals in each borehole. Our experience shows that the efficacy of straddle-packer hydraulic tests is enhanced when used in combination with liner profiling, particularly when the packer tests are done after the liner profiling so that the profiles can be used to guide selection of the packer test intervals. In boreholes where the sensitivity of the liner method is minimal in the upper part of the hole because of a relatively high transmissive zone in the lower part of the hole, straddle-packer tests can be used to measure T values in the intervals where the liner method detects only larger fractures. Not every small drop in the monotonic fit curve is a reliable identification of a small fracture, but the sum of all the transmissive features is a reasonable estimate of the transmissivity of the borehole. As experience is gained through use of the liner profiling method and with comparisons to T values obtained by other methods, we can expect that the data interpretation procedure will improve.

The liner profiling method is an important addition to the group of techniques used for examining the hydrogeologic features of boreholes and offers the greatest potential for enhanced insights when used in combination with straddle-packer hydraulic tests and borehole geophysics, including temperature profiling in the holes after the liner is installed (Pehme et al. 2010, 2013). The exploration into the rigorous use of liner profiling in combination with these other methods is in its early stage.

This profiling method is an efficient means of measuring T profiles in some types of holes for which straddle-packer testing is not practical, such as holes where the borehole wall is unstable rock or where the rock is so highly fractured that strong short circuiting during packer tests is unavoidable. Another situation where the profiling method is exceptionally efficient and cost-effective relative to packer testing is for boreholes of very large diameter (e.g., >250 mm, 10 inches) because use of such large-diameter packers is commonly problematic. In contaminated site investigations where minimization of cross contamination between different levels in the borehole is mandatory, or at least desirable, the profiling method done soon after drilling the hole is completed occurs quickly as part of the borehole sealing procedure, whereas packer testing to measure T is done at the expense of cross connection.

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