Information Available in a FLUTe Transmissivity Profile

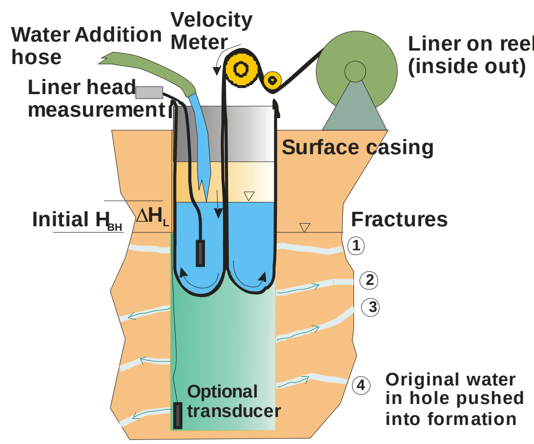
Introduction

The FLUTe transmissivity profiling method is relatively new to the hydrologic community and sometimes not well understood. This paper describes how to use a Profile and how it compares to traditional measurements. The geometry of the measurement is shown in Fig. 1.

How the profile is measured

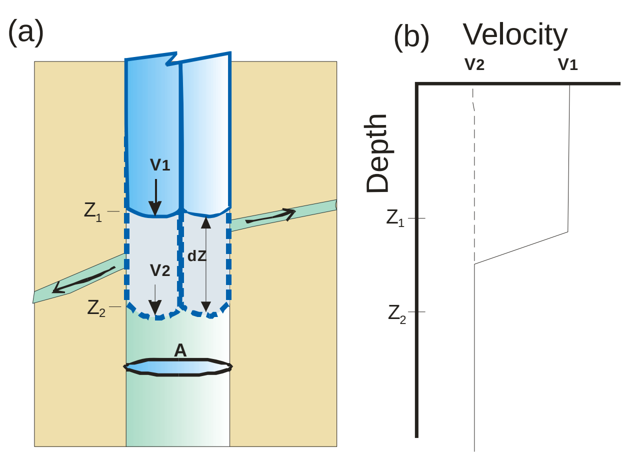
An ordinary FLUTe blank liner is installed in an open borehole to the water table. The liner is restrained and filled with water to a level 10 ft, or more, above the formation water table as tagged in the open hole. The liner is then released and the descent rate of the liner is measured as well as the head in the open hole beneath the liner. The water level inside the liner is maintained as nearly constant and well above the formation water table to develop a substantial overpressure in the borehole.

Fig. 1. Geometery of profile measurement



The release of the liner develops an instantaneous increase in the borehole pressure which causes a very steep gradient at the borehole wall and a large flow rate of water out of the borehole. That outward flow develops a lower gradient as the flow rate from the borehole approaches the steady state flow rate. The initial high flow rate rapidly decays to the steady state flow rate. Fortunately, that approach to the steady state occurs before the liner has descended more than 10-15 ft. typically, but can persist longer. That initial high flow is called the “transient.” A correction for the transient will be discussed hereafter.

Fig. 2. Velocity change upon passing a fracture



Flow rate into the fracture, $\Delta Q = A(V_1 - V_2)$, where $V_1 > V_2$

$T = \Delta Q \ln(r_0/r_w)/(2\pi \Delta H_{BH})$ in the interval Z_1 to Z_2

As the liner descends by the eversion of the liner (the reverse of inversion), the water is driven from the borehole as rapidly as the transmissivity of the borehole allows. Initially, all the flow paths in the borehole are open and the liner descent is most rapid. However, as the liner descends, it sequentially seals, from the top down, the permeable features (fractures, bedding planes, or permeable beds). The sealing of each permeable feature reduces the transmissivity below the everting liner and the liner descent rate slows. That is the essence of the transmissivity profiling method. The velocity change as the liner seals a flow zone, when multiplied by the cross section of the borehole, is the flow rate of the feature sealed by the liner (Figure 2). In other words, the descending liner is essentially a flow meter which measures the flow rate out of the hole. Each time a permeable feature is sealed, the flow rate out of the borehole drops and so does the descent rate of the liner. A plot of the liner velocity with depth shows a monotonic decrease in velocity of the descending liner. Each decrease in velocity identifies the location of a permeable feature and the magnitude of the velocity change is a direct measure of the flow capacity of that feature. Figure 3 is a typical data set.

The calculation of transmissivity from the liner descent

The liner decent is measured by an encoder on a roller at the surface in the machine called a "Profiler". The encoder measures the liner depth every half second, typically. From the liner depth and the time is calculated the velocity of the liner as it travels that discrete depth interval. High in the hole where the liner is descending more rapidly, the interval traveled per time step is larger than it is deep in the hole where the liner is traveling more slowly. Therefore, the spatial resolution of the location of a permeable feature is better deeper in the hole. However, the distance traveled in a half second time step is usually less than a hole diameter.

Because the driving pressure in the borehole is measured on the same half second time interval, the transmissivity can be calculated from the change in velocity as follows (The Thiem equation):

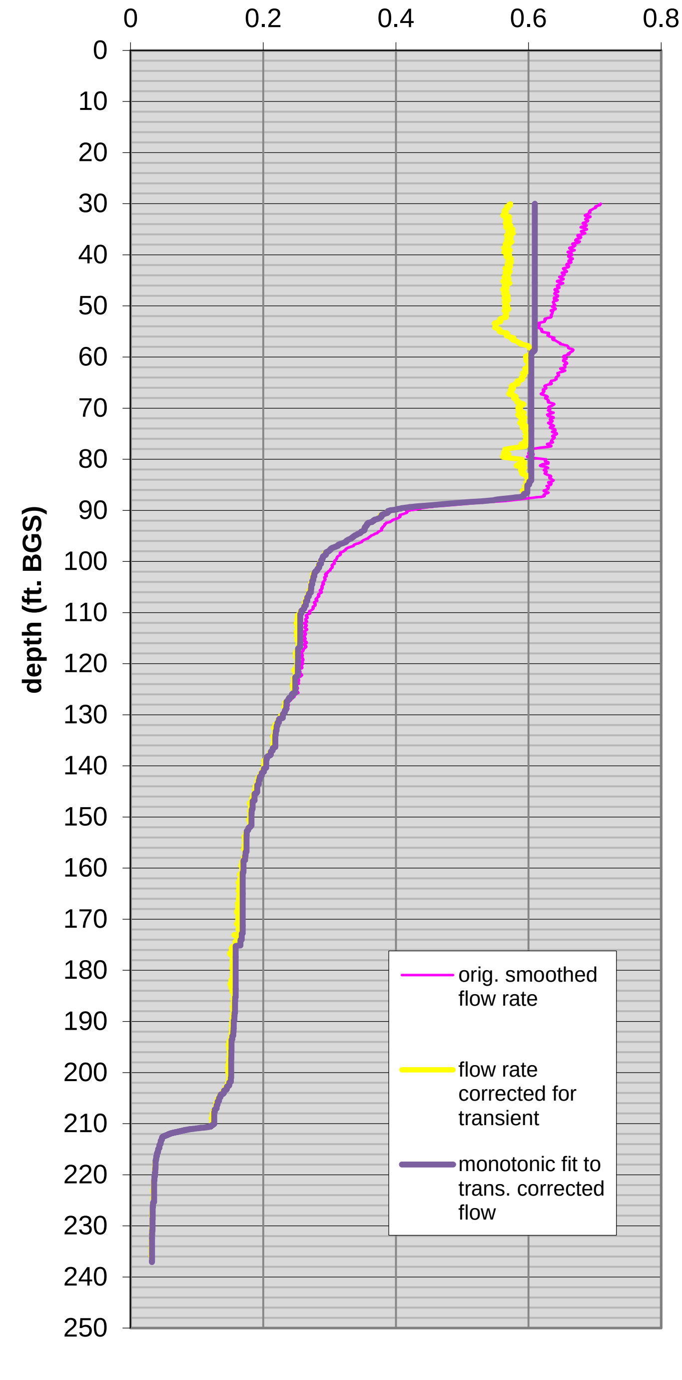
$T = \Delta Q/H \ \ln(r/r_0)/(2\pi)$, where $\Delta Q = \Delta v\, A$, where Δv is the velocity change over the interval traveled in a half second, and A is the borehole cross section. The ratio r/r_0 is the radius of influence divided by the borehole diameter. As with packer testing, r/r_0 is assumed to be constant. The term H is the measured driving head beneath the liner. From this simple expression, a transmissivity can be calculated for each interval of the borehole traversed in each half second. If there is no velocity change, the transmissivity is zero, within the limit of resolution of the measurement. Experience shows that the resolution is dependent upon the liner velocity and about 1% of the velocity.

The data as plotted in the Results Spreadsheet

The measurements are made in the English units so the flow rate out of the borehole is in ft/s in^2/psi which is a volumetric flow rate per unit driving pressure. That result is plotted in the first graph of the results sheet as the pink curve of Fig. 3. Because of the transient, the first portion of the pink curve is a steeply decaying flow rate which is not due to flow into the casing wall (the casing extends to 52 ft.). In those situations where the transient is obvious (e.g., a rapid decay in a surface casing before the liner enters the borehole) a first order correction is often made to the data to remove the transient effect on the velocity. That correction is made by calculating the transient to steady state in a 1D cylindrical geometry using the conductivity estimated from the borehole flow rate and an estimate of the storativity of the formation. There are several reasonable constraints on the transient correction. The subtraction of the estimated transient flow must not produce an increasing velocity with depth in the casing. In the casing, the corrected flow rate should be constant. When a casing measurement is not available (e.g., when the measurement is started below the surface casing), the constraint is only that the velocity should not increase with depth after the transient is removed.

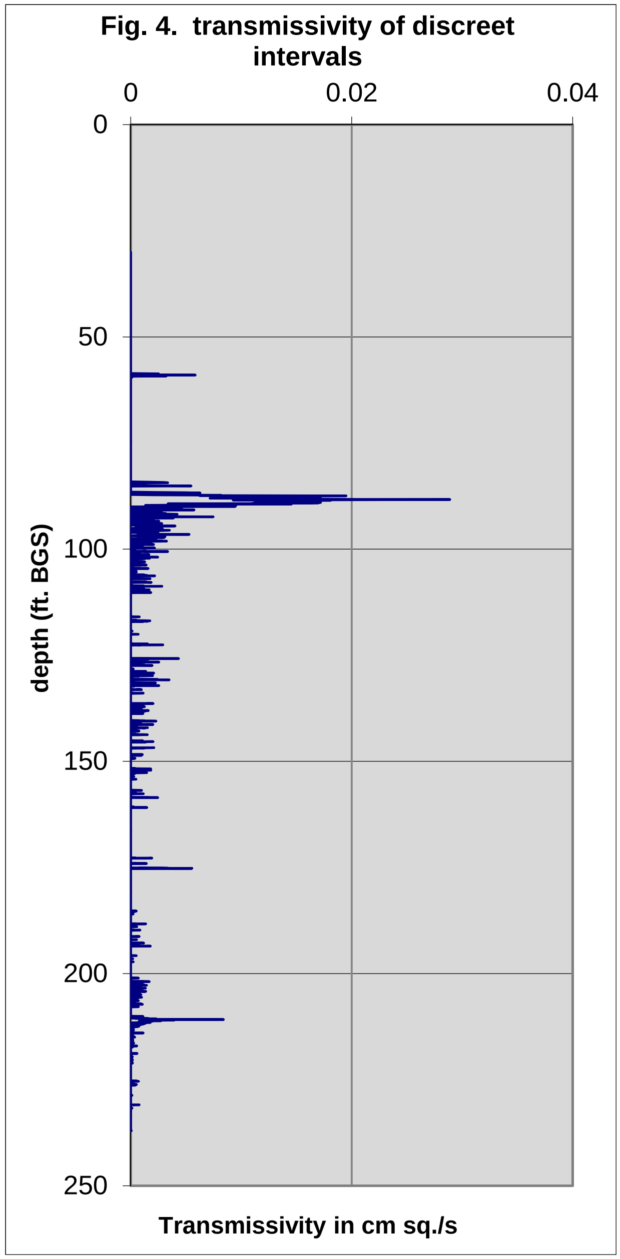
The corrected flow rate in the example of Fig. 3 is the yellow curve. In this data set, the casing extends to 52 ft bgs and indeed the corrected flow rate in the casing from 30 to 52 ft. is relatively constant.

Fig. 3. Flow rate with depth in hole ($ft.\ in^2/s/psi$)



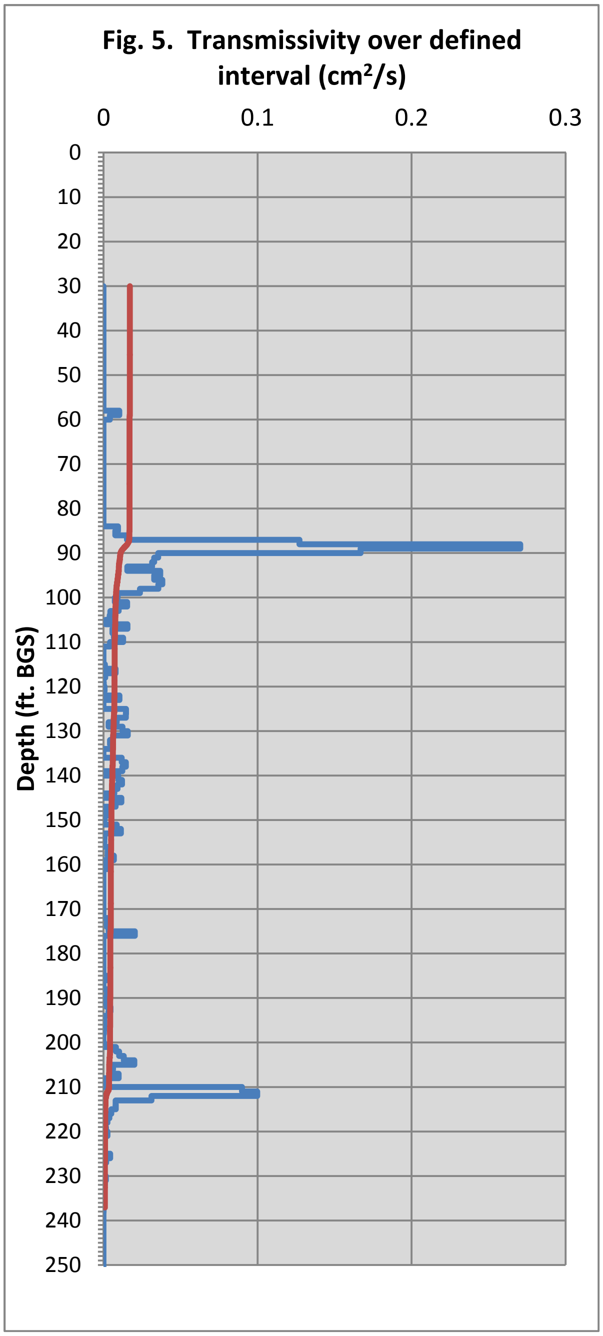
Another concern is that as the liner traverses an enlargement of the borehole, the liner dilates and the velocity of the descending liner must therefore decrease proportionately. As the liner exits the enlargement, the diameter will return to the nominal borehole diameter and the velocity will increase. This drop in velocity followed by an increase in velocity is ignored as unrelated to a flow zone associated with the initial drop in velocity. The method for ignoring such a temporary drop in velocity is to fit a monotonically decreasing curve to the data set. That curve is the black curve in Figure 3. The monotonic fit suggests that the portion of the borehole below the casing (30 to 52 ft.) has numerous extensive enlargements. Note, a 10% increase in borehole diameter will cause a 21% decrease in the liner velocity. Below 52 ft. the yellow curve and the black curve are essentially the same. The degree to which the yellow curve matches the black curve is a measure of the data quality and associated resolution. The transmissivity is calculated from changes in the flow rate of the black monotonic fit curve. If there is a permeable interval in the enlargement, the monotonic fit causes that transmissivity to be assigned to the upper portion of the enlargement where the initial velocity decrease occurred.

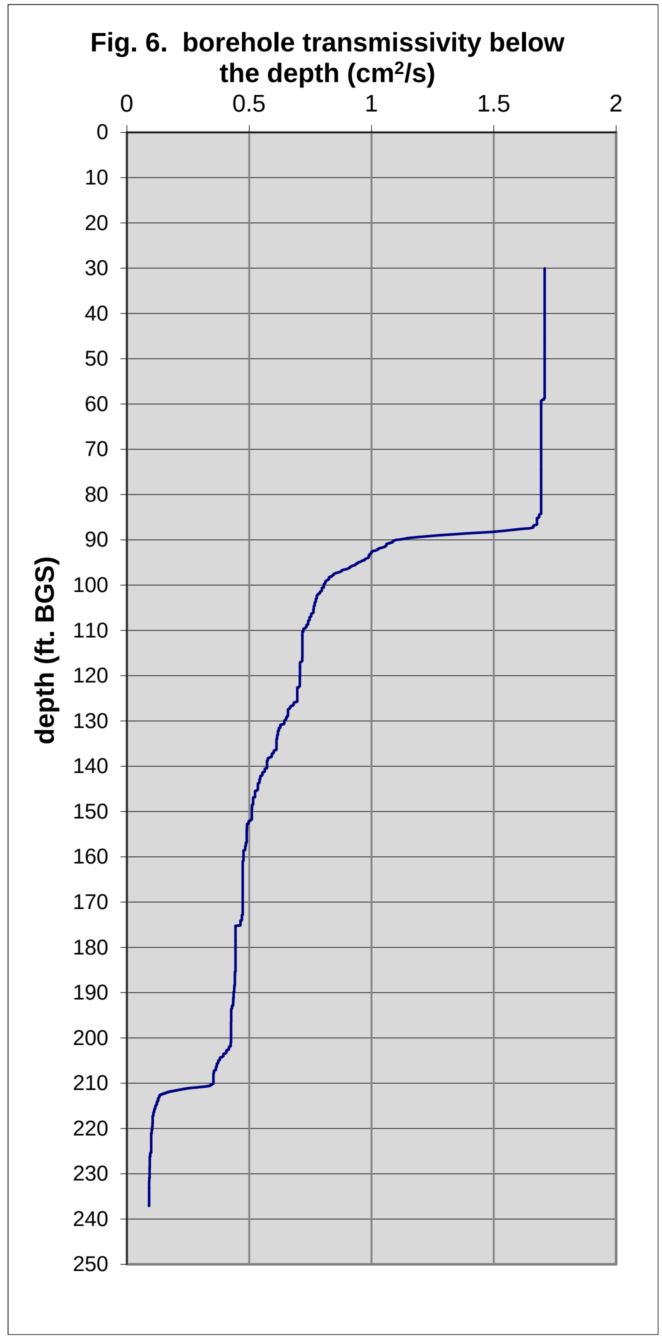
The drop in velocity from 52 to 54 ft. is typical of an enlargement below the bottom edge of the casing. The rise in velocity/flowrate from 54 to 58 ft is typical of the entrance of the liner into a borehole whose diameter is less than the casing.



The second graph of the result spreadsheet (Fig. 4) is the plot of the transmissivity calculated for each half second of travel down the borehole. Because the interval traveled per time step is longer at the top of the hole, the plot can be visually deceiving. The large drop at 90 ft is shown as a very large transmissivity whereas the major drop in flow rate at 212 ft is shown as many small transmissivities over very short intervals. In order to overcome that illusion, the fourth graph on the results sheet (Fig. 5) is an integration of the variable interval transmissivities in Fig. 4 over a constant interval, usually a one foot interval. This is the result expected if the transmissivity profile was determined by a continuous series of one foot straddle packer tests. Here the large flow at 90 ft in Fig. 5 is more clearly a large flow about twice that at 212 ft. Figure 5 may be the plot most easily compared to other measurements in the borehole. It is the plot of the data "sum over the interval" (col. U) versus the "depth of the interval" (col. V).

Figure 6 is the third graph of the "Results". This plot is the integral of the transmissivity data of the second curve (Fig. 4) from the bottom of the hole to the top of the hole. The result is identical to the monotonic fit curve of Fig. 3, but in units of transmissivity of the borehole below the indicated depth. Since the liner velocity is a measure of the transmissivity of the borehole beneath the bottom of the liner, Figure 6 should have the same shape as Fig. 3. The utility of Fig. 6 is that the transmissivity of any interval of the borehole is easily determined by the difference of values of Figure 6 between two depths. For example, the transmissivity of the interval between 93 ft (T=1 cm2/s) and 153 ft (T=0.5 cm2/s) is 0.5 cm2/s. The transmissivity of the interval from 84 ft to 93 ft is about 0.69 cm2/s. In this simple manner, one can determine the transmissivity of any interval in the borehole. Figure 6 is also helpful in that it is easy to see where there are very large flow zones, probably fractures, at 90 ft and 112 ft. The interval from 123 to 146 ft is a slope of more distributed permeability either as a matrix permeability or a pervasive fractured zone. In contrast, the interval from 160 to 170 ft. is relatively impermeable. The curve of Figure 6 is the plot of column T, the integral transmissivity below the liner, versus column O, the depth of the liner. The value of the integral transmissivity at the top of the hole is the total borehole transmissivity (1.7 cm2/s).





The red curve of Fig. 5 is the nominal resolution limit of the transmissivity data. The red curve is simply 1% of the value of the integral transmissivity of Fig. 6. In many situations, transmissivity peaks of Fig. 5

just below the red curve will match measured flow zones in the borehole. If the yellow curve of Fig. 3 is essentially the same as the black curve, the resolution limit is often better than the red curve on Fig. 5.

Conclusion

A particular advantage of the profiling technique is that the sum of the measured transmissivities is the transmissivity of the entire borehole. Such is not the case, for example, with straddle packer tests. If there is any leakage in the straddle packer tests due to a rough hole wall or bypass in the formation to the open hole above or below the packers, the total sum of the packer measurements will exceed the total borehole transmissivity.

Another significant advantage is that the transmissivity profile is a continuous measurement allowing the determination of the transmissivity of any interval in the borehole. Also, of course, the Profiling technique requires a very small part of the time required for detailed straddle packer testing of a borehole and much higher resolution than most packer tests.

A disadvantage of the profiling technique is if the borehole transmissivity is primarily due to a large fracture at the bottom of the borehole, the large velocity throughout the rest of the borehole down to that large fracture provides poor resolution of much less permeable flow paths in the upper portion of the borehole.

A detailed description of the transmissivity profiling method is available in a paper submitted to Ground Water by Keller, et al. The transmissivity profile is often used to determine where discrete sampling intervals should be located for assessing the extent and type of ground water contamination. The technique has also been used in conjunction with the Water FLUTe multilevel sampling and head measurement system to assess municipal ground water supplies and the hydrologic environment near mining operations. Any questions about the method or profiling results should be directed to info@flut.com or to 505-455-1300 or 505-930-1154.