Revisitation of the dipole tracer test for heterogeneous porous formations

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Introduction

In dipole tracer tests, also named two-well test or doublet tests, a tracer is introduced at a recharge well and the breakthrough curve (BTC) is measured at a pumping well. The pumped water can optionally be used for recharge in a recirculation. The test setting has the advantage of circumventing the problem of removal of waste water and the need for an additional water source. However, the complex flow pattern causes the interpretation of the transport behavior to be more complicated than uniform flow tracer test. The non-uniform dipole shape of the flow field gives that the observed concentration at the pumping well to be a superposition of tracer transport along different streamlines with different tracer arrival times. Dipole tests in the presence of significant spatial heterogeneity of hydraulic conductivity have rarely been studied. Though, the actual streamline structure of dipole tests is strongly impacted by aquifer heterogeneity.

The foremost aim in this work is to present an alternative interpretation method for dipole tests in heterogeneous media. It will be given a simple solution for interpretation of dipole test in view of geostatistical aquifer characterization. The analytical form of the solution allows a detailed investigation on the impact of heterogeneity, the tracer input conditions and ergodicity conditions at the well. It is further presented how the solution can be used for interpretation of dipole field test in view of geostatistical aquifer characterization on three illustrative examples.

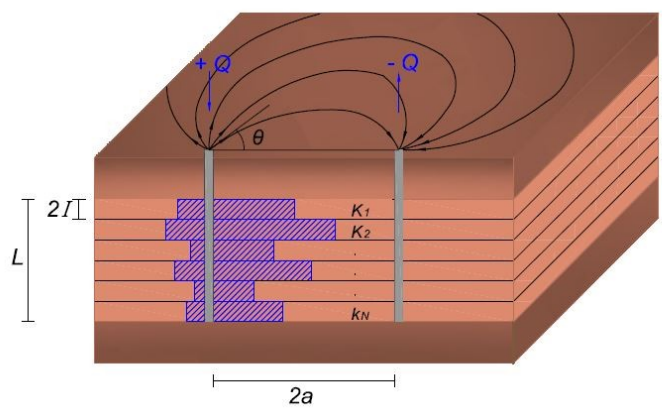

Figure 1: Illustration sketch of the conceptual model with injection well (left) and pumping well (right) at distance 2a, recharge/discharge Q in an stratified aquifer of thickness L with N layers of independent random conductivity K_i.

Mathematical Framework and Characteristics of the Solution

Heterogeneity of hydraulic conductivity is taken into account making use of a geostatistical approach due to the limited data availability in subsurface hydrology. The characteristics of conductivity are captured by the statistical parameters of mean conductivity K_G and the log-conductivity variance σ^2_Y.

The analytical solution for the tracer breakthrough curve at the pumping well in a dipole tracer test is developed by considering a perfectly stratified formation (Figure 1). The heterogeneous confined aquifer is made up from N layers

of vertical thickness 2I, with I the vertical integral scale of hydraulic conductivity. Each layer is of random and independent conductivity K_i. A dipole is created by injecting and extracting a discharge Q in two fully penetrating wells at relative distance 2a. The analysis is carried out making use of the travel time of a generic solute particle, from the injection to the pumping well. Injection conditions are adapted to different possible field setting. Solutions are presented for resident and flux proportional injection mode as well as for an instantaneous pulse of solute and continuous solute injections.

The derived analytical solution associates the shape of the BTC with statistical properties of the conductivity field. Main results related to the analytical solutions are discussed in view of the probability density function of the travel time and the degree of heterogeneity of the aquifer system. The dipole setup always determines a wide variety of paths in the medium, causing a similar variability of arrival times and hence dispersion. The spatial distribution of conductivity present in the aquifer system further enhances the dispersion of solute. For increasing degree of heterogeneity, the travel time distributions depart from the solution for homogeneous formations in two ways: (i) a stronger preferential flow and (ii) a more persistent tail.

The injection mode, flux proportional or resident concentration, has a strong impact on the travel time distribution, especially for highly heterogeneous formations. The effect of the injection condition is small to negligible when heterogeneity is small, while it is important when heterogeneity increases. In particular, the resident concentration injection condition generally leads to a less pronounced preferential flow and a heavier tail.

Conductivity Characterization by the Dipole test with Application Examples

The developed solution can be used for the characterization of hydraulic conductivity, especially to determine the log-conductivity variance σ^2_Y, which epitomizes the degree of heterogeneity in the aquifer. In particular, the results of a dipole test can be interpreted by fitting the analytical solution to the experimental BTC in order to obtain the variance. A few application examples are presented. In all cases a log-normal conductivity can be assumed, and hence the solution is employed for the fitting of the experimental data. A visual fit of the analytical curve with the experimental data for two of the field test examples are given in Figure 2. The estimated variances are compared to available data of previous geostatistical investigations at the sites. The estimates are in very good agreement with the determined heterogeneity of the aquifer at the example sites.

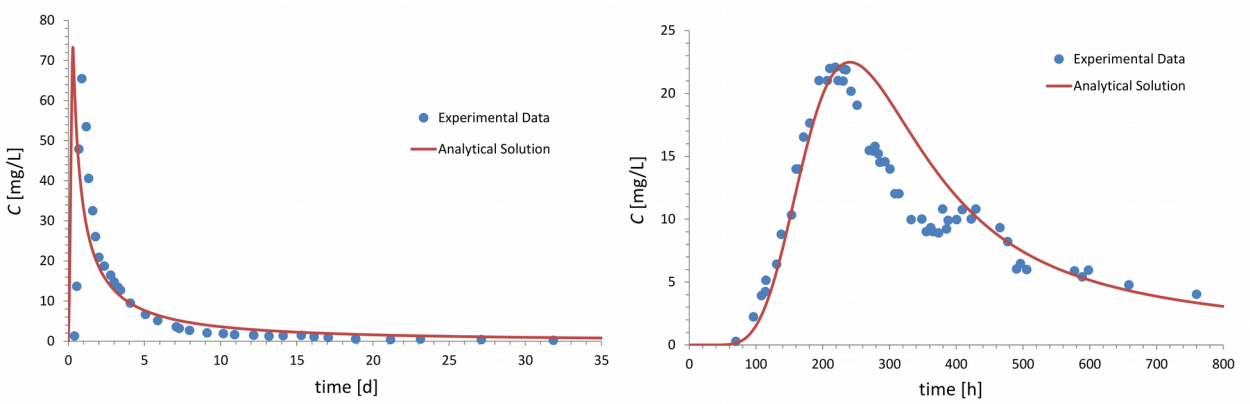

Figure 2: Experimental results of dipole tracer tests and their interpretation by the proposed analytical model: (left) Dipole test at the MADE site [1]; (right) dipole tracer test at the Mobile site [2].

References

[1] Bianchi, M., Zheng, C., Tick, G. R., Gorelick, S. M., Investigation of Small-Scale Preferential Flow with a Forced-Gradient Tracer Test. *Ground Water* **49** (4), 503–514, (2011)

[2] Molz, F. J., Güven, O., Melville, J. G., Crocker, R. D., Matteson, K. T., Performance, analysis, and simulation of a two-well tracer test at the Mobile Site. *Water Resour. Res*. **22** (7), 1031–1037, (1986).