Hydrologic Characterization of Fractured Rock Using Flowing Fluid Electric Conductivity Logs

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Introduction

Flowing fluid electric conductivity logging provides a means to determine hydrologic properties of fractures, fracture zones, or other permeable layers intersecting a borehole in saturated rock. The method involves replacing the wellbore fluid by deionized water, then conducting a series of fluid electric conductivity (FEC) logs while the well is being pumped at a constant low flow rate Q (typically a few L/min). At depth locations where formation water enters the borehole (denoted as "feed points"), the FEC logs display peaks, which grow with time and are skewed in the direction of water flow. The time-series of FEC logs are analyzed by modeling fluid flow and solute transport within the wellbore, treating feed points as mass sources or sinks, and optimizing the match to the observed FEC logs by varying the feed point properties. Results provide the location, hydraulic transmissivity, salinity, and ambient pressure head of each permeable zone.

The flowing FEC logging method is found to be more accurate than spinner flow meters and much more efficient than packer tests in evaluating hydraulic transmissivity values along the wellbore (Tsang et al., 1990; Paillet and Pedler, 1996; Karasaki et al., 2000). Spinner flow meters are very sensitive to variations in wellbore radius, because they measure a local fluid velocity that is inversely proportional to wellbore radius. In contrast, fluid FEC logging provides a more integrated measure of fluid velocity in the well, as reflected by the movement of FEC peaks, making it less sensitive to minor variations in wellbore radius. However, large washout zones may create fluid velocity changes that introduce spurious effects into the FEC logs. Engineered changes in wellbore radius also affect the fluid velocity in the wellbore, but these may be accounted for explicitly in the analysis if their depth and magnitude are known.

Analysis Methods

The original analysis method (Tsang et al., 1990) employed a numerical model called BORE (Hale and Tsang, 1988) and was restricted to the case in which flows from the fractures were directed into the borehole (inflow). Recently, the method was adapted to permit treatment of both inflow and outflow, which enables analysis of natural regional flow through the permeable zone and internal wellbore flow, by development of a modified model BORE II (Doughty and Tsang, 2000). Generally, inflow points produce distinctive signatures in the FEC logs (Figure 1), enabling the determination of location z_i, inflow rate q_i, and salinity C_i for the *ith* feed point.

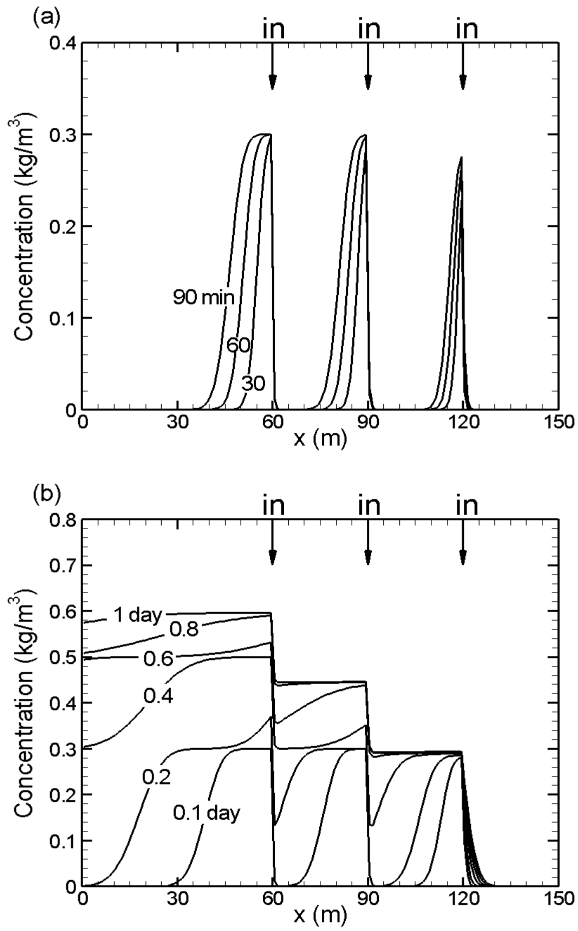

Figure 1. Synthetic flowing FEC data showing a typical time series of logs produced by inflow feed points for (a) early times, before peaks from individual feed points interfere with one another; and (b) late times, when peaks begin to interfere. The one-day log shows nearly steady-state conditions.

Outflow feed points

Identifying outflow locations and flow rates is more difficult, because outflow feed points generally do not produce a distinct signal of their own in the FEC logs, but do influence the evolution of peaks from deeper (or upstream) inflow points (Figure 2a). Therefore, we utilize the depth-integral of the FEC log, denoted M, and examine its time variation $M(t)$ to infer outflow point location and flow rate (Figure 2b). As long as an inflow peak has not encountered an outflow point as it moves up the wellbore, $M(t)$ increases linearly, with constant slope dM/dt denoted S_{early}. When the peak reaches one or more outflow points, some fluid leaves the wellbore, and the rate of $M(t)$ increase slows. When the peak has passed the uppermost outflow point, $M(t)$ again becomes linear, with a smaller constant slope S_{late}. By comparing the time-series of FEC logs with the $M(t)$ plot, outflow point location can be bracketed. The decrease in slope of the $M(t)$ plot determines outflow point flow rate q_i according to

$$q_i = \frac{S_{\text{early}} - S_{\text{late}}}{C_{\text{max}}}. \qquad (1)$$

where C_{max} is the maximum salinity of the peak passing the outflow point.

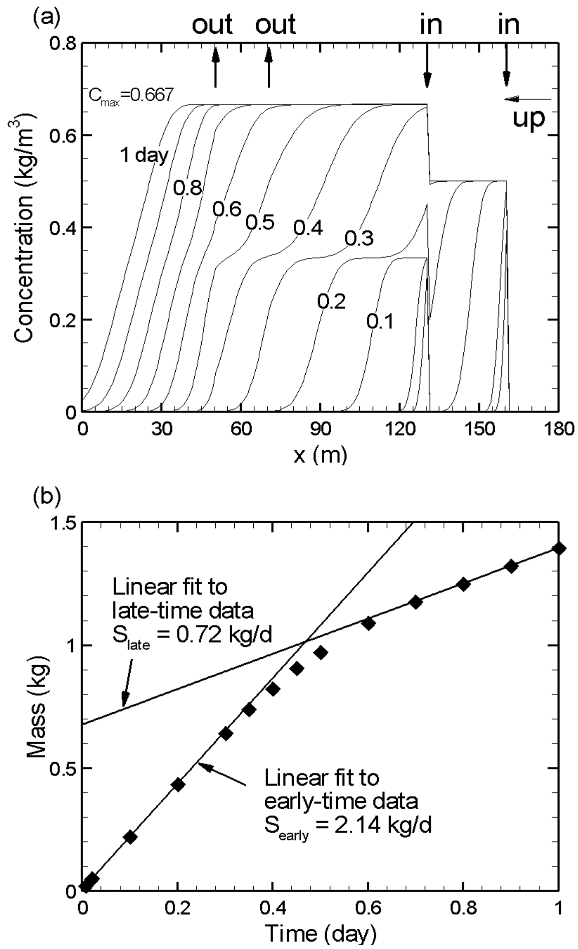

Figure 2. (a) Synthetic flowing FEC data showing a time series of logs produced by inflow and outflow feed points; (b) the corresponding mass integral M as a function of time (symbols) and linear fits for early and late times (lines).

Multi-rate analysis

If the pressure drawdown in the wellbore during pumping is measured, and if the ambient pressure heads h_i of all the feed zones are assumed to be equal, then feed-point flow rate q_i can be converted to the hydraulic transmissivity T_i of the corresponding fracture or permeable zone using Darcy's law. Conducting flowing FEC logging using two different pumping rates can provide information on T_i and h_i in the general case when all the h_i are not the same. For each pumping rate Q, FEC logs are analyzed to produce a set of feed-point strengths q_i and salinities C_i. We generally assume that the C_i values do not change with Q, so feed-point properties are adjusted until a single set of C_i values produces a good match for all pumping rates. We then examine the changes in q_i for a given change in Q. Specifically, suppose that two sets of flowing FEC logs are collected, using $Q^{(1)}$ and $Q^{(2)}$, with $Q^{(2)} - Q^{(1)} = \Delta Q$, and that the resulting BORE II analyses yield $q_i^{(1)}$ and $q_i^{(2)}$, with $q_i^{(2)} - q_i^{(1)} = \Delta q_i$. Then a simple derivation (Tsang and Doughty, 2003) gives

$$\frac{T_i}{T_{tot}} = \frac{\Delta q_i}{\Delta Q} \qquad (2)$$

$$\frac{(h_i - h_{avg})}{(h_{avg} - h_{wb}^{(1)})} = \frac{q_i^{(1)}/Q_1}{\Delta q_i/\Delta Q} - 1 \tag{3}$$

where $T_{tot} = \Sigma T_i$ can be obtained by a normal well test over the whole length of the borehole, $h_{avg} = \Sigma(T_i h_i)/T_{tot}$ is the steady-state pressure head in the borehole when it is shut in for an extended time, and $h_{wb}^{(1)}$ is the pressure head in the wellbore during the logging conducted while $Q = Q_1$. Figure 3 illustrates this procedure, using field data.

Signature catalog

We have found that the inverse problem of determining feed-point properties by matching modeled and observed FEC logs can be expedited by developing a catalog of typical FEC signatures produced by specific feed-point features (Doughty and Tsang, 2002). With such a catalog, complex FEC logs can be interpreted in terms of the individual features, not only yielding parameter values for hydraulic properties of the fractures or permeable layers corresponding to feed points, but also providing insight into flow processes occurring at the site.

Acknowledgments

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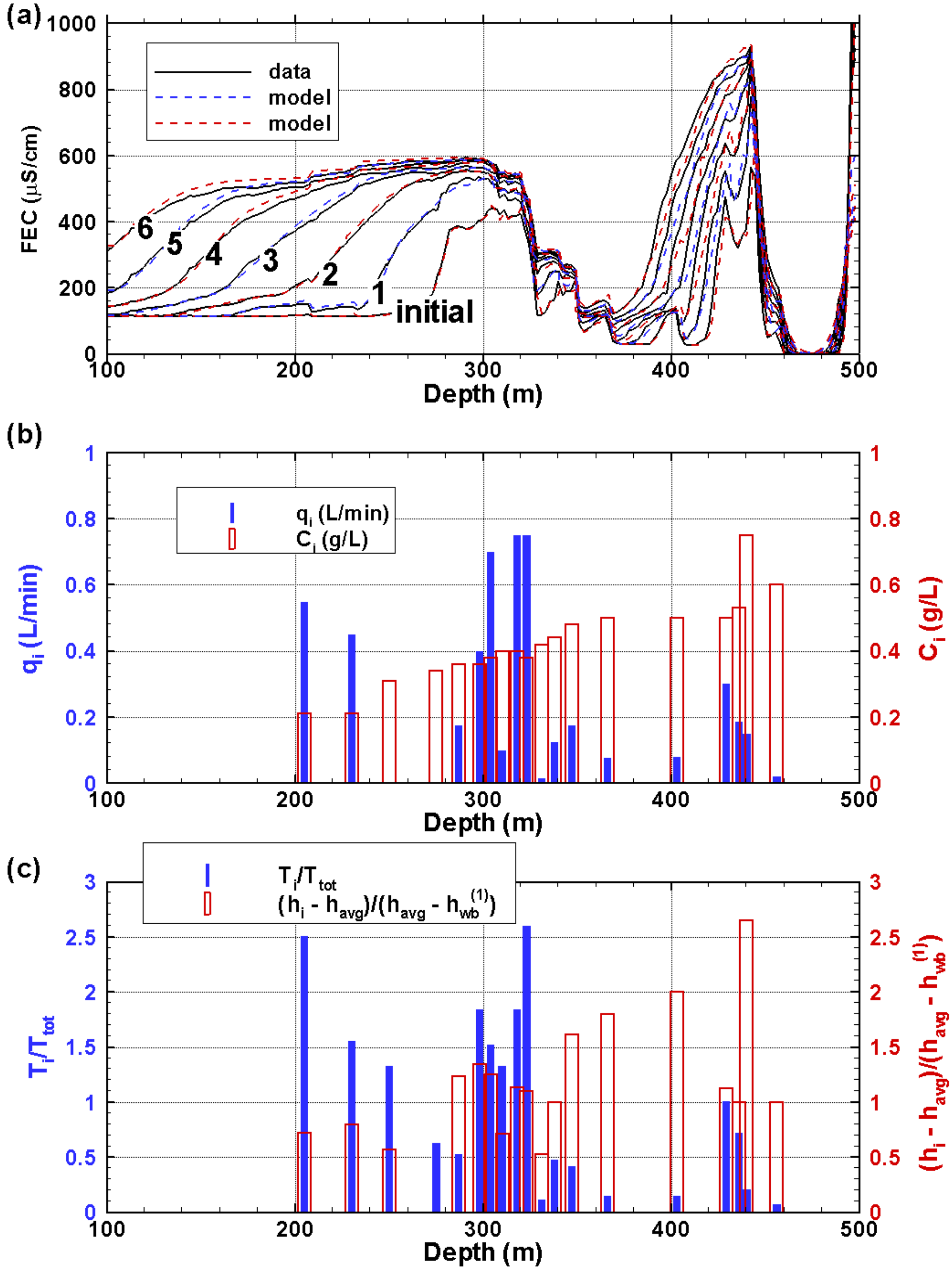

Figure 3. (a) Flowing FEC data showing a time series of logs for field data (black lines) and a calibrated model (red and blue lines). This is the result of analyzing one set of logs at one constant Q. (b) Feed-point inflow rates and salinities inferred from the match shown in (a); and (c) Feed-point transmissivities and ambient pressure heads inferred from flowing FEC logging conducted at two pumping rates by combining two sets of result like (a) and (b) and using Equations (2) and (3).