Practical Use of Flexible Liner Transmissivity Profiling Results

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Abstract : The FLUTe hydraulic conductivity profiling technique first published in 2004* has now been used in over 200 boreholes at 43 sites under a wide variety of conditions. Most applications have been at chlorinated solvent sites in fractured rock where detailed information on transport paths is especially useful for a wide range of remediation and monitoring designs. The method uses a flexible liner to map the transmissivity distribution of the formation intersected by an open borehole. There have been many refinements in the method in the last 5 years. However, the most common problem now is the general understanding of the application, both its utility and limitations of its use. This is largely due to the fact that this is a new method and many hydrologists have not used the method in their traditional practice. With the ever growing experience in a wide variety of geologic and hydrologic situations, it is now possible to judge when the method is most relevant. The measurements are usually quick (~2-3 hrs. per hole) and usually produce excellent data. This paper will explain why larger diameter boreholes are easier to measure than small diameter holes. The small holes can be more problematic when performed in situations of extremely large vertical gradients and extremely high formation conductivity. Very deep water tables (greater than 100 ft) are more difficult than intermediate water table depths. Shallow water tables usually require an extension of the casing. The measurement has higher spatial and conductivity resolution in the lower portion of the borehole than in the upper portion of the borehole. That high spatial resolution can be misleading if the transmissivity result is only plotted as it is measured over a variable interval. A technique is demonstrated for graphic representations that make the results more useful for assessment of the relatively high flow zones. The same graphical technique makes the results directly comparable to straddle packer measurements and more useful in numerical modeling. Limits of the conductivity resolution are described as they have been observed from actual experience. Data tests for self-consistency are explained. The most complementary traditional measurements are described and the need for those is explained, including which measurements are best made prior to the transmissivity profile and which are useful after the profile.

(*Method developed and patented by FLUTe: no. 6910374 and 7281422)

Introduction

The flexible liner measurement of borehole flow paths is a relatively simple method in concept (Keller, 2004; Keller, et al, 2010). The practical application of the measurement concept has required a special effort to design the equipment and to refine the procedure to reduce the influence of uncontrolled parameters. Once that was achieved, the verification of the results for practical situations by hydrogeologists became necessary. Since the method is only about 6 years old, it is not part of traditional practice nor yet taught in many universities. The obvious questions are how does this method compare to other methods of measurement and how are the measurement results best applied to the problem of understanding flow in the subsurface, mainly in fractured rock situations? What are the limitations and what are the advantages? This paper addresses those questions.

The general method description has been presented at numerous conferences and the comparison with straddle packer measurements is addressed in detail in a paper submitted for publication (Keller, et al, 2010). That will not be repeated here beyond a simple description of the method. The focus here is how one can use the results of the measurement in the form provided.

The profiling method

The profiling technique uses an everting borehole liner to displace the water in a borehole as shown in Fig. 1. The everting liner is driven by the addition of water to the interior of the liner and as the liner descends by eversion (the reverse process of inversion), the water in the borehole is driven continuously into the flow paths available such as fractures, permeable beds, or the matrix rock. The water level inside the liner is maintained at a constant level well above the water table in the formation and that over-pressure dilates and drives the liner down the hole. The liner is fed from a reel adjacent to the wellhead. The descent rate of the liner is governed by the excess head in the liner and the transmissivity of the borehole beneath the liner. It is obvious that the liner descent rate (velocity of the everting bottom end of the liner) multiplied by the cross sectional area of the borehole is equal to the flow rate out of the borehole beneath the everting liner.

As the liner descends, it seals the borehole. That sealing process covers the borehole flow paths, sequentially, from the top down. Each time a flow path is covered, the transmissivity of the hole beneath the liner is reduced and therefore, since the driving pressure is essentially constant, the liner velocity (flow rate out of the remaining borehole) is reduced. A careful measurement of the liner descent rate produces a monotonically decreasing flow rate with depth in the borehole. As each flow path is sealed by the liner, it produces a distinct drop in the liner velocity curve at the elevation of the flow path just sealed. That drop in velocity identifies the elevation of the flow path. The change in liner velocity is a measurement of the flow rate out of the hole at that flow path and hence a measurement of the flow into that flow path prior to its being sealed by the liner. In this manner, the descending liner is used to measure the location and the flow rate of the significant flow zones in the borehole.

As the liner everts through the borehole, it eventually seals all of the significant flow paths and the liner velocity (i.e., the flow rate out of the borehole) drops to such a low rate that the measurement is terminated, and the transmissivity of the remaining unsealed hole is calculated from the final small velocity.

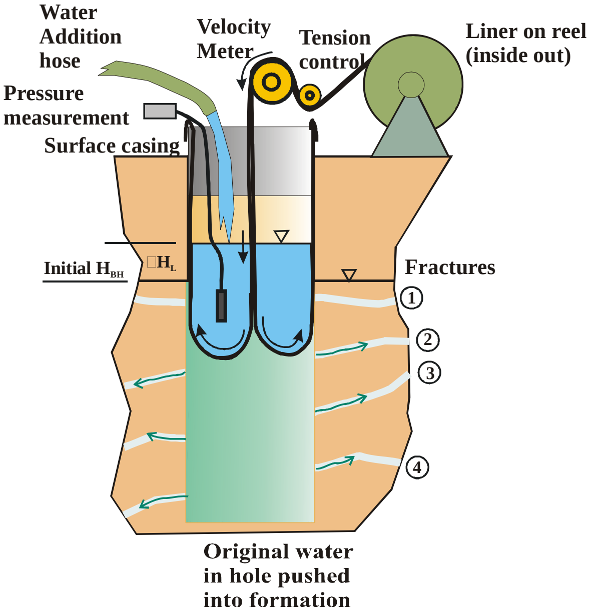


FIGURE 1. Measurement Geometry

The results

The measurement method records the depth every one-two seconds, the driving pressure interior to the liner (the excess head), and the tension on the liner at the wellhead. The driving pressure in the borehole beneath the liner is often measured with a recording pressure transducer at the bottom of the hole prior to the liner installation. These measurements at discrete time intervals are used in the calculation of the flow rate out of the borehole per unit borehole driving pressure as a function of liner depth in the hole. A typical result is shown in Figure 2. From that flow rate with depth curve, the transmissivity distribution in the borehole is calculated (Figure 3).

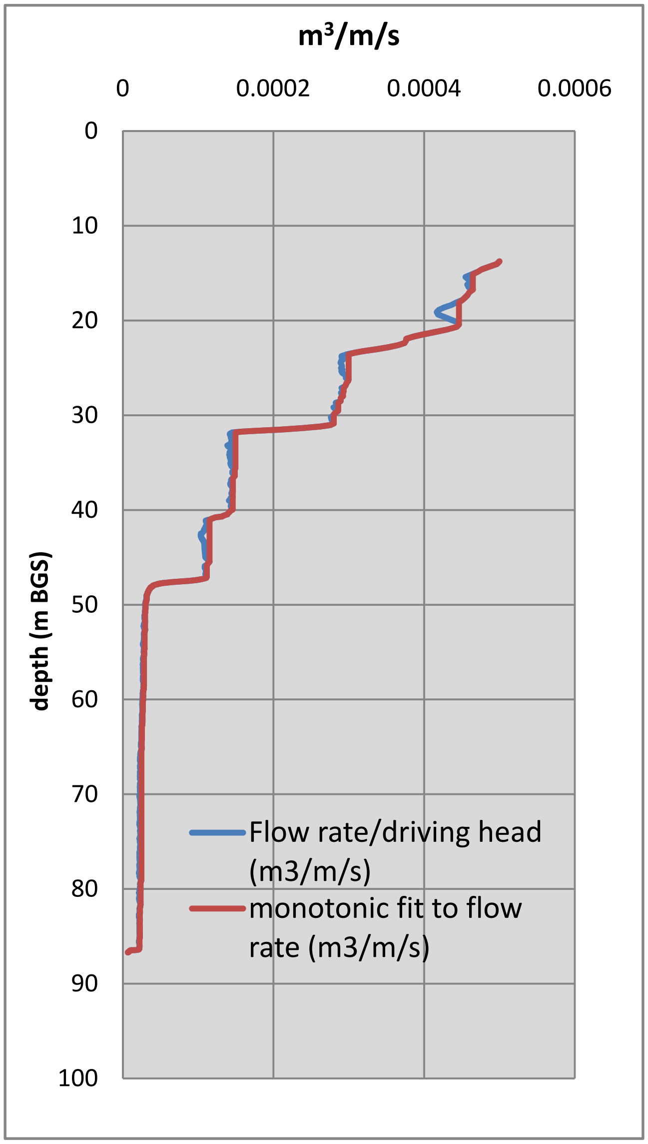


FIGURE 2. Flow rate vs. liner depth

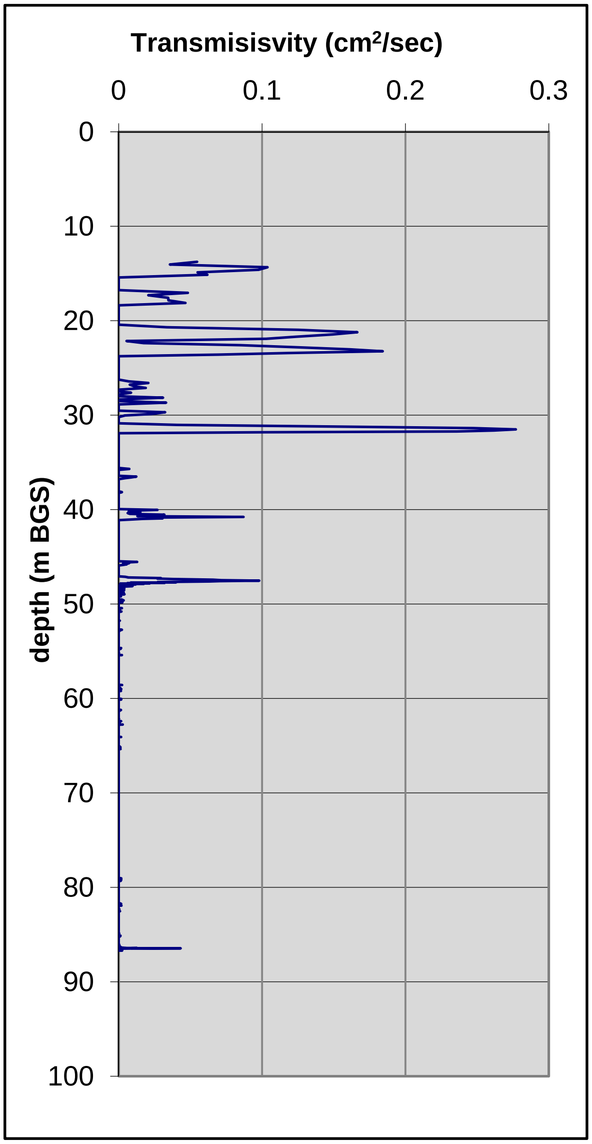
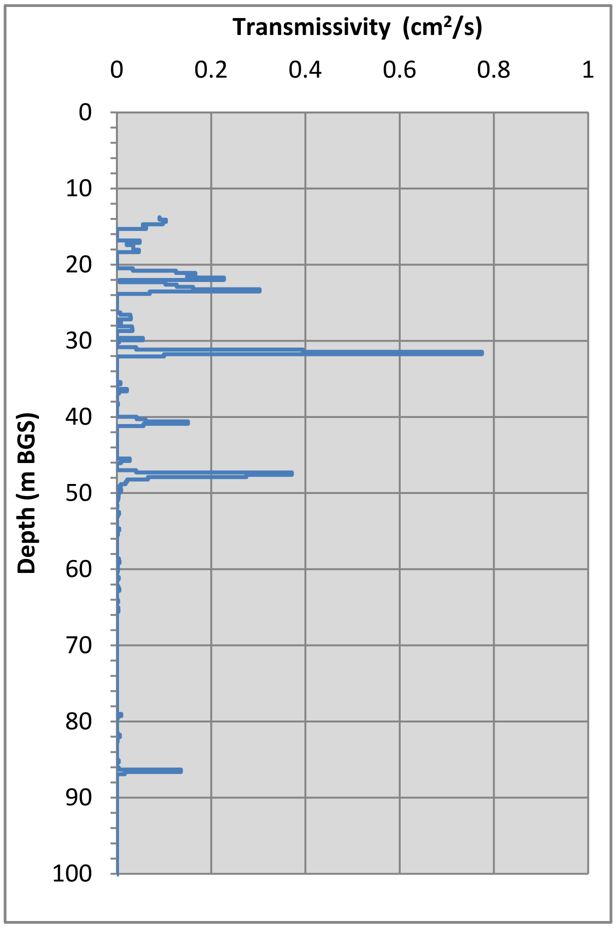


FIGURE 3. Transmissivity from flow rate

Because the liner velocity starts with a relatively high velocity and then decreases, the distance that the liner travels in each time step is also decreasing with depth in the hole. The transmissivity of the borehole wall is calculated for each time step and therefore over a decreasing hole interval. That results in finer spatial resolution of the transmissivity for the lower portion of the borehole than for the upper part of the borehole. Figure 3 is a transmissivity plot for that decreasing depth interval. However, a high flow zone measured in many small intervals will produce many small transmissivity values. The plot in Fig. 3 shows just such a result in the interval from 86 to 88 m. If the transmissivity values are summed over many discrete intervals of the same length (0.3 m in this case), the result is Figure 4a. This shows that the lower interval from 86 to 88 m has a total transmissivity higher as compared to 40-42m than was apparent in Fig. 3. For that reason, the results of the transmissivity measurement are provided in both the form of Fig. 3 and of Fig. 4. For purposes of modeling, the high resolution measurements may be much finer than the mesh size of the calculation. Figure 4b shows the same results of Figure 4a integrated over a larger interval (5 ft) perhaps more typical of the model mesh.



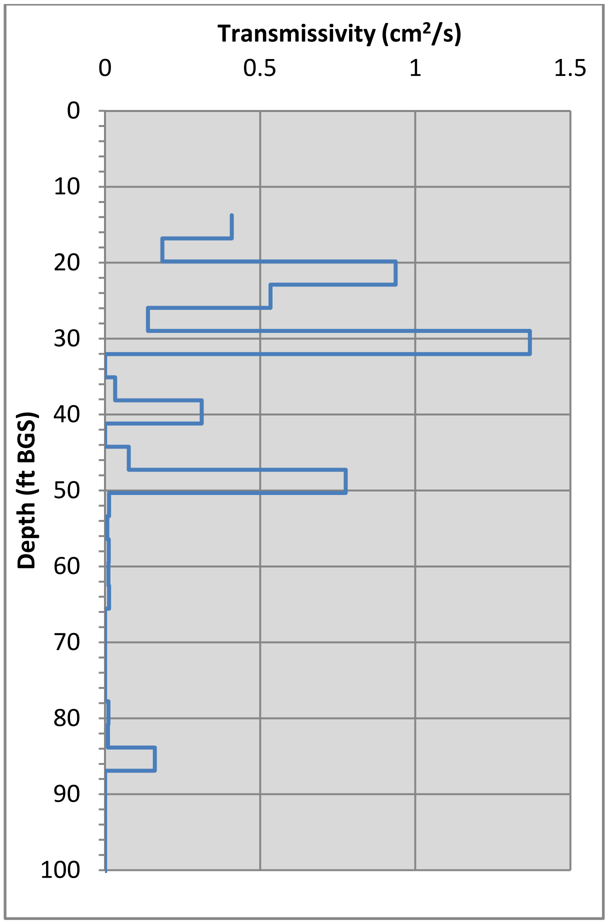


FIGURE 4a. Transmissivity in 0.3 m intervals. 4b. Transmissivity in 1 m intervals. Note, the transmissivity value is the total over the width of the bar. The total transmissivity of each graph is equal to 5.00 cm^2/s.

Figure 5 is the conductivity distribution of the borehole calculated from the transmissivity of Figure 4. This is just a scaled version of the same distribution of Figure 4a. By plotting it on a log scale, one can better see the conductivity variation. If the results are to be compared to straddle packer tests, the integration intervals used for the conductivity calculation can be the same intervals as used for the straddle packer testing. Such a comparison has been discussed in detail (Keller, et al, 2010) where several boreholes were measured with continuous straddle packer testing and with the liner profiling technique. Overall the liner results were very comparable to the straddle packer tests.

Use of the results

Often the measurement of the borehole transmissivity is for the purpose of understanding the spatial distribution of flow in the formation and for the selection of sampling intervals for multi level measurement systems to obtain discrete water samples and for measurement of the head at those intervals (Cherry, et al, 2007). The flow curve of Fig. 2 makes the identification of the larger flow zones relatively easy (e.g., 21-23m, 32m, 41m, 47m, 86m). Those are the intervals of large drops in the velocity curve. The transmissivity distribution can be integrated from the bottom of the hole to the top to give a curve as shown in Figure 6. This is essentially identical to the flow curve of Figure 2, since it was derived from Figure 2. The only difference is that the units are of transmissivity (cm^2/s). The transmissivity at the top of the hole is the transmissivity of the entire hole. The transmissivity at any lower elevation is the transmissivity of the open borehole below that elevation.

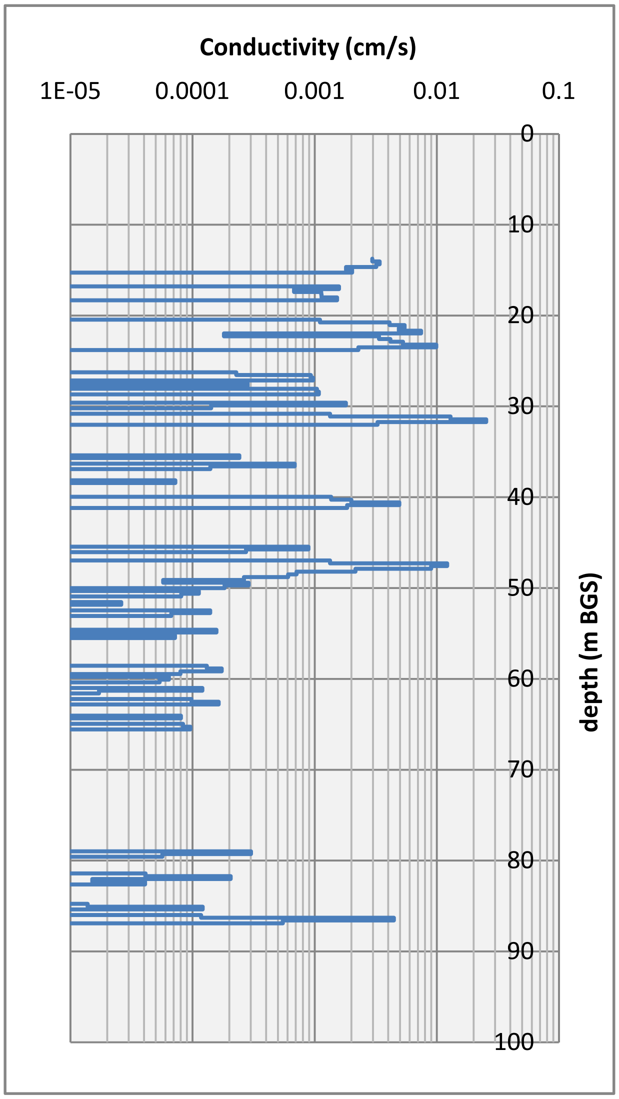


FIGURE 5. The conductivity distribution from Figure 4a

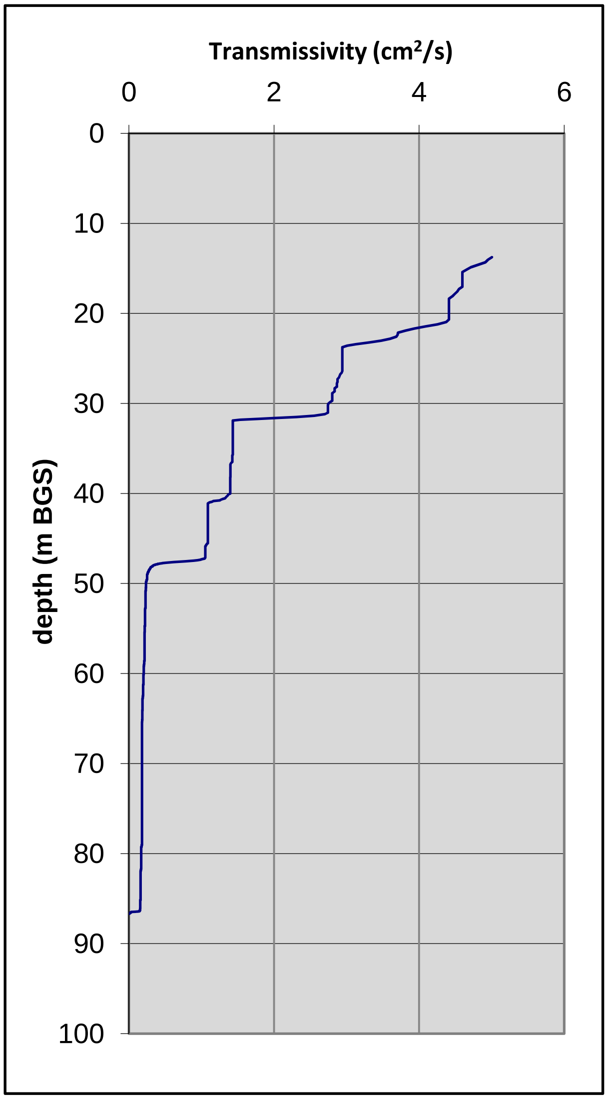


FIGURE 6. Integral of transmissivity from bottom of the hole upwards (from Figure3).

The identification of the top and bottom of a sampling interval allows one to calculate the conductivity of that interval from Figure 6. For example, the integrated transmissivity at 30m is 2.75cm^2/s and at 32m is 1.43cm^2/s. The difference in the transmissivity values is 1.32cm^2/s, which divided by the interval, 200cm, yields a conductivity of 0.0066cm/s for that interval. If information from a video log shows that the transmissive feature has a span of only 0.1cm (a guess), the conductivity of the feature itself would be 13.2cm/s, a very high value. In modeling that fracture, any of the conductivity values are correct as long as the appropriate spatial dimension and appropriate porosity are used to obtain the transport velocity in that feature.

Because one hole volume of water is displaced and the transmissivity distribution is a measure of where it flowed out of the hole, the entire data set is self consistent and conserves mass and transmissivity. Another feature of the measurement is that there is no leakage past the liner to an open hole above the end of the liner. Therefore, the sum of the individual transmissive intervals is the total transmissivity. For some other kinds of flow measurements, leakage during individual measurements will lead to a total of the measurements exceeding the flow capacity of the entire hole.

The transient at the beginning of the measurements

As the liner is released to perform the measurement, the head in the hole beneath the liner immediately jumps to essentially the full excess head inside the liner. That instantly develops an extremely steep gradient in the hole wall and a very high flow rate out of the entire hole. Before that transient has faded, the decay of the liner velocity violates the basic assumption that a liner velocity decrease is due to flow into the hole wall in the interval traversed in that time step. Instead, the liner velocity drop is due to the decay to steady state throughout the entire hole. However, as the liner descends with the same excess head, the gradient from the hole wall into the formation approaches the steady state gradient. Figure 7 (dashed curve) shows the flow rate of Figure 2 before the calculated transient was subtracted from the measured flow rate.

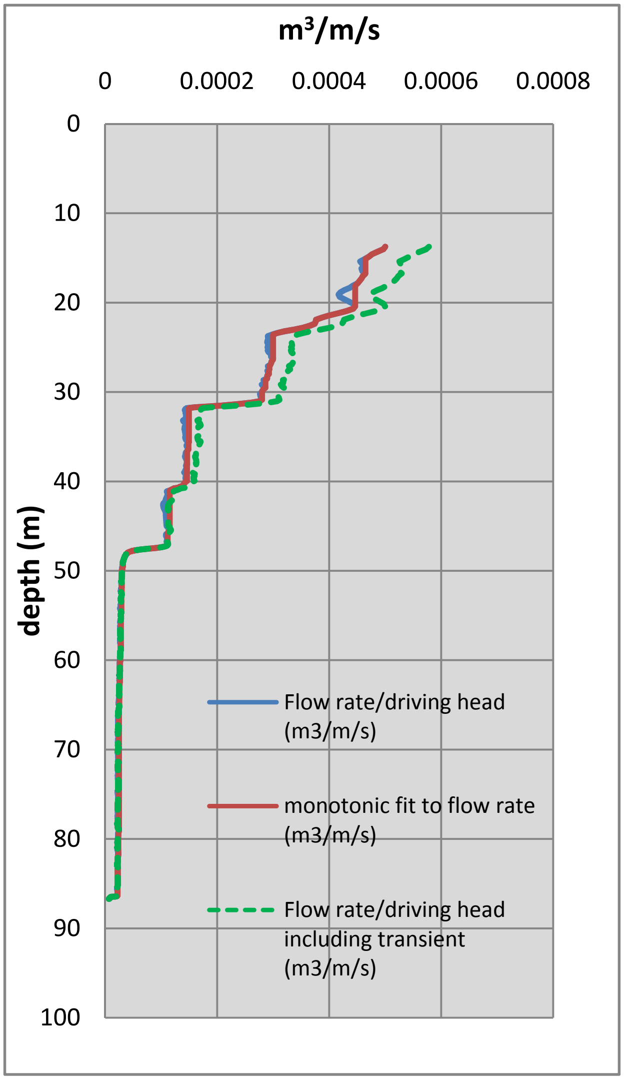


FIGURE 7. Showing the flow rate before the transient is removed

Ideally, the transient has largely passed before the liner emerges from the surface casing. However, that is not the case for short casings or very low conductivity media. In most cases, that portion of the initial measurement clearly dominated by the transient is cropped, leaving one uncertain of what borehole transmissivity may exist in that upper interval. The data reported starts at the depth considered relatively independent of transient effects. However, liner velocity drops at very large flowing fractures are superimposed on the transient of the slow flowing fractures. In Figure 7, the flow zones above 20 ft should be confirmed with other measurements or be considered questionable. Currently, a transient seen to occur in the casing can be fit to an appropriate combination of conductivity based on the liner velocity and an estimated porosity/storativity so as to match the observed transient. The transient can then be subtracted from the data set to reveal any remaining velocity drops due to transmissive features as in Figure 7. There are some methods, such as prior water addition to the hole, to assure that when the liner measurement begins that the transient has decayed to insignificance and the outflow from the hole is near steady state when the liner measurement is initiated. The effect of nonlinear flow on the measurement results has been determined from very careful straddle packer measurements at Guelph, Ontario (Quinn, 2009). In extremely fast flowing zones, the liner profiling method can underestimate the conductivity by a factor of 2-5.

Measurements with steep gradients in the medium

The initial liner measurement and data reduction assumes that the blended head in the borehole is near or equal to the head in the formation and therefore the excess head in the borehole is the driving pressure for the measurement. For situations where that is not the case, when the head distribution in the formation becomes known (e.g., after a multi level system is installed), that measured head distribution can be used in the correction of the head in the transmissivity calculation.

Further utility of the transmissivity profile

Figure 2 shows quite clearly the location of major flow paths. Some profiles show a variety of other aspects of the transmissive zones. It is beyond the scope of this paper to describe the implications of the shape of the velocity curve, but there is useful information in the detailed distribution of the transmissivity curve (Keller, et al, 2010).

The resolution of the method

The fast moving liner can resolve a velocity change greater than about 2%. So a fast moving liner will not detect low transmissivity features. The vertical depth resolution is better than about 0.3% of the depth (i.e., 0.3m at 100m). In the data reported is a graph of both the actual data and an over plot of a monotonic curve of the data. The purpose of the monotonic curve is that it ignores the temporary drops in liner velocity such as caused by a washout. If there are no perturbing features and very little noise in the data, the two curves will be nearly identical. If the data plot differs significantly (a difference obvious to the eye) from the monotonic fit, the results are less reliable. The monotonic fit is used to calculate the transmissivity curve. The monotonic fit tends to be constant over a region of large fluctuations in the data with depth since it only matches the peaks in a noisy data set. A caliper log is very useful prior to the liner measurement to verify that the hole is open and to identify temporary drops in velocity as due to hole enlargements.

Fast moving liners also tend to provide more noisy data sets due to fluctuating drag effects of several kinds. Small hole diameters (<10cm) with deep water tables (>30m) can aggravate the drag on the liner due to wet film adhesion. The use of transducer at the bottom of the hole avoids these effects. The data set of Figure 2 is a good data set. The initial flow rate is about 190 l/min. with a 5.5m head, a moderate rate. Even then the data set is better below 50m.

A small drop in velocity (<2%) may be due to a very small flow zone or it may be due to noise. If there is confirming information such as a video log showing a small fracture in the same location, it is probably a flow path. Other measurements in the borehole or examination of core are very useful in confirmation of apparent small flow paths. An overall drop in velocity in a noisy interval is reliable, but the location of individual flow paths may not be reliable (e.g., Figure 3, 35-36m and 46m). The very small spikes (Figure 3) from 50-80m in a very low conductivity zone are not reliably located.

Conclusion

The identification of the significant flow zones in the liner profile data plot is easy. The fact that the entire hole is measured makes it less likely that an important flow zone will be missed. The liner is relatively immune to bypass leakage which allows a reliable measurement in boreholes with very rough walls. Because of the continuous measurement, any portion of the borehole data can be assessed on any scale needed for flow measurements or incorporation into a model. The continuous measurement also assures that the total transmissivity is conserved. The transmissivity resolution is better in the lower portion of the hole than in the uppermost portion of the hole. As with many forms of subsurface measurement, some data sets are better than others. The earlier problematic situations were very fast flowing holes (greater than ~100 gal/min.) or very deep water tables (>150 ft) with small hole diameters (< 4”). Those limitations have been addressed with design changes. The fact that the liner is usually purchased to seal the hole against cross connection of contaminated ground water, and the speed and low cost of the liner profiling method, make the additional profiling measurement very cost effective. Any questions about the data should be addressed to the data reduction person listed with each borehole data set.

References

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