Liners and Packers: Similarities and Differences

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Abstract

The flexible liner and the straddle packer are both used for measuring hydraulic conductivity in boreholes. This paper compares the theory and general characteristics of the two methods.*

Both methods use the Theim equation for 1-D cylindrical flow to deduce a hydraulic conductivity from the flow rates measured into the borehole wall. The flow rates are measured very differently. The packer test waits to achieve the steady state condition. The liner measurement develops an initial transient to the steady state condition in the borehole which may interfere with the first part of the hole measurement. The spatial resolution of the packer test depends upon the packer interval. The liner usually has much higher spatial resolution. Packer tests can measure to very much lower conductivity values than the liner measurement unless the packers are leaking. Without monitoring for leakage, the packer results are unreliable. The straddle packer will leak for a rough hole wall, a highly fractured zone, or for a very permeable matrix. The liner method is relatively unaffected by these factors. The liner system only measures flow paths that connect to the far field. Liner measurements use less equipment than straddle packer measurements. The time/labor for the straddle packer measurement of an entire hole of 300 ft is 10-15 times that required for the liner measurement. Straddle packers can be used to obtain a sample from the straddled interval. The liner does not provide a sample. Straddle packers allow a head profile measurement in the borehole. The liner does not usually. Comparisons of the liner results with straddle packer results have shown that substantial bypass leakage occurs for some straddle packer intervals. Those same fractured intervals are well measured by the liner method. The liner is usually left in place to seal the entire hole. The packers can be left in place for a partial seal of the hole.

Introduction

The method of measuring the transmissivity profile in a borehole using an everting flexible liner was described at the NGWA September conference in 2004 in Portland, ME (Keller, 2004). Since then ~107 measurements of transmissivity profiles have been done in boreholes in fractured rock at 36 sites. Liner measurements were explicitly compared to straddle packer measurements in boreholes in a Geologic Society paper for a site in Guelph, Ontario (Keller,et al, 2006). The straddle packer measurement method has been in use for many decades and is described in the paper by P. A. Lapcevic et al, (1999) as applied to ground water measurements. Since an objective of the liner measurements is the same as one objective of straddle packer measurements (i.e., the measurement of the distribution of the flow paths in the formation), it is worthwhile to consider the similarities and differences between the two methods. The purpose of this paper is to describe the general strengths and limitations of the two methods.

The two methods

Similarities

Both methods measure the flow rate into a defined interval of the borehole wall. Both methods measure the driving pressure used to drive that flow. Both methods use the Theim equation to calculate the effective transmissivity of the defined interval and the average conductivity of the formation for that interval. Both methods strive to develop a steady state flow condition before measuring the flow rate into the hole wall. In these respects, the two methods are very much alike. However, there are significant differences in the implementation of the measurements of flow and in the definition of the interval being measured.

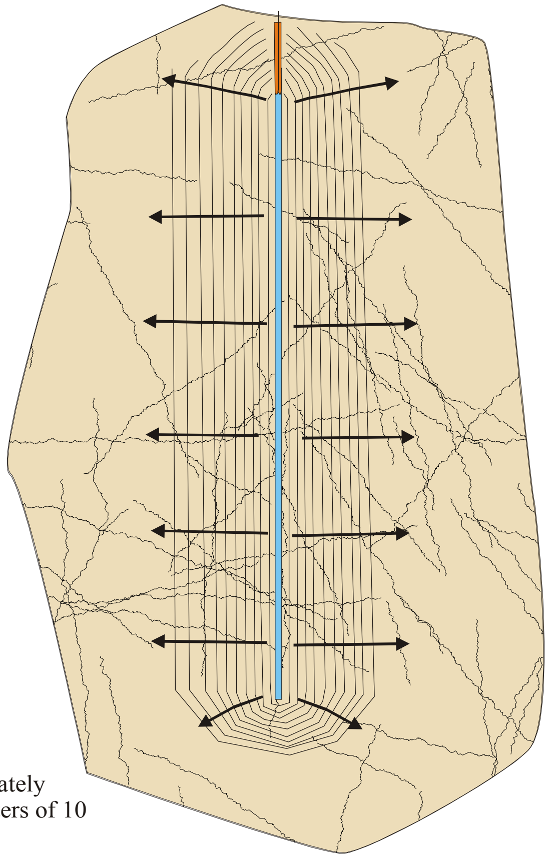
In summary, each method measures the flow rate per unit head, Q, into the defined interval of length, L, in the hole of diameter, $D = 2 r_o$, to calculate the transmissivity, T, in the same Theim equation. Hence, $T = L C = Q \ln(r/r_o)/(2 \pi)$, where r is the radial distance to the ambient head and r_o is the hole radius. C is the average conductivity in the interval L.

Differences

<u>The flow field</u>

The flow field developed by the two systems is usually very different. Fig. 1 shows the installation geometry of the liner as it is everted into the hole. The typical contour map of the pressure distribution in the formation shows how very long is the flow field developed by the liner. It also shows that the entire hole below the liner is at a uniform pressure, since the impedance to flow in the hole is essentially zero, compared to that of the formation. The flow field is very near the cylindrical one dimensional flow field assumed in the Theim equation as applied to both the liner and the packer calculation of the formation conductivity. With the uniform pressure throughout the hole, local fractures which do not connect to the far field are not measured because there is no flow in them.

Fig. 1. Everting Liner flow field



Appoximately last 5 meters of 10 cm hole

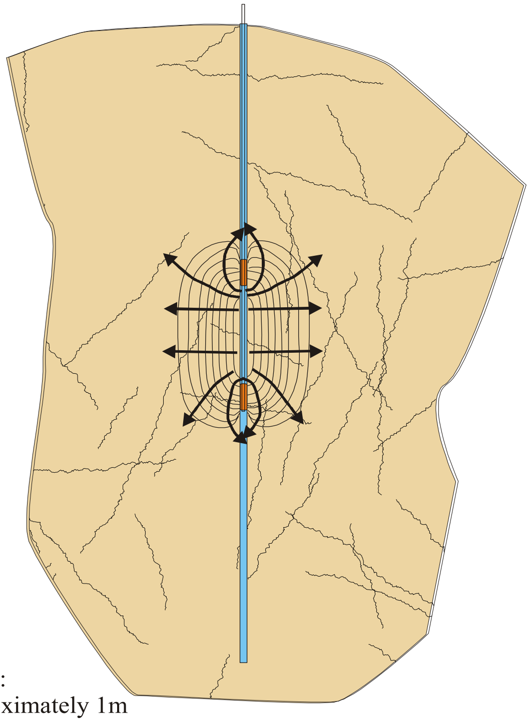
In contrast, the flow field

developed at a straddle packer interval, shown in Fig. 2, is essentially cylindrical near the center of the straddle packer, but at greater distance and near the ends of the packer, the flow field is not cylindrical unless all flow paths are horizontal planes with no vertical fractures. For the packer test interval, short local fractures that connect to the borehole beyond the straddle packer will be measured as part of the conductivity of the formation.

Potential leakage

In Figure 1, the nominal flow direction from the borehole is shown by the arrows to be horizontal. In Figure 2, the flow field diverges until at some distance it begins to appear spherical. The flow paths shown in Figure 2 can also be due to several forms of leakage possible with straddle packers. The first leakage path of concern is between the packer bladder and the hole wall. For a smooth hole wall and a packer without deep cuts or scratches, and properly inflated, the seal to the hole wall can be very good. However, a rough hole wall with the stiff rubber most common for packers are likely to allow some leakage to the open hole above or below the packer. The second leak path of concern is through fractures that intersect the straddled interval and also intersect other fractures that connect to the bore hole above or below the packer bladders. A third form of leakage is through the matrix rock if it has a significant conductivity even without fractures (e.g., a very permeable sandstone). These three potential leak paths combine to form a total leakage component in the total flow measured out of the straddled interval. Therefore, it is very important that straddle packer tests be monitored for leakage above and below the packers. If the monitoring is done with pressure transducers, it is difficult to determine the actual flow rate of leakage even if the pressure transducers show that leakage is occurring, because the pressure measured depends upon the transmissivity of the entire open hole above or below the packers. This concept of packer leakage is not new to the community and is one of the major concerns with the validity of packer testing. Any connection with the borehole above or below the straddled interval can frustrate head or water sample measurements with the packers. If there are no leakage terms, the more spherical flow field of the straddle packer is not so important, because the flow rate is dominated by the gradient and material properties near the hole wall.

Fig. 2. Packer Flow Field



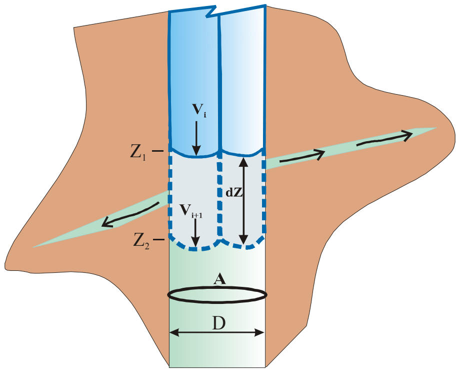
Scale:
Appoximately 1m
spacing in 10 cm hole

The obvious question is whether such leakage is also a concern with the liner measurements. In Figure 1, it is clear that it is not possible to bypass the liner to an open hole above. The entire hole above the bottom end of the liner is sealed by the liner. It is also true that the pressure inside the liner is slightly greater than the pressure in the borehole and that the liner is very flexible and conforms very well with the hole wall irregularities. This close melding of the thin (~25 mil) flexible liner with the hole wall is seen in videos of the interior of the liner in a hole. There is no downward potential leak path with the liner. The entire hole is open below the liner.

The flow measurement

The interval of the hole over which the liner flow is measured is defined by the distance traveled by the liner between two recording times (typically two seconds). That distance depends upon the liner velocity into the hole. The amount of flow into the interval is determined by the change in flow rate out of the hole between the upper level and the lower level of that interval. The flow rate out of the hole is the liner velocity multiplied by the hole cross section (see Fig. 3) Therefore Q, the flow rate into the defined interval is $(v_i\text{-}v_{i+1})$ x πr_o^2 . The change in velocity over the interval, $v_i\text{-}v_{i+1}$, is determined from the velocity profile for the liner descent in the hole. It is necessary that the velocity of the liner be measured very carefully without extraneous influences other than the transmissivity of the borehole.

Fig. 3. Liner Transmissivity calculation



Flow rate into the fracture, Q = $A(V_i\text{-}V_{i+1})$, where $V_i>V_{i+1}$
Transmissivity over dZ is: C x dZ= fctn(A, dZ, Q, ...)

The velocity profile of Fig. 4 for a typical liner installation shows very clearly where the liner velocity is changing. Figure 5 is the transmissivity profile calculated from the velocity profile of Fig. 4. The liner can pass through a highly fractured zone with an effective measurement of the transmissivity where a straddle packer seal can not be obtained. The velocity change over a highly fractured zone is a slope much like that obtained for a uniformly permeable material, rather than a step change. Flow rates as low as 0.004gal/min. and lower have been measured with the liner. The limit depends upon how long one wishes to prolong the measurement. Most measurements are terminated when the liner velocity drops below 0.001 ft/s or 0.04 gal/min for the remainder of the open hole.

Fig. 4. A typical liner velocity profile

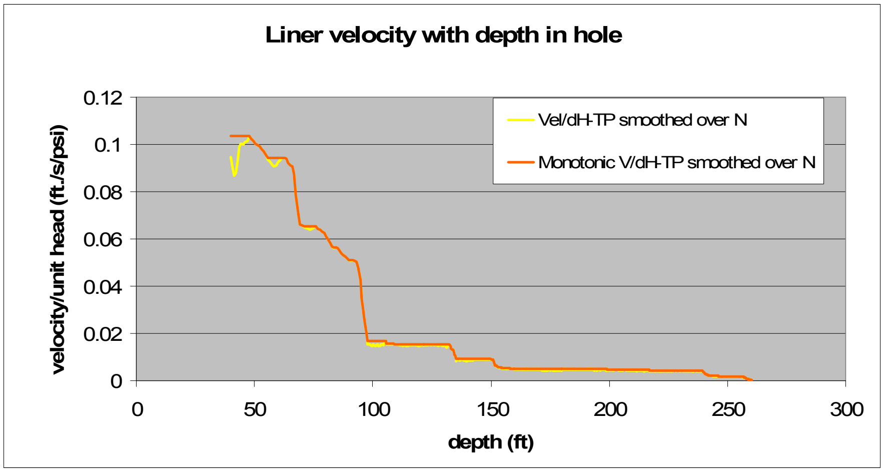
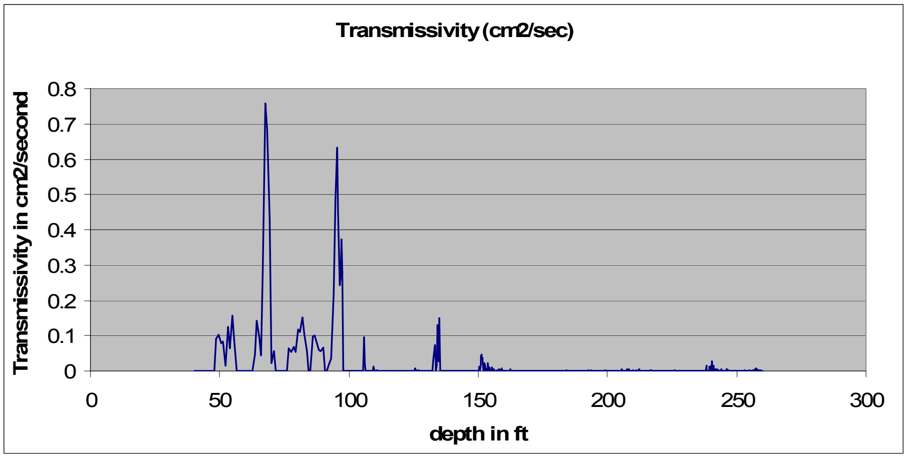


Fig. 5. The transmissivity from the liner velocity (Fig. 4)



In the straddle packer test, the flow rate into the straddled interval is measured in a much more conventional manner. The flow volume over a timed interval is measured to produce the flow rate. The flow measurement may be as simple as picking two levels on a sight glass on a graduated water column at precise times. However, a continuous recording is better to assess the achievement of a steady state flow. It is uncertain what the lowest credible flow rate is, but it is certainly lower than is usually measured with a liner.

<u>The driving head measurement</u>

The head in the packer test during injection or extraction is usually measured with a transducer in close proximity to the straddled interval.

The driving head in the liner is usually calculated from the water level measured inside the liner (the excess head above the water table in the formation), the measured tension on the liner, and the measured minimum eversion pressure obtained for each kind of liner and hole size. This inferred head beneath the liner has been compared to the measured head beneath the liner, and Fig. 6 shows the comparison. The match was much better than was expected and better than is important to the calculation of the transmissivity distribution in the hole.

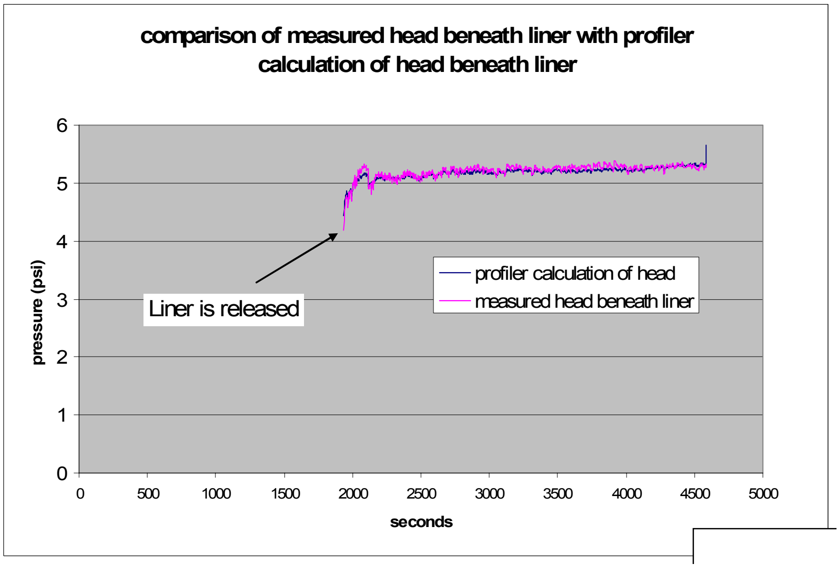


Fig. 6. The measured head beneath the liner is essentially the same as the calculated head from the liner parameters.

Transmissivity resolution

The liner transmissivity resolution is determined by the precision with which the velocity can be measured. That seems to be about 1-5% of the velocity at any time. That means that if the remaining borehole transmissivity beneath the liner is 1cm^2/s, the liner can resolve zones of about 0.01-0.05cm^2/s in that portion of the hole. However as the flow zones in the borehole are sealed, the velocity drops and the transmissivity resolution increases accordingly. Near the bottom of the hole, the transmissivity resolution can be as low at 0.0001cm^2/s or a conductivity of 1.0e-06 cm/s.

Without any leakage, a straddle packer can measure to much lower levels anywhere in the hole. However, it is noteworthy that at such low flow levels, any packer leakage can lead to significant errors in the measurement.

Therefore, the liner measurement is more useful in measurement of the major flow paths in the hole (i.e., those accounting for ~99% of the flow out of the hole).

Spatial resolution

The spatial resolution of the packer measurement is that of the straddled interval (typically 5-10 ft). Higher resolution adds to the number of intervals required to measure the entire hole.

The measurement resolution of the liner depends upon the velocity of the liner and the distance traveled in 2 seconds (the typical recording frequency). The resolution ranges from ~1ft in the top of the hole to 0.01ft near the bottom of the hole. Generally, the spatial resolution is better than one hole diameter. High angle fractures and permeable/fractured zones produce distinctly different velocity profiles from simple horizontal flow paths. The latter are more abrupt step changes in the velocity. Figure 4 shows the slopes and steps of those two features. The liner measurement usually has much higher spatial resolution than packer testing. Figure 5 shows the detail available from a liner measurement.

Time/cost to measure the hole

The typical 300ft borehole is profiled with a liner in about 2 hrs. If there is an interest in the measurement of a low conductivity zone in the bottom region of a borehole, the profile may take 7 hrs (the longest measurement ever done).

The packer testing with sixty 5 ft straddled intervals in a 300 ft hole usually takes several days.

Generally, the liner measurement requires about 10% of the time to perform packer testing of the same hole. Both measurements usually involve at least two people. The time to perform the liner measurement is not very dependent upon the hole depth. It depends much more on the velocity of the liner and therefore the transmissivity of the borehole.

Equipment required

The liner measurement requires a liner at ~$12/ft. plus the rental of a 150 lb machine and the use of a generator and compressor. A water source is required to fill the liner. The equipment (not the compressor and generator) is sometimes shipped via air freight to the site. The liner is usually left in the hole to seal the hole against cross contamination. The photo in Fig. 7 shows the profiling machine, control box and liner for an 8" hole. The recording laptop computer is in the bed of the pickup.

Fig. 7. The liner
Profiling machine

The packer measurement requires the same compressor and generator and water supply. The packer assembly can vary depending upon the hole size and packer spacing. A crane or tripod is used to support the down hole assembly of packer and pipe string. A van containing the water measurement system and winching assembly is shown in Fig. 8 for a 3.78" hole. The insert shows the interior of the van containing the pressurized water tanks and control system. The nitrogen tanks in the foreground are used to pressurize the packers. Generally, the packer measurement system is much larger and heavier than the liner measurement system.

Fig. 8. A 3.78" straddle packer measurement system.

Formation head measurements

The liner does not allow a head measurement as it is normally used. The straddle packer allows a head measurement of the straddled interval at each elevation.

The liner has been used in a "head profiling mode" instead of a "transmissivity profiling mode" at some sites, but that is not the usual application. The head profiling technique uses the measured tether tension when the liner is stationary at sequential depths to deduce the head beneath the liner. Formation head measurements are better made with the multi level sampling liner which is often installed after the blank liner is removed.

Unless the head distribution in the formation is known from other measurements, the profiling calculation assumes a uniform head in the formation. Because the driving head in the liner is usually much higher than the head in the formation, the error of that assumption in the conductivity calculation is usually small.

Sample collection

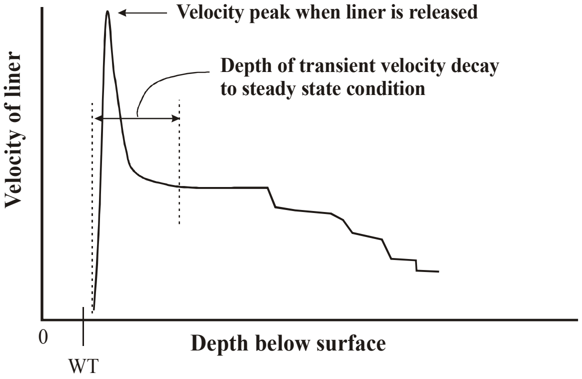
The profiling liner does not allow the collection of a sample. The straddle packer does. If there is a concern with the reliability of the packer sample because of the open hole, the use of the a multi level sampling liner which seals the entire hole does allow the collection of a sample with good isolation. However, that is a substantial cost increase for that system over the blank sealing and profiling liner.

Steady state condition

Since the Theim equation assumes a steady state 1-D flow condition, steady state should be obtained for both measurement methods. Steady state flow for the straddle packer system requires that one wait for that condition to develop with each straddle interval tested. For very conductive zones, that occurs quickly. For slow flowing zones, it can take a very long time. This time to develop the steady state for each packer interval tested can add substantially to the time for measurement of the entire hole. However, the error in the flow measured is probably not great if one is near a steady state condition.

Steady state for the liner measurement develops at a rate controlled by the entire hole. Since the measurement time is relatively long for most of the hole, the limitation is not significant for most of the hole. However, the steady state is not obtained instantly when the liner is first released at the top of the hole. Therefore, the upper portion of the hole is traversed by the liner as the steady state condition is still developing. That leads to an over estimate of the flow rate, since the flow into the hole wall decreases as the gradient out of the hole becomes less steep as the steady state develops. However, the even greater effect is that as the entire hole approaches a steady state, the velocity of the descending liner is decreasing because the flow rate out of the entire hole is decreasing. That decreasing liner velocity due to the decay to a steady state may be confused with the velocity decrease as flow paths at the top of the hole are being sealed by the descending liner. Figure 9 shows the transient velocity history after the liner starts down the hole. The net effect is that there is a “dead zone” at the top end of the hole where the liner velocity is dropping rapidly due to the approach to a steady state in the entire hole. In that interval, only the most dramatic flow paths are detectable as step changes in the velocity profile. Fortunately, that dead zone is only 6-18 ft long. If we are lucky, that dead zone occurs in the surface conductor and we do not miss any of the open hole measurement.

Fig. 9. The transient velocity



Because the time to steady state is relatively long for very low conductivity zones, and the hole is a mixture of high and low flow zones, there is a significantly long tail on the asymptotic decay to the steady state flow rate for most liner measurements. This long tail is seen in very long casing situations where the decay is not due to flow through the casing. Generally, that tail is insignificant in the abrupt velocity changes measured, but it must be considered in the data assessment at the top of the hole. Changes in the procedure are being considered to avoid or reduce the steady state dead zone at the start of each measurement. That effect is also being explored with time dependent flow modeling at the University of Guelph (Beth Parker, personal communication, 2007). There is probably useful information on the aquifer in the transient. See G. Flach, et al (2000) for a discussion of the duration of the transient for flow meter testing.

Once the liner has passed through the transient part of the steady state development, the rest of the hole is measured under a well developed steady state condition.

Hole size

Liners are custom built to each hole diameter. The liner cost is the same from 4-8 inch diameter. It is about $2/ft greater cost up to 12 inch diameter. Even larger holes are practical with the liner technique. Liner measurements are best done in 4 inch diameter holes or larger. Enlargements in the borehole are not significant to the data quality. The liner everts through enlargements and measures the transmissivity of the enlarged interval. Highly fractured zones are measured equally as well as less fractured zones.

Packer tests are done with bladders of fixed size. Three inch diameter packers are available. Above 6 inch diameter, the packer system weight and cost are such that they are less commonly available. The packer can not seal an enlargement and therefore must straddle any significant enlargement in the borehole. This makes packer placement very important. Highly fractured zones can not be measured with packers which do not straddle the entire fractured zone.

Risk of entrapment in the hole

The risk of entrapment of the packer assembly in the hole during the frequent inflation/deflation and the raising and lowering of the packers is a serious concern in that the movement of the packer hardware in the borehole may cause a slough of the wall material on top of either packer. Because of the small clearance between the packers and the hole wall, the slough can lead to the loss of the entire packer assembly, and also the entire hole, if the packer can not be removed. It may be possible to drill out the packer assembly and piping if it is constructed of mainly plastic materials.

The everting liner does not touch the hole wall until it is supporting the hole wall during installation. During removal the inverting liner supports the hole wall until the liner has been inverted. A profiling liner has never been entrapped in a borehole due to slough of the hole wall or any other mechanism with over 100 measurements in different holes in primarily fractured rock.

Other differences not addressed in this paper

The actual effective implementation of each method involves procedures that are quite different for the two methods and beyond the scope of this basic method comparison. Some of those features for packers are: packer construction, packer inflation pressures, optimum flow rates and driving pressures, use of other geophysical measurements and borehole videos for correlation with the data. How packers can be monitored for leakage is not addressed. Use of packers for cross-hole hydrologic tests is not addressed, but it has been done.

For the liner measurement, the features not addressed herein that may influence the data quality or procedure are: hole diameter, depth of the water table, liner removal procedures, the distribution of the transmissivity in the borehole, data reduction methods, correlation as possible with other borehole information, and liner construction. Liner systems have been used for cross-hole hydrologic tests. These subjects have been addressed in previous papers or they are being addressed in projects in progress. The details of the entire liner measurement method are described in much more detail in a paper in preparation on the liner hydraulic conductivity method (C. Keller, et al, 2007) to be offered to a juried journal. That paper addresses much more explicitly the comparison of results to other measurement methods and the fine points of the liner measurement method.

Interesting comparisons not addressed in this paper are those of the liner technique with other methods such as vertical flow velocity logging, single packer testing, and other conductivity profiling methods (e.g., Hydrophysics™) that have been in use since before the liner technique was devised. However, two generalizations are offered: none of these other methods provide a seal of the borehole when the measurement is finished and they usually take more time to perform the measurements. They do usually provide information on relative head differences albeit in the unnatural situation of an open borehole.

Similarities and differences of the two methods are summarized in Table 1.

Table 1. Comparison of various aspects of liner and straddle packer measurements

(Assumes: 300ft. hole, 4-6 inch diameter, measurement of the entire hole)

Parameter	**K Profiling liner**	**Straddle Packers**
Spatial resolution	1 inch to 1 ft. (velocity dependent)	5 ft typically smaller spacing adds time
Time for measurement	2-4 hours (relatively independent of hole depth)	2-6 days (directly dependent on hole depth)
Range of measurement	4.0e-07m/s to 1.0e-03m/s	4.5e-08m/s to 2.0 e-04m/s or less with good seal
Borehole size limits	Any size above 3.5 inches	Depends upon packer Availability
Seal bypass potential	none	Significant concern

Time hole is open for cross connection	2-4 hrs	2-6 days
Seal of borehole afterwards	Sealing liner left in place	None, to intermittent seal
Meets Theim assumptions	Very good	Uncertain to good
Head measure. capability	None[+]	yes
Sampling capability	None[+]	Possible
Cost per hole. *(2 travel days plus field time)*	$2000 +$12/ft+3 days of travel exp ($12/ft +$850 for second hole in same day)	$5120 + rental of equip.+6 day travel expenses (single hole of 300ft/4 days, 60 test intervals)
Equipment needs	~500# of equipment (Including liner)	crane truck or tripod, van, plus packers and piping

+sampling and head measurements are available with the flexible liner multi level system.

Conclusion

This paper is a more general comparison of the methods of the two measurement techniques and not a comparison of results. Table 1 is a brief comparison of the two measurement methods which may be helpful in the selection of the appropriate method for the particular data needs.

Both methods use the Theim equation/model and assume 1-D cylindrical steady flow for the calculation of the conductivity from the measured flow rate in a specific interval of the hole. The method of flow measurement, the flow field, and the range of the measurement are quite different for the two methods.

The normal spatial resolution, the cost, and the utility in highly fractured or large diameter holes are usually better for the liner technique. The initial transition to a steady state when the liner is first released to propagate down the hole causes the potential loss of a short portion of the borehole measurement unless that transient is effectively completed within the surface casing.

The straddle packer method is capable of much lower conductivity measurements, head measurements and sample collection in the open hole. That is not true for the blank liner. The potential for leakage makes straddle packer measurements unreliable in each of these applications unless there is some form of monitoring to identify the existence and amount of leakage.

The liner measurement is more difficult in the combined situation of very small holes, deep water tables (>100ft), and high transmissivity. It is left to other publications to address these features in more detail. The packer measurement is less practical in large holes (>6 inch diameter) and very deep holes can be quite expensive to measure over their entire length with packers.

Acknowledgement

The graphical results from liner measurements are graciously provided by some of FLUTe's customers who allowed the early testing of this method. Discussions of this method with Dr. Cherry and Dr. Parker of the University of Waterloo and Quelph University respectively have been very helpful in the refinement of this method. The field comparison data from the same sources has been especially appreciated.

** note the FLUTe hydraulic conductivity profiling technique described in this paper is patented as US pat. no. 6910374 B2, and numerous foreign patents are pending or approved.*

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Biographical Sketch of author

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