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Title:

A REFINED APPROACH TO ESTIMATING EFFECTIVE FLOW POROSITY FROM CROSS-HOLE TRACER TESTS IN FRACTURED MEDIA

Author(s):

Paul W. Reimus
C-INC

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A Refined Approach to Estimating Effective Flow Porosity from Cross-Hole Tracer Tests in Fractured Media

Paul W. Reimus
Chemistry Division, Los Alamos National Laboratory

Introduction

Effective flow porosities derived from cross-hole tracer tests in fractured rock using analysis methods that assume radial flow are often significantly higher than would be expected based on fracture density and aperture data obtained from borehole logs and/or cores. Flow surveys of pumped wells in fractured rocks frequently indicate a small number of relatively discrete flow zones, suggesting that most water is produced from a few individual fractures or narrow fracture zones. This situation should result in very small flow porosities. In a heterogeneous fracture network, it is possible that a large percentage of the water drawn to the production well may make essentially no contribution to a cross-hole tracer response because it comes from a fracture or fracture zone that has no hydraulic connection to the tracer injection well. If the heterogeneous flow field is such that the fraction of the production flow rate that contributes to the cross-hole tracer response is less than it would be in the case of ideal radial flow, an overestimation of the effective flow porosity will result. The purpose of this study is to investigate the errors and biases associated with flow porosity estimates obtained from cross-hole tracer tests in fractured systems using analysis methods that assume radial flow, and to suggest guidelines for "correcting" these estimates to obtain better estimate the "true" flow porosity.

Methods

Simulations of cross-hole tracer tests in 2-D hydraulic conductivity fields that represent fractured rock were conducted, and the resulting apparent flow porosities calculated from the tracer responses assuming radial flow were compared with flow porosities obtained from constant-gradient flow and transport simulations across the same 2-D fields. The latter flow porosities were taken to be the "true" flow porosities of the flow domains.

The simulations were conducted as follows:

(1) Two-dimensional hydraulic conductivity fields were stochastically generated in which two fracture sets were superimposed on a background conductivity field. The fracture sets were oriented at a 70-degree angle to each other, with the primary set having longer fractures and an average conductivity 10 times greater than the secondary set. An example of a resulting hydraulic conductivity field (log conductivities) is shown in Fig. 1. Conductivity fields were randomly generated with the primary fracture set oriented at 0-, 22.5-, 45-, 67.5-, and 90-degree angles relative to the horizontal direction in Fig. 1, which was the direction that the two wells were always oriented in cross-hole flow and transport simulations. Also, for each orientation, conductivity fields were generated in which the fracture conductivities were 10000 times and 1000 times higher than the background conductivities.

(2) For each combination of fracture orientation and fracture conductivity (relative to background), flow simulations were conducted on twenty-five different realizations of random conductivity fields. For each field, simulations were conducted for (1) constant-gradient flow across the domain, (2) steady flow to a production well at the center of the domain, and (3) steady flow between an injection well and a production well, with the injection flow rate being 10% of the production flow rate. The latter two cases represented

flow fields in cross-hole tracer tests with no recirculation and 10% recirculation, respectively, from the production well to the injection well. Fig. 2 depicts flow fields for the constant-gradient and the 10%-recirculation cases associated with the conductivity field shown in Fig. 1.

(3) Tracer transport in each flow field was simulated using a particle-tracking algorithm. In the constant-gradient cases, particles were introduced at the left boundary of the domain and the times required to reach the right boundary were calculated. In the cross-hole cases, particles were introduced at the injection well and their times to reach the production well were calculated.

(4) The "true" effective flow porosity for a given conductivity field was taken to be the mean or median arrival time of the particles in the constant-gradient simulations multiplied by the total volumetric flow rate through the domain (obtained from the flow simulations), divided by the total domain volume (length times width times thickness).

(5) Effective porosity estimates from the tracer tests were calculated by inserting either the mean or median particle arrival times from the cross-hole tracer test simulations into a flow porosity expression that assumes radial flow.

Results

Fig. 3 shows cumulative probability distributions of flow porosity "correction factors" (defined as the ratio of apparent porosity to true porosity) obtained from 25 no-recirculation simulations and 25 10%-recirculation simulations with conductivity fields having properties corresponding to Fig 1 (that is, different realizations with the primary fracture set oriented at a 45-degree angle to the two wells). These results are typical of all fracture orientations (relative to the two wells) and conductivity contrasts (relative to background) in that they show a tendency for apparent flow porosities derived from cross-hole simulations to overpredict "true" flow porosities. Assuming there is information available on fracture network statistics for a given flow system, cumulative distributions similar to those of Fig. 3 could, in principle, be used to obtain probability distributions of "true" flow porosities associated with flow porosity estimates derived from tracer tests.

The following generalizations can be made about the results of all simulations:

- The cross-hole simulations with 10% recirculation yielded flow porosity estimates that tended to be much closer to "true" flow porosities than simulations with no recirculation. Also, the standard deviation of log flow porosity estimates from tests with recirculation was always less than from tests with no recirculation (for the same conductivity fields).
- The cross-hole simulations yielded flow porosity estimates that were closer to "true" flow porosities when fracture conductivities were only moderately greater than background conductivities (as opposed to being much greater than background conductivities). Also, the standard deviations of the log of the flow porosity correction factors were smaller when fracture conductivities were only moderately greater than background conductivities.
- There was a general, but not universally followed, trend of decreasing overestimation of flow porosity from cross-hole simulations as the orientation of the primary fracture set became better aligned with the two wells.
- Flow porosity estimates obtained from mean tracer arrival times tended to be closer to true flow porosities than estimates obtained from median arrival times.

Conclusions

This study shows that effective flow porosities derived from cross-hole tracer tests have a strong tendency to overpredict true flow porosities in heterogeneous fracture systems. The tendency toward overprediction decreases as the fracture conductivity relative to background conductivity decreases and as the orientation of the most conductive fractures becomes better aligned with the two wells. Tracer tests with small amounts of recirculation of water from the production well to the injection well are predicted to result in much better estimates of true flow porosity (on average), and much less variability in the estimates, than tests with no recirculation. However, the advantage offered by recirculation decreases as the fracture conductivity relative to background conductivity decreases. A methodology is suggested for using fracture network statistics to obtain probability distributions of effective flow porosities associated with tracer responses in cross-hole tracer tests.

Figures

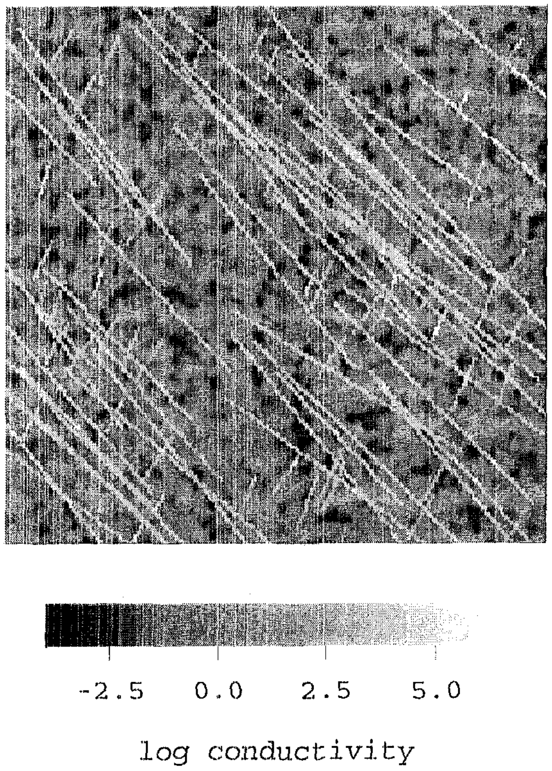
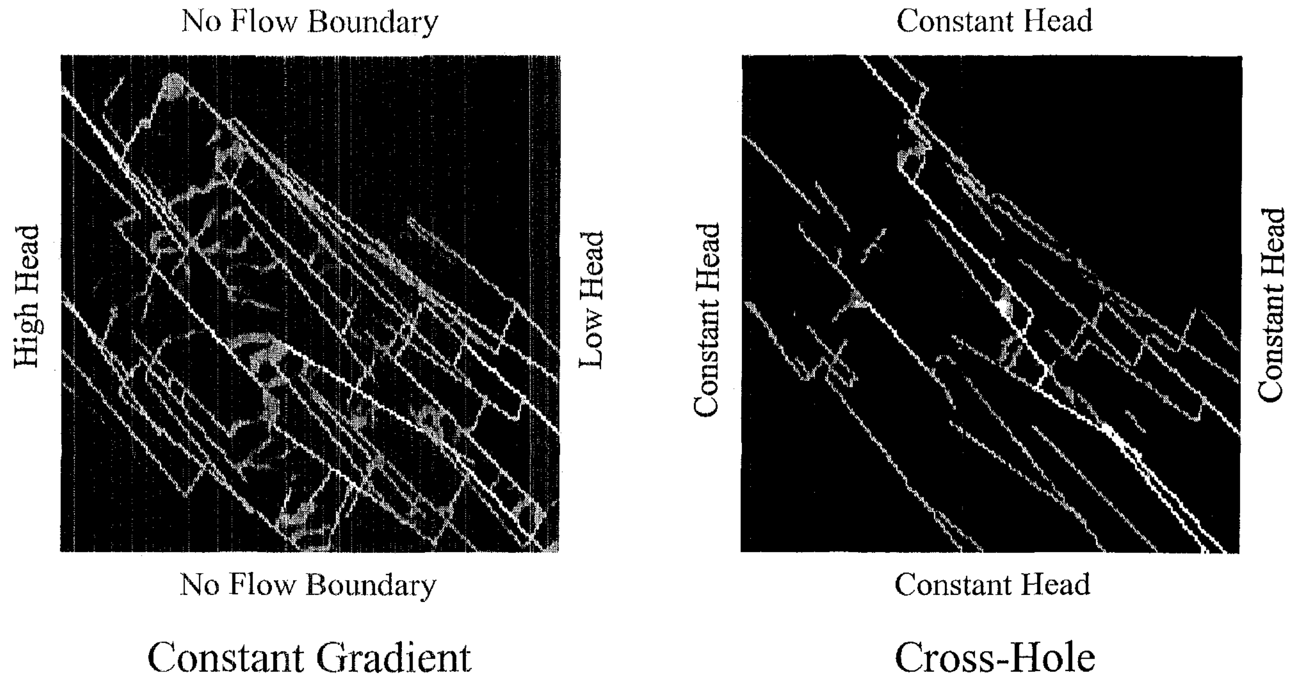


Figure 1. Randomly-generated log hydraulic conductivity field with the primary fracture set oriented at a 45-degree angle to horizontal.



Constant Gradient

Cross-Hole

Figure 2. Representation of flow fields solved within the hydraulic conductivity domain of Fig. 1 for a constant-gradient simulation (left) and a cross-hole simulation with 10% recirculation (right). Light areas indicate where volumetric flow rates are high. The boundary conditions are indicated. For the cross-hole simulation, the production well is located at the center of the domain (bright spot), and the injection well is located at the light dot in the left-hand side of the domain. The apparent effective flow porosity from the cross-hole simulation was 14-20 times the actual flow porosity (depending on whether the mean or median arrival time was used in the calculations).

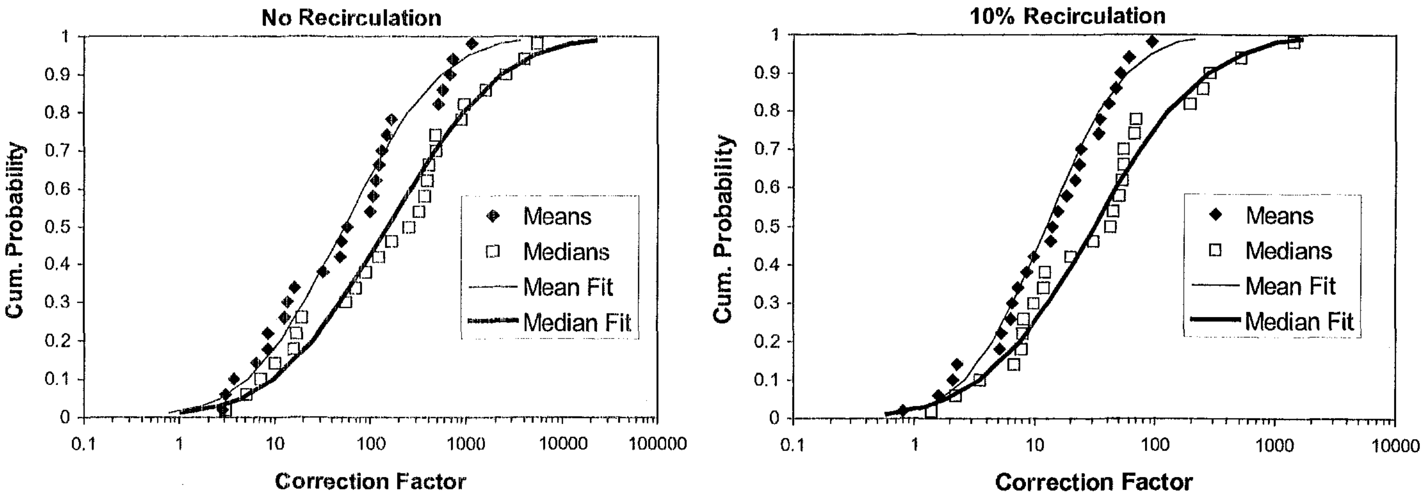


Figure 3. Cumulative probability distributions of flow porosity correction factors obtained from mean and median arrival times in simulations with no recirculation and with 10% recirculation in 25 conductivity field realizations in which the primary fracture set is oriented at a 45-degree angle to the two wells. The lines are fits of lognormal distributions to the data.