Why and How FLUTe corrects for the Transient in

Transmissivity Profiles

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Background

When a transmissivity profile measurement is initiated by release of the water filled liner, the borehole pressure goes from the blended head in the borehole to a higher head as the liner is allowed to abruptly pressurize the water in the borehole. Until the subsequent outward flow from the borehole approaches the steady state gradient, the outward flow is greater than the steady state flow. However, the data reduction assumes a steady state gradient in the borehole wall and that every drop in liner velocity is due to flow into the borehole wall being interrupted by the descending liner.

The transmissivity distribution of the borehole is calculated from those changes in velocity. If there is a decay of the liner velocity that is not due to flow into the borehole wall, the calculation will assign an erroneous transmissivity to that interval over which the liner travels while that velocity reduction occurs. Therefore, the common decay to the steady state outward flow can be a cause for an overestimation of the transmissivity in the upper portion of the borehole.

In many cases, the liner descent rate will decay to a relatively constant velocity in the surface casing before the liner enters the open borehole. In those situations, the velocity decay in the casing is ignored and has not effect on the overall measurement. In some cases, the decay is still in progress as the liner exits the casing and in other cases, the entire transient occurs in the open hole because the measurement was started below the cased portion of the borehole (e.g., when the water table is below the bottom end of the casing).

For the above reasons it is useful to remove the transient portion of the velocity decay to the extent that it can be done without violation of the velocity profile's use for calculation of the transmissivity distribution.

An example of the transient is shown in Figure 1. The profile was begun at 19 ft below the surface in a casing that extends 52 ft below the surface. The velocity decay from 19 to 52 ft is certainly not due to flow into the cased hole wall and the obvious

Fig. 1. Flow rate with depth in hole (ft in²/s/psi)
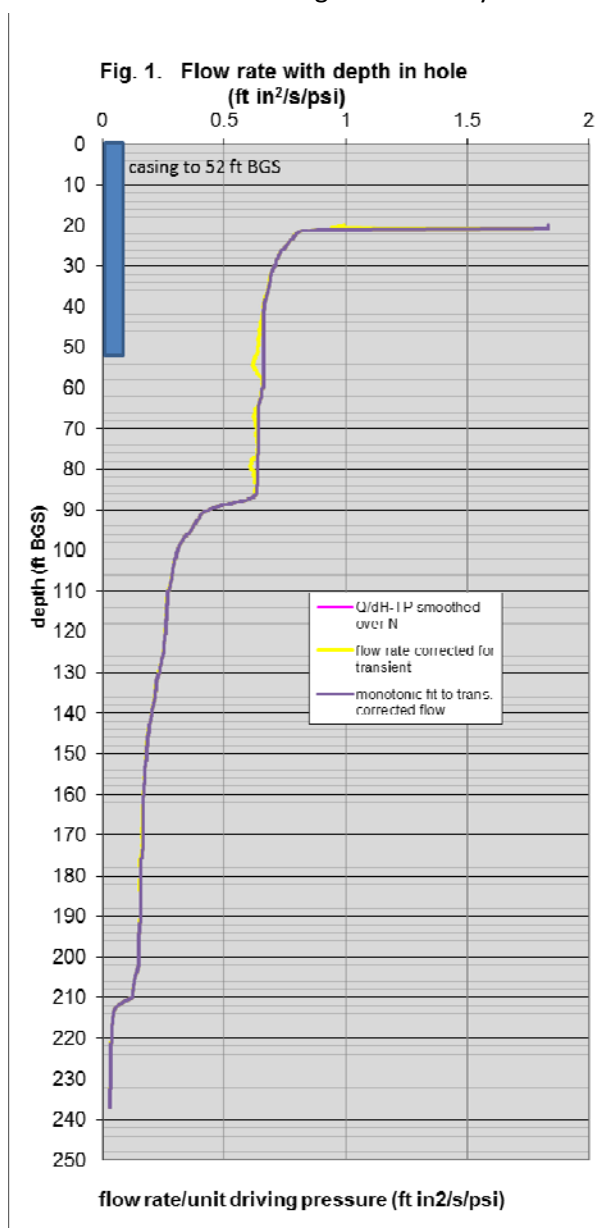
decay curve of the velocity in the casing is that of a typical transition to steady state flow. If one is to remove a transient effect, one must be able to calculate a transient effect as a function of reasonable flow parameters. A 1D porous flow code was written which performs a simple radial one dimensional flow calculation as a function of time after an abrupt step increase in the driving pressure on the inside surface of a cylindrical boundary. A typical result of a calculated flow rate per unit driving pressure into the hole wall is shown in Fig. 2. It is also interesting

Fig. 2. flow rate into hole wall
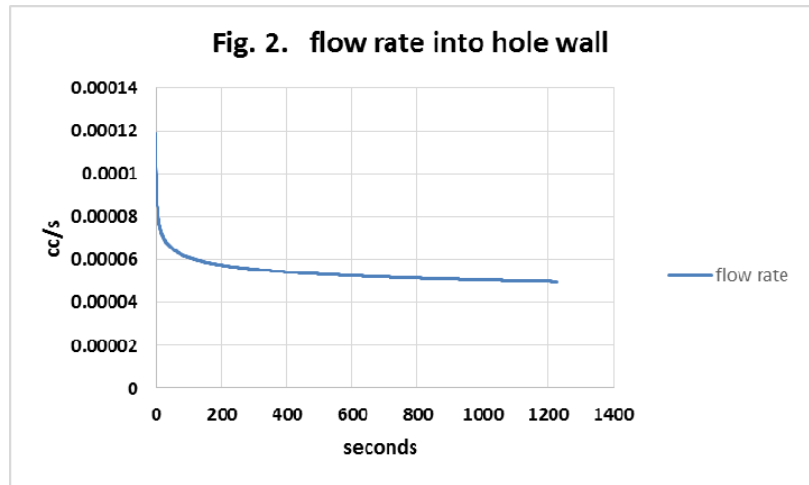
to compare the flow rate calculated to the steady state flow rate by calculating the ratio of the time dependent gradient at the hole wall to the steady state gradient. Fig. 3 shows that ratio for the same calculation. As the ratio approaches 1.0, the flow is said to be approximately the steady state flow. The same calculation in Fig. 2 was run with different flow characteristics of Conductivity (C) and Storativity (S). The smaller Storativity causes a shorter duration of the transient and a smaller conductivity increases the decay time.

If one subtracts the steady state flow from the transient flow, that difference would be a reasonable estimate of the correction of the transient flow to obtain the steady state flow. The concern is that the selection of the parameters for the transient calculation may not be realistic and that the correction obtained is arbitrary or "fudging the data" as it has been described.

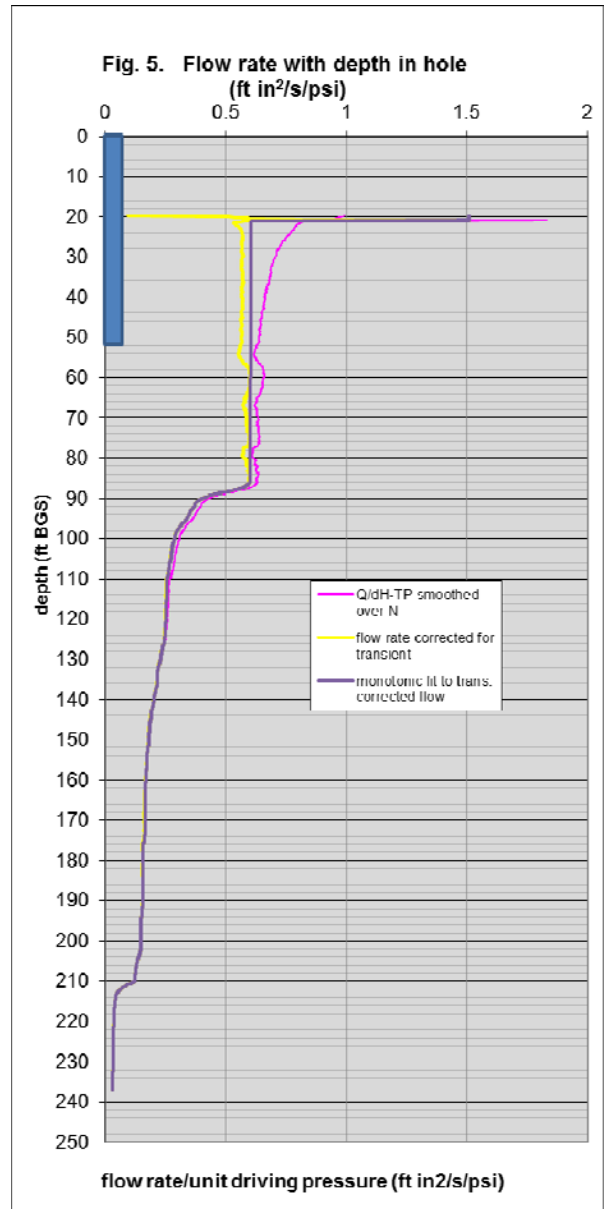
Fig. 3. fraction of steady state gradient
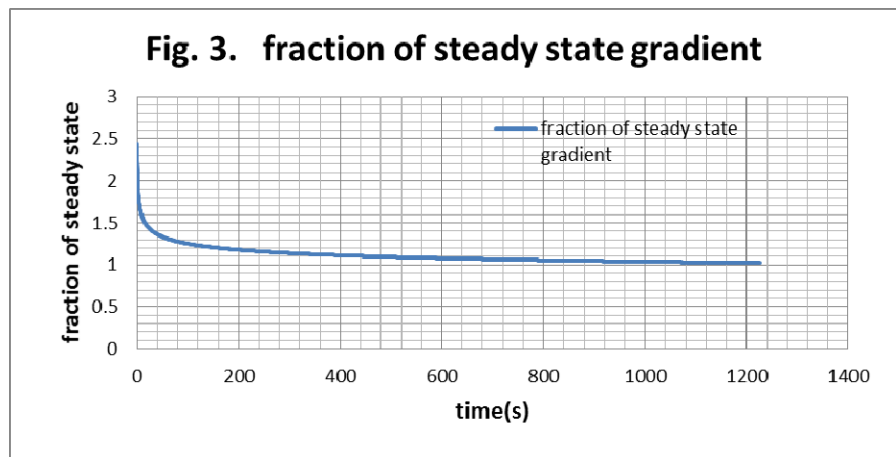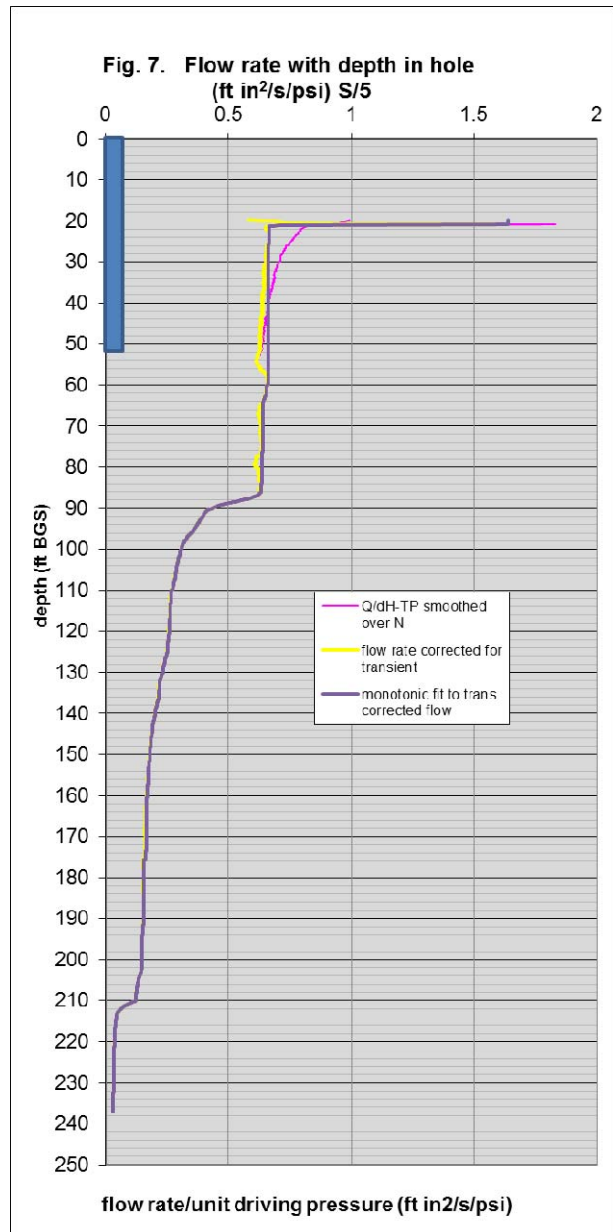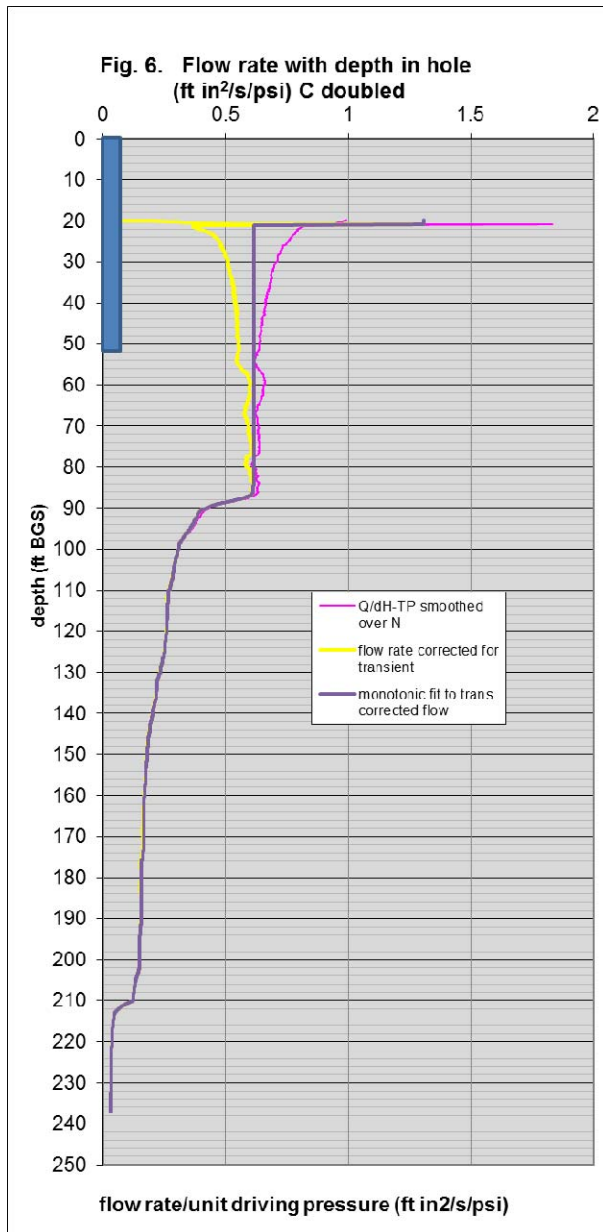
How the correction is performed

An actual data set like that shown in Figure 1 allows a reasonable selection of the parameters used in the calculation of the correction to the transient effect. The correction is defined as the difference between a steady state

Fig. 4. transient correction to flow rate with time
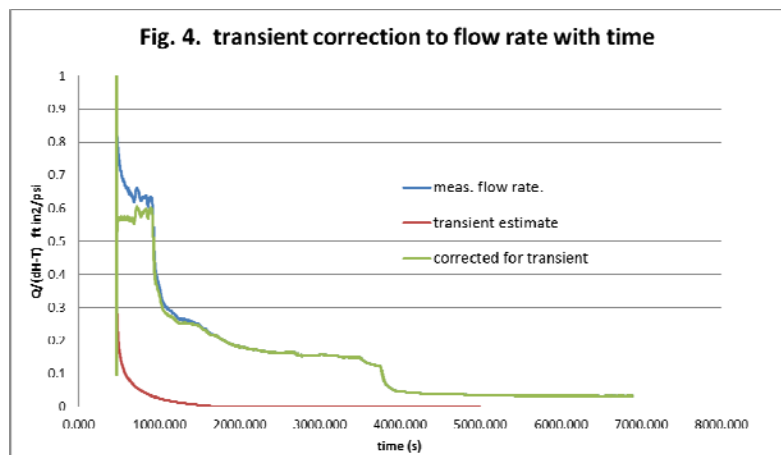
calculation and a time dependent calculation which can then be reasonably subtracted from the measured flow rate to produce a more realistic flow rate in that interval of the data set where a transient condition is considered significant. Clearly as the liner descends in time with a constant driving pressure, the transient is decaying and becomes, in most cases, insignificant deeper in the borehole. The data of Fig. 1 allows an estimate of the borehole transmissivity below the casing. The flow rate per unit driving pressure ranges from 0.2 to 0.6 ft in^2/psi and leads to a conductivity of 0.7 to 2.04e-04 cm/s for an estimated average conductivity for the borehole of 1.35e-04 cm/s. Entering that data and the actual driving pressure of about 8 psi leads to a transient correction in time shown as the red line in Fig. 4. Figure 4 also shows the original flow rate (blue), and the original flow corrected for the transient (green). Note this plot of flow in Fig. 4 is in time rather than the flow of Fig. 1 as a function of depth. The time and depth are connected for each time step of 0.5 second. The liner was released at 466.5 seconds. Using the correction as described, the result is Fig. 5 where the yellow curve is the corrected version of the pink curve. The only difference from Fig. 4 is that it was found that a conductivity of 1.5e-04 cm/s made the flow rate in the casing more nearly constant than the 1.35e-04 cm/s initially used. The data also suggests a slight enlargement just beneath the casing and a borehole smaller than the casing at ~57 ft.
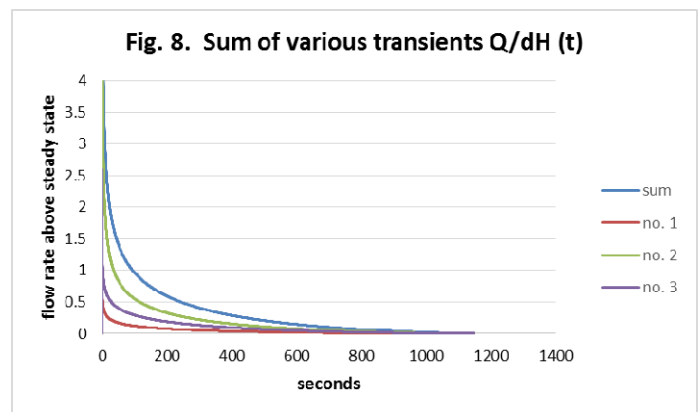
The only other hydrologic parameter used in the calculation is the Storativity. The value of 1e-07 was used as a reasonable estimate for this rock type. As a

Fig. 5. Flow rate with depth in hole (ft in^2/s/psi)

demonstration that one can not be too cavalier in the properties used in the transient calculation, Fig. 6 shows the result of doubling the conductivity to 3e-04 cm/s. The resulting velocity increase with depth in the casing is not realistic. Figure 7 shows the result of reducing the Storativity by a factor of 5. Then the velocity is not constant in the casing. Increasing the Storativity extends the decay farther down the hole. If the correction is overdone as in Fig. 6, the result is an increasing velocity in what are otherwise impermeable intervals of the borehole where the velocity should be constant. These same limitations on the transient correction apply in the open hole below a casing, but

Fig. 6. Flow rate with depth in hole (ft in²/s/psi) C doubled

depth (ft BGS)

flow rate/unit driving pressure (ft in2/s/psi)

Legend:
- Q/dH-TP smoothed over N
- flow rate corrected for transient
- monotonic fit to trans corrected flow

Fig. 7. Flow rate with depth in hole (ft in²/s/psi) S/5

depth (ft BGS)

flow rate/unit driving pressure (ft in2/s/psi)

Legend:
- Q/dH-TP smoothed over N
- flow rate corrected for transient
- monotonic fit to trans corrected flow

in that case, it is more a matter of experience in the selection of the correct transient calculation parameters. Generally, it is easier to detect an over-correction.   It is less obvious that the correction was under estimated in an open hole unless there are obvious straight line segments that are only likely in impermeable intervals and must be constant valued after a correction.

Since the actual transient in a borehole is the sum of many different transients for each

Fig. 8. Sum of various transients Q/dH (t)

flow rate above steady state

seconds

Legend:
- sum
- no. 1
- no. 2
- no. 3

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different rock type and transmissive interval, the above correction is not exact. However, it is interesting that the sum of many different transients as shown in Fig. 8 still looks like a transient with the same asymptotic decay.

The advantage of the "first order" correction described here is that it reduces the error due to the transient decay of the liner velocity as shown in Figure 5 between 19 and 50ft. Fortunately, the significant transient effect in a borehole extends for a relatively small portion of the borehole.

Other observations

When a transmissivity profile is initiated in an uncased hole, the initial transient is sometimes far greater than that predicted by the above calculation for a confined aquifer. The suspicion is that the Storativity at the top of the aquifer may be more characteristic of the unconfined aquifer at the water table and nearer the value of the unsaturated porosity of the medium at the water table as the flow tends to be upward toward the water table. As the liner propagates more deeply, it "sees" less the effect of mounding of the water table instead of lateral flow. The same effect can occur in a casing if the casing is not well grouted or shallowly seated in the bedrock. (The borehole is often enlarged at the bottom of the casing due to its being emplaced in weathered rock.) The disadvantage of these effects is that they cause a steep initial decay in the liner velocity due to effects not related to radial flow paths being sealed by the liner.

Another aspect of reality versus the calculation is that when the liner is released, the descent velocity does not instantly jump to the high value of the calculation due to the inertia of the water in the liner and borehole. Rather, it accelerates to the peak velocity. Therefore, one sees the over-correction evident in Fig. 5 at the start of the profile. This inertial effect lasts about one second and should be ignored.

Alternatives

One alternative to the numerical correction is to start the liner measurement after the hole has been filled above the water table to a constant level equal to the liner excess head for some time, before the liner is released. This can be done with a pipe installed past the initial end of the liner. In this manner, the steady state outward flow could be developed before the liner is released with the same excess driving head. Whereas this is possible, many environmental contractors do not like the concept of adding water to the borehole as a perturbation of the natural formation water chemistry. It is also common that that rate of water addition is quite high.

It is always easier if the water table is high in the casing and the transient is well decayed by the time the liner exits the casing. The error of under correction is to produce a slightly greater calculated transmissivity than actual in the low flow intervals of the top portion of the borehole. The large step changes in velocity are not perturbed much by the transient error.

Conclusion/Discussion

The transient is defined to be the flow rate decay in a liner transmissivity measurement due to the transition from the initial high flow rate to the lower steady state flow rate throughout the borehole. The transient is known to be inherent in the data and it violates the assumption that all reductions in velocity are due to flow into the borehole wall. The transient in Fig. 1 would have been 40% of the transmissivity of the borehole if not removed. The correction for the transient is not arbitrary, but constrained by reasonable

values of parameters deduced from the flow history and constrained by the realistic flow conditions. An approximate correction as described allows one to recognize flow features that are otherwise masked by the transient below the surface casing. When a deep casing is present and the water table is high in the casing, the transient correction is very well constrained by the known conditions. Also, in that case the transient is often insignificant by the time the liner exits the long casing. When the measurements starts below the casing some of the same constraints still exist. Finally, the transient corrections have allowed better correlation with other kinds of flow measurements in the same boreholes by allowing the normal calculation to identify flow zones high in the hole. One must recognize that extremely high flow rates at the start of a profile may not be due to flow zones but due to the transient effect. In some cases, no reasonable selection of parameters for the transient calculation is possible. That may be because the flow rate decay was actually due to a high flow zone near the start of the measurement in an uncased hole. In that case, other information must be obtained for flow assessment in that short interval. For most measurements, the transient correction described leads to credible and useful results for transmissivity measurements high in the borehole. The measurements deeper in the borehole are unaffected unless the liner descent is arrested. Upon continuation of the profile after a stop, there may be evidence of a second transient. This is often much shorter and addressed by simply removing the velocity peak from the data. If the velocity before and after the stoppage is the same, this remedy for the second transient is easy and justified.