How to locate, and flow test, every major fracture in a borehole in one hour

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Abstract

A new method has been developed for measuring the flow paths intersected by a borehole. The method uses a flexible, everting liner to drive the water from the borehole. The velocity of the propagation of the liner down the hole decreases as the everting liner seals the flow paths sequentially from the top to the bottom of the hole. Using the velocity of propagation, the excess head driving the liner, and the other measurements of significant parameters, the flow rate into each flow path is calculated. That flow rate is used to define a transmissivity profile for the borehole. Results of measurements with the method are shown for numerous sites. This method is compared to traditional straddle packer techniques to illustrate the similarities and differences. The liner method compares very well to measurements made with packers. The main differences from straddle packer testing are: there are no concerns about bypass leakage, the technique uses 5-10% of the time typically required for packer testing, the spatial resolution of flow paths is far better than possible with packer testing, the liner is usually left in place to seal the entire hole against cross contamination, there is less risk of hole slough entrapping the liner. On the other hand, the liner method, by itself, does not produce water samples for testing. The time to perform a measurement depends more on the flow rate out of the hole than upon the depth of the hole. Small diameter holes are measured more quickly than large diameter holes. The limitations of the method are reviewed with respect to hole size, depths possible, differential pressure limits, and others. Generally, these are not very limiting to most environmental applications. The technique is being extended to possible use in direct push holes with flexible liners emplaced for other purposes*.

The Problem Addressed

Most ground water problems are aided by a good understanding of the existing flow paths. Measurement of those flow paths is central to the science, and the subject of this paper.

Flow path measurements range from simple slug or pumping tests to many other measurements, some of which are broadly collected under the term geophysical measurements. Examples are gamma, resistivity, sonic, and other logs related to the stratigraphy, but not really flow path measurements. Others like caliper, sonic tele-viewer, thermal, chemical, and optical logs tend to locate fractures and beds, but they also are not flow measurements. Natural velocity logs, pumped velocity logs, and packer tests are flow measurements. These measurements are all performed in boreholes, the common means of access to the subsurface.

The method described hereafter is offered as an alternative to pumped hole velocity logs and to straddle packer tests. The advantages are the lower cost, better spatial resolution and collateral benefits. The collateral benefit is the sealing of the borehole against the vertical migration of contamination.

The method in general

The long name for this method is the flexible liner hydraulic conductivity profiler, FHCP. The process is the forcing of water into every flow path, at a known pressure, and the measurement of the flow rate. That sounds like a straddle packer test. Throughout this paper, there will be a comparison with straddle packer methods to illustrate the similarities and the differences.

The process is to install a flexible, everting liner into the borehole. The liner is driven by an internal pressure. As the liner everts (a term that will be explained) down the hole, it forces the borehole water into the formation. The essence of the method is the measurement of the flow into every “significant” flow path as the liner progressively seals the borehole from the top to the bottom. The advantages are the location and hydraulic conductivity measurement of all significant flow paths in the borehole in one-half hour to several hours, relatively independent of the hole depth.

The method in detail

First, one must understand how an everting flexible liner is installed in a hole. The flexible liner installation procedure is shown in Fig. 1. The liner is fed, inside out, from a shipping reel at the wellhead. The open end of the liner is clamped to the casing and the liner is then pushed down into the well. Water is added to the concentric pocket formed by the liner. The water pressure forces the liner deeper into the hole. When the liner reaches the water table in the hole, the water in the hole is forced out of the hole by the pressure of the descending liner. Since the liner is everting (the opposite of inverting) as it rolls out against the hole wall, the liner does not slide against the hole wall. Rather, it grows in volume at the bottom end, which we call the *eversion point*. As the liner grows in length at the eversion point, it forces the water in the hole out the available flow paths. As the liner descends, it sequentially covers the flow paths. The liner descent rate is controlled by the rate that water can flow from the hole into the formation.

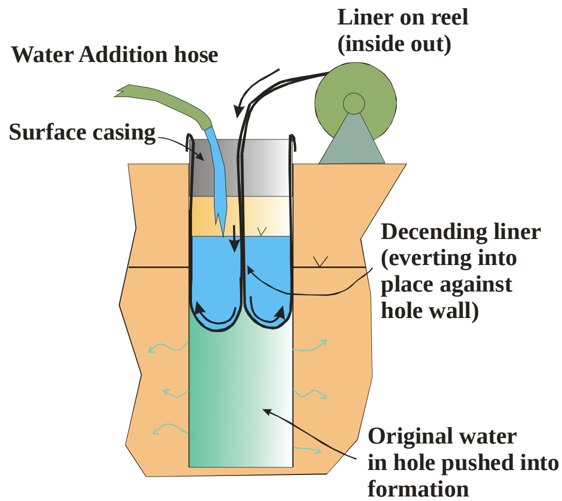


FIGURE 1. Blank liner installation

This blank liner installation is relatively simple and is often done by someone standing at the wellhead with a water hose to supply the water. Often a chair is desirable for that person to be comfortable while the liner descends, pulling itself off of the reel. It takes little effort on the part of the installer. (See Fig. 2 for an installation of a liner in Maine. The operator is switching a pump as needed to keep the liner filled to the top of the casing as the liner descends.) As the liner descends, it slows as the available flow paths are sealed and the remaining transmissivity decreases. The liner descent rate is usually dominated by the hole flow path distribution, the conductivity of those flow paths, and the rate at which water is supplied to the interior of the liner. The liners are removed by the reversal of the procedure.

FIGURE 2. Liner installation

By adding a distance meter to the liner installation, Fig. 3, and a measure of the excess head in the liner above the water table in the formation, we convert the normal blank sealing liner into a flow meter. The flow measured is the flow rate out of the hole. The liner of cross-section A, as shown in Fig. 4, is displacing the water downward with a velocity v_z. The flow rate out of the hole is $Q = v_z \times A$. As the liner propagates, it covers the flow paths sequentially. When the liner travels down the hole, the pressure distribution in the hole below the liner is that shown in Fig. 5A. It is a uniform overpressure throughout the open hole, and there is no overpressure where the liner has sealed the hole. Under the uniform overpressure, flow is occurring out of all unsealed flow paths below the liner. The transmissivity, T(z), below the liner is due to all the unsealed flow paths. As the liner eversion point depth, z,

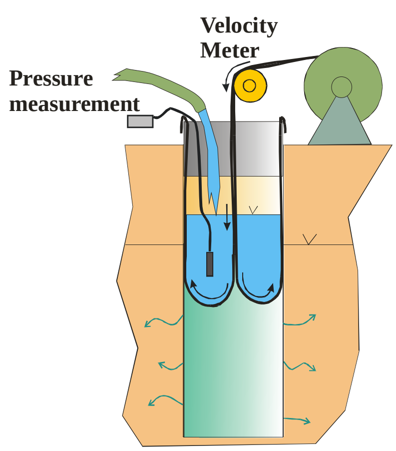


FIGURE 3. Additional measurements to convert a blank liner installation into a profiling device

increases, T decreases.

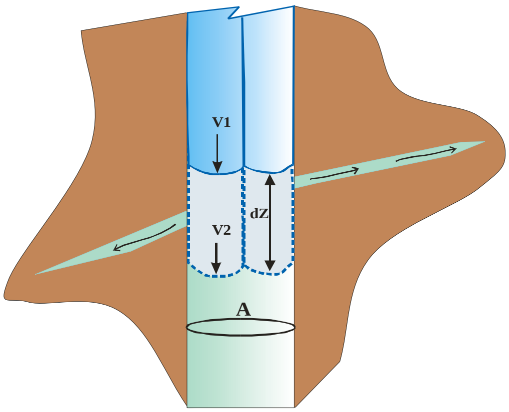
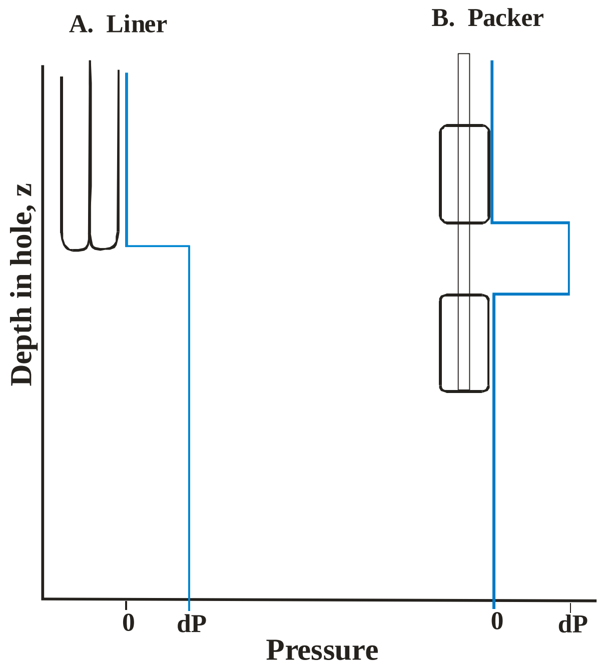


Fig. 4. Liner passing a fracture

When the liner seals a flow path, the transmissivity drops by an amount dT. There is a corresponding drop in the flow rate out of the hole dQ = A x dv_z, where dv_z is the drop in the velocity of the liner propagating down the hole. As the liner depth, z, increases, T decreases. Another way of saying that is that the velocity v(z) is monotonically decreasing as the liner moves more and more slowly down the hole.

Fig. 5. Pressure distribution with liner and packer



We measure the velocity of the liner propagation down the hole to obtain a velocity with depth curve as seen in Fig. 6 (a hole in Paterson, NJ). The velocity is monotonically decreasing as the liner propagates to the bottom of the hole for a constant excess head in the liner. If the liner excess head is varying, the velocity will actually increase as the head increases and decrease as the head decreases. Since this is essentially a linear relationship, we simply divide the velocity by the driving head in the liner to get the velocity per unit driving pressure. That velocity is the one that should be monotonically decreasing. That is what is plotted in Fig. 6.

One can easily see in Fig. 6 where the step changes occur in the velocity. Each step is the location of a flow path. The magnitude of the velocity change is a direct measure of the flow rate into that flow path before it was sealed by the advancing liner.

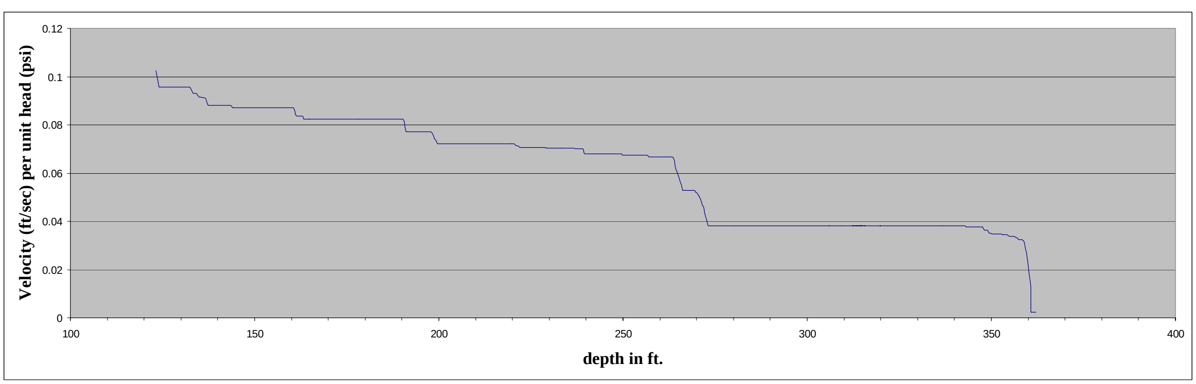


Figure 6. Liner velocity profile in hole

The liner velocity is typically measured every 2 seconds. The excess head, the liner driving force, is recorded at the same time. The pressure in the water below the liner is essentially that in the liner, if the liner is fed freely into the hole. In reality, the liner has some tension on it and the pressure below the liner is calculated as a function of the tension on the liner.

Once the flow rate, the driving pressure for the flow, and the location of the flow path are in hand, we can calculate either a transmissivity distribution (the preferred result) or a conductivity distribution in the hole, and plot it as seen in Fig. 7 (the conductivity). The transmissivity is independent of the liner velocity, but the length of hole assigned to the conductivity calculation depends upon the liner velocity. However, both are correct within the mathematical definition. As the liner passes a permeable bed, the velocity change will occur over a longer interval as a slope in the velocity curve rather than a step change. In the measurement, it is a series of small step changes.

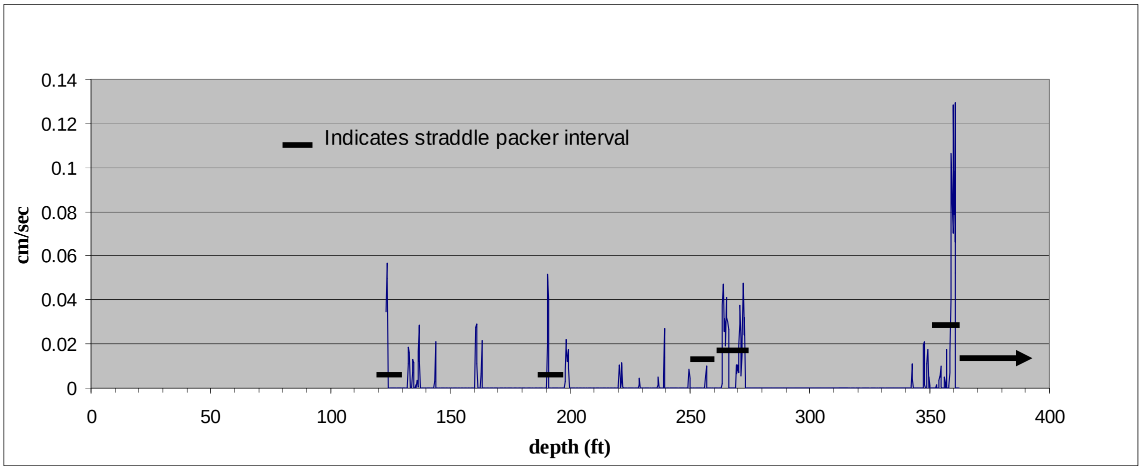


Figure 7. Conductivity profile from velocity profile

It is noteworthy that the conductivity plot of Fig. 7 calculated from a real velocity plot, Fig. 6, shows very fine spatial details of the flow path distribution as well as flow capacity. The very large flow path at 360 ft is obvious in the velocity curve.

Comparison with Straddle Packers

We were provided with straddle packer tests results after we performed the measurement in Fig. 6. The packer tests were done before the liner installation. Fig. 8 shows the integration of the detailed liner measurement over the same interval as the packer test, plotted with the packer test results. The results from this early test of the method were quite satisfying.

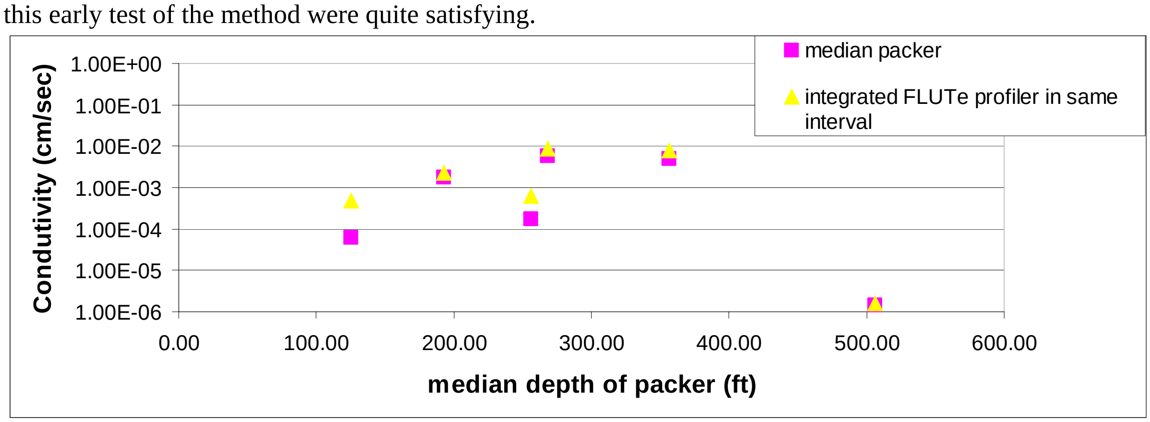


Figure 8. Comparison of straddle packer results to FHC Profiler results

So, what is different from a packer test? First, there is the time to perform the measurement. The measurement of the data in Fig. 6 was done in about 1.5 hr. for 370 ft of hole. A measurement of a hole in Cambridge, Ontario took ~36 min. for 328 ft. That same hole had a complete suite of packer tests over its entire length that took two people, four days. The set up time in each case is about an hour. In other words, it takes only 5-10% of the packer testing time to perform the blank liner installation. The longest liner profiling done to date is 4 hours. That was because of the desire to measure to very low transmissivity levels in a hole with very low flow out of the bottom quarter of a 400 foot hole (those results are shown in the Field Test Results section hereafter).

The time it takes to profile a hole is dependent upon the transmissivity of the hole. That factor is more important than the depth of the hole. Therefore deep holes are often measured in less time than some shallow holes.

Another difference from packer testing is that the liner can be sized to fit any size hole and an undersize hole (e.g., 7”) can be measured using a larger liner (8-9”) without significant effect. The smallest practical size is probably 2” diameter for the current liner fabrics and measurement equipment. The smallest done to date is less than 3.78 inches.

Another comparison with a straddle packer is shown in Fig. 5B. The pressure profile in a packer is high in the straddled interval and ambient above and below. Therefore, there is a tendency for the injected water to try to bypass the packer by flowing upwards or downwards into the open hole beyond the packers. That flow, called leakage, may be via the formation through fractures or matrix permeability, or between the packer and the hole wall (e.g., a rough hole wall). Such bypass is unlikely for a liner because there is no open hole above the bottom end of the propagating liner. The liner is far more flexible than packers, and therefore conforms quite well with the hole wall. Figure 9 is a snapshot from a video of the interior of a liner showing how very well the liner conforms. It looks like it is painted on the hole wall.

During the liner installation, the liner displaces only one hole-volume of water, no more or less. The integral of the flow measurement is correct. For packers, the total flow measured includes a leakage component that can be large, or small, depending upon hole ruguosity and/or formation permeability where the packer is set. Hence, the packer testing provides only an upper bound on the transmissivity of the straddled interval. If another set of guard packers is used (i.e., 4 packers) with pressure transducers, some of the leakage affects can be detected, but the correction for leakage is not practical

Fig. 9. Interior view of liner conforming to hole

In packer testing, one can inject water or extract water to perform the packer test. The highest extraction rate is usually limited by the size of the pump that can be placed down hole through the access pipe. There are no serious limits on the flow rates (conductivities) that can be measured with the liner system. The limit is how fast water can be poured down the open hole.

The installation of a liner is very gentle with respect to hole stability. The liner roles smoothly out against the hole wall, supporting the hole wall material against sloughing. When the liner is later removed by the reverse process (inversion), the liner is gone when the hole wall is no longer supported. The significance is that the liner is unlikely to be trapped in the hole by sloughing of the hole. In contrast, the scraping of the hole wall with the installation, inflation, deflation, and repositioning of the straddle packer assembly is much more likely to cause the hole wall to slough. Entrapment of a straddle packer assembly is a very real concern of straddle packer testing. The consequence is not only the loss of the packer assembly, but sometimes the loss of the hole.

One disadvantage of the liner method is that one can not obtain a sample from the blank liner measurement. However, there is no contaminated-water disposal cost either. There are flexible liner sampling systems available that do collect samples and measure the head at each sampling interval. That is the subject of other papers at this conference.

The realities of field tests and results

Whereas the concept of the liner measurement is quite simple, the implementation requires some diligence. The machine built to perform the measurements is shown in Fig. 10. This machine measures: the position of the liner, the tension on the liner in time, and controls the tension of the liner to a preset value. That data, plus the head measurement inside the liner, is recorded in a lap-top computer every 2 seconds, or as often as desired. A spreadsheet in the same computer converts the raw data to the plots which are shown in this paper.

Most of our customers purchase a blank liner to seal the hole against vertical flow and associated contaminant migration immediately after the hole is drilled. Measuring the velocity of the installation is a simple addition to the normal installation of a sealing liner.

Other results of actual field measurements are shown in Fig. 11 for a site in Paterson, NJ and in Figs. 12 and 13 at Media, Pennsylvania. The time to collect the data is shown on the graph. The velocity graph alone is a very good identification of the significant flow paths.

Fig. 10. Profiler machine over 8" hole

Like a pumped-hole velocity profile, the limit of the FHCP resolution is depth dependent. At the top of the hole, where the liner velocity is higher, the resolution is less than at the bottom of the hole. Fortunately, for many geologic sites, the upper most portion of the bedrock is also the most fractured with the largest flow rates and is not limited by the resolution of the method. At the bottom end of the hole, the resolution is extremely high (sub inch) in space and very low flows (< 0.001 gal/sec).

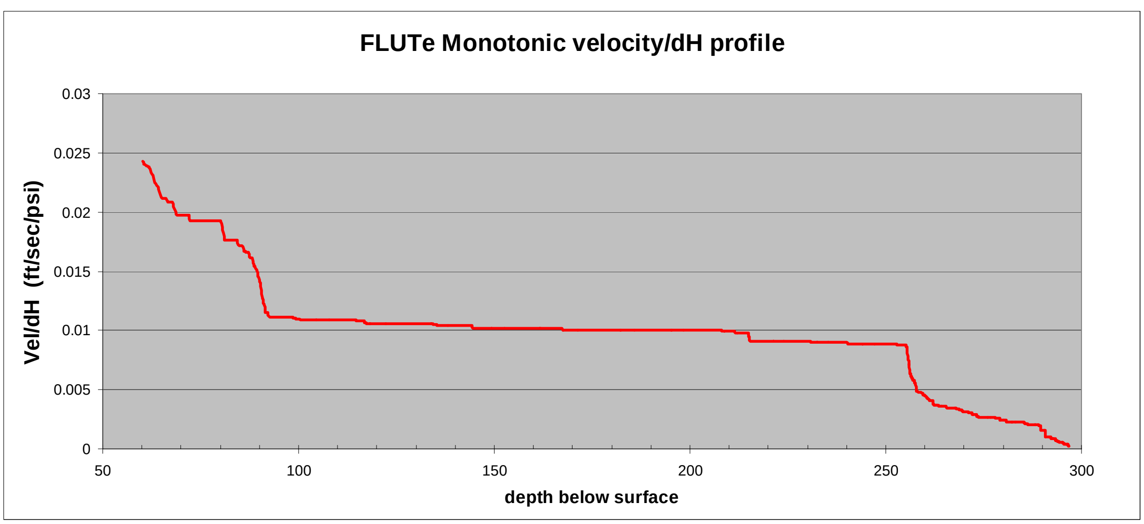


Fig. 11. Profile in 4" hole in Paterson, NJ

Unlike pumped hole velocity profiles, there is no limit on how fast the hole is "pumped" for the liner installation except for how fast water can be poured down the hole. This has an important significance in that the excess head typically is much higher in the liner than the natural head in the hole, and so all flows are outward from the hole with no confusing inflow zones to violate the model. The use of a water flow rate capable of maintaining at least 10 ft of excess head is desirable.

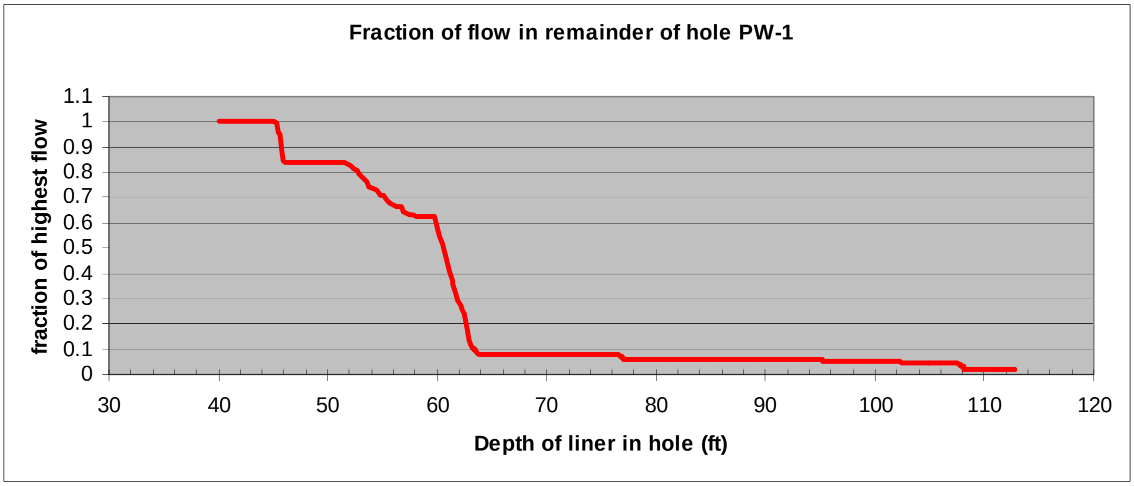


Fig. 12. Profile measured in 200 ft hole in ~3 hrs.

Later, measurements of actual head distribution in the formation (e.g., using a multi level system) can be incorporated into the calculation of a refined transmissivity distribution in the hole. The initial assumption is that the head in the formation is constant.

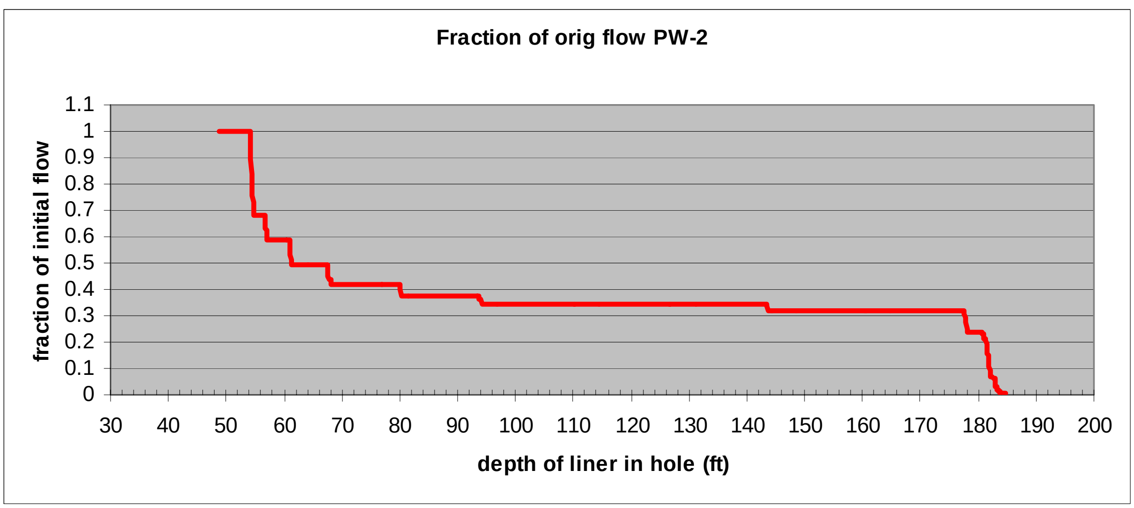


Fig. 13. Profile measured in 185 ft hole in ~30 minutes.

This kind of measurement was first done with our linear capstan system which can pull liners out of holes with 1000 lb of force while measuring the tension and velocity of the liner. Since then, there have been continuing improvements in the procedures and the hardware to obtain better and better sensitivity of the measurement. The data shown was obtained with the state of the art 6-12 months ago. Much has improved since then.

Mathematical models have been developed which can now predict the liner descent velocity based upon estimates of the conductivity profile. This is very useful in assessing the effects of the many variables on the installation such as hole diameter, depth, conductivity, excess head, and friction. Small diameter holes can be profiled more quickly than large diameter holes intersecting the same flow paths because the liner displaces one hole volume, or most thereof.

There is always a question of how this method will work with different conditions. There is no theoretical limit to how deep these liners can go in a hole. The practical limitations are the differential pressures that the liner may experience with great depths. The liner will burst at about 65 psi, if unsupported, in a 6 inch diameter. That is about 150 ft of excess head. Smaller diameter holes can withstand higher differential pressures. The liners propagate through most breakouts quite well. A very large, eccentric breakout with a flat floor can stop the liner, but rarely does. For very deep water tables, there is a certain amount of adhesion of the wet inverted liner against the everted liner. There are several procedures for reducing that effect. Overall there are a wide range of ordinary conditions in which this technique works very well.

Extensions of the method

We are currently working on an FHCP system which will measure the same flows while the liner is being withdrawn. This has an attractive application for our NAPL FLUTe system liners which are installed through direct push rods. Those slender (2.5-3") liners may allow the measurement of the hydraulic conductivity in soft sediments (i.e., no stable hole required) as the liners are being inverted <u>out</u> of the hole. The primary purpose of those liners is to map the DNAPL pure product distribution. The conductivity profiling would be helpful to the remediation design.

Conclusion

The FHCP is a simple concept that has been well tested in the field, and has been shown to be a very convenient and inexpensive means of measuring the significant flow paths intersected by a borehole. The data produced is much more detailed than is obtained with normal straddle packer tests. The limits of resolution are already very good and are getting better with refinements of procedures and hardware.

The largest cost of the method may be the liner. In clean holes, liners are easily reused (just pull/peel/invert it out of the hole). In contaminated holes, the liner is left in place to seal the hole as long as desired. Typically the flow data is used to select the sampling intervals for a multi level sampling system which can measure head and water quality. We often pull the blank and install our flexible liner multi level sampling system in the same day.

The characteristics of the FHCP make it a very attractive alternative to conventional packer testing. One does not need to select where in the hole the test is to be performed, because the whole hole is easily measured. In combination with the ability to provide a long term seal of the hole by leaving the liner in place, the system seems to have very good utility.

Acknowledgements:

We are very thankful to those who provided the holes for our initial tests and refinements. We are especially thankful to those who also provided other information like packer test results, and video logs of the holes for comparison with the FHCP measurements. These were mainly contaminated sites and not eager for public recognition, but we thank them none-the-less. One research site of the University of Waterloo has been especially useful to our testing of this concept.

* Patents are pending on this method and apparatus in the USA and abroad.

Carl Keller, received a BS in Physics and in Math from Valparaiso University and an MS in Engineering Science from Rensselaer Polytechnic Inst. He spent 3 years developing nuclear reactor calculation models and 25 years designing containment systems for underground nuclear tests. For 10 years he was in charge of all research and containment design for all DOD underground nuclear tests. For 15 years he has developed applications of flexible liners for underground measurements. He received the R&D 100 award in 1994, and holds 12 patents mainly on flexible liner methods. He is owner and principal scientist for Flexible Liner Underground Technologies, FLUTe, 6 Easy St., Santa Fe, NM 87506, carl@flut.com, 505-455-1300, fax 505-455-1400.