Journal of Hydrology 510 (2014) 504–512

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Application of tracer injection tests to characterize rock matrix block size distribution and dispersivity in fractured aquifers

Amin Sharifi Haddad, Hassan Hassanzadeh *, Jalal Abedi, Zhangxin Chen

Department of Chemical & Petroleum Engineering, Schulich School of Engineering, University of Calgary, 2500 University Drive NW, Calgary, AB, Canada T2N 1N4

ARTICLE INFO

Article history:
Received 5 July 2013
Received in revised form 26 December 2013
Accepted 6 January 2014
Available online 10 January 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Jean-Raynald de Dreuzy, Associate Editor

Keywords:
Ground water
Fractured rock
Solute transport
Breakthrough curve
Aquifer characterization
Dispersivity

SUMMARY

The complexity of mass transfer processes between the mobile and immobile zones in geohydrologic settings and the limitations that currently exist in the characterization of contaminated sites demand the development of improved models. In this work, we present a model that describes the mass transfer in structured porous media. This model considers divergent radial advective–dispersive transport in fractures and diffusive mass transfer inside rock matrix blocks. The heterogeneous nature of fractured formations is included with the integration of various distributions of rock matrix block sizes into the transport model. Breakthrough curves generated based on the developed model are analyzed to investigate the effects of the rate of injection, dispersivity and the immobile to mobile porosity ratio on mass transfer between mobile and immobile zones. It is shown that the developed model, in conjunction with tracer data collected from a monitoring well, can be used to estimate the dispersivity and fracture intensity. Results reveal that the dispersivity is independent of the rock matrix block size distribution for dispersion-dominant transport in fractures. These findings are used to develop a methodology to characterize rock matrix block size distribution in fractured aquifers and to estimate dispersivity based on a tracer test, which will improve our decisions concerning the remediation of contaminated sites.

1. Introduction

It is estimated that a quarter of the world's population is supplied by water from fractured aquifers (Ford and Williams, 2007). Therefore, a better understanding of fluid flow and transport in fractured formations is important. The characterization of subsurface formations is a multidisciplinary field that is applied to hydrocarbon bearing zones and subsurface hydrology. This approach relies on expertise from geology, geophysics and engineering disciplines. There are different methods to characterize the natural fractures in the aquifers, which are discussed briefly in this section.

A core analysis and logging tools can be used to study aquifers. However, observations of the fractures in core and image logs typically provide limited information on fracture orientation, aperture and intensity. Modeling approaches have been used to develop geostatistical and geomechanical models for the estimation of fracture distribution, based on core samples and outcrop data (e.g., Gauthier et al., 2002). Some researchers tried to model fracture density with fractal geometry (e.g., Kulatilake et al., 1993; La Pointe, 1988; Roy et al., 2007; Watanabe and Takahashi, 1995).

Geomechanical methods based on the mechanical properties of the rock along with the information related to the process of fracturing have been used to generate a logical model of fractures, including their spacing, length, connectivity, and aperture (Olson et al., 2001). Seismic methods provide another approach for the analysis of fractured rocks (Lines and Newrick, 2004). Neural network methods have also been used to investigate fractured reservoir characterization (Ouenes, 2000; Ouenes et al., 1995; Zellou et al., 1995). Well testing and hydraulic properties are another source for modeling of fractured formations (e.g., Niemi et al., 2000).

The effects of rock matrix block size distributions in fractured formations have been investigated in some works related to a pressure transient analysis (Belani and Jalali-Yazdi, 1988; Braester, 1984; Cinco-Ley et al., 1985; Jelmert, 1995; Johns and Jalali-Yazdi, 1991; Spivey and Lee, 2000). A more detailed review on the pressure transient analysis can be found in Sharifi Haddad et al. (2012).

A large number of investigations have shown the impact of heterogeneity on solute transport in subsurface formations (e.g., Haggerty and Gorelick, 1995; Jardine et al., 1999; Neretnieks, 1980; Roubinet et al., 2013; van Genuchten, 1985). One of the heterogeneity sources that affect the preferential path of contaminants in the subsurface is the variation of the rock matrix block size distribution in fractured aquifers. Different test designs, such

* Corresponding author. Tel.: +1 403 210 6645; fax: +1 403 284 4852.
E-mail address: hhassanz@ucalgary.ca (H. Hassanzadeh).

0022-1694/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2014.01.008

as forced divergent flow, convergent flow and natural gradient flow, have been used (Gelhar et al., 1992). In addition, various multi-tracer injection schemes with different tracers were tested to study the mass transfer behavior in the fractured aquifers (e.g., Liu et al., 2004b; Rasmuson and Neretnieks, 1981).

Laboratory studies of solute transport in fractured rocks have led to well documented findings (e.g., Fleming and Haggerty, 2001; Gwo et al., 1998; Hu and Brusseau, 1995). Numerous tracer tests have also been conducted in the investigation of mass transfer in field-scale investigations at many sites (e.g., Becker and Shapiro, 2000; Jardine et al., 1999; Sanford et al., 1996; Webster et al., 1970). Based on the observations in laboratories and field-scale tests, conceptual and mathematical models were derived to represent the mechanisms of solute transport and migration of radionuclide in subsurface considering the heterogeneity of the geological formation (Carrera et al., 1998; Haggerty and Gorelick, 1995; Lee et al., 1992; Maloszewski and Zuber, 1985, 1990, 1993; Neretnieks, 2006; Rasmuson and Neretnieks, 1980, 1981; Sudicky and McLaren, 1992; Tang et al., 1981; Wilson et al., 1998). A brief review of the previous works on mass transfer in fractured rocks is provided in Sharifi Haddad et al. (2012).

van Genuchten and his colleagues developed models of solute transport in soils and groundwater, which included various models for macropores during an advective–dispersive process (van Genuchten, 1985; van Genuchten and Dalton, 1986; van Genuchten et al., 1984, 2009). In addition, van Genuchten (1985) proposed a shape factor parameter as a function of the average matrix concentration, which was consequently time-dependent. The shape factor was derived to represent an equivalent first-order mass exchange model for unidirectional advective–dispersive transport.

Studies on the solute transport were conducted through modeling and experimental tools (Becker and Shapiro, 2003; Cihan and Tyner, 2011; Gwo et al., 2005; Liu et al., 2004a, 2004b, 2007; Mathias et al., 2007, 2009; Neretnieks, 2002; Zhou et al., 2006, 2007), which resulted in an understanding of mass transfer in fractured rock systems.

Doughty and Karasaki (2002) simulated a single-well pump test in a fractured aquifer with hierarchical fracture networks with well-defined fractal dimensions. They concluded that there is a relationship between fractal dimension and other variables such as breakthrough time and maximum concentration. Roubinet et al. (2013) also simulated the effect of heterogeneity on the solute transport in the fractured porous media through two-dimensional Sierpinski lattice structures. They found that hydraulic and structural properties of the fractured rocks control the solute travel time. Sharifi Haddad et al. (2012) performed modeling of mass transfer between mobile and immobile zones in the presence of the rock matrix block size distribution for the case of a piston flow regime inside the fractures. They found that, during the transient period, the rock matrix block size distribution had a significant impact on the rate of mass transfer between the mobile and immobile zones. They identified that the rate of injection and the radial distance from the injection well affect the stabilized value of the mass transfer coefficient. They demonstrated that this stabilized value is independent of the rock matrix block size distributions. However, a piston flow assumption does not allow for reliable determination of rock matrix block size distribution from tracer breakthrough data.

To alleviate this problem, we extend the Sharifi Haddad et al. (2012) model by considering a more representative physical system, which includes the dispersive solute transport in fractures. The existence of dispersivity increases the complexity of the problem, but provides a more reliable and practical model for fractured rock characterization.

In the above investigations, the rock matrix block size was demonstrated as a key parameter for solute transport. Therefore, methods such as a seismic approach, well logging and a pressure transient analysis were employed to characterize the rock matrix block size distribution. However, each of these methods has its own advantages and disadvantages, such as in the radius of investigation and indirectness (seismic) of the data obtained for interpretation of the subsurface rock properties. Each of the methods introduced for characterization of the rock matrix block size distribution uses different methodology and reports the fracture intensity based on the measure of a specific variable depending on the nature of the phenomenon. Therefore, the measured fracture intensity from a seismic, mechanical or pressure transient analysis approaches and a tracer test can be different. These analyses can be used for fractured rock characterization from different sources of measurements.

In this study, an analytical model of tracer injection is used as a complementary technique to characterize the fractured rocks. This method involves the whole subsurface interval from an injection point to the monitoring well with its heterogeneous nature. It is shown that, based on the concentration data from the monitoring well, the dispersivity of the aquifer can be estimated in the field scale. Thus, the tracer concentration in the monitoring well can be used as a complementary diagnostic tool to characterize the rock matrix block size distribution in fractured aquifers. The developed method in this paper is a complementary method for fractured aquifers characterization and aims at the minimization of probable inaccuracies, which may arise as a result of using a single source of data. Inaccuracies in the sources of data such as the limitation of the wavelength in seismic methods, core sampling related measures and variable hydraulic properties of fractures during tracer tests motivated the study of the tracer test as one source of data to be used along with other methods for characterization of rock matrix block size distribution.

This paper is structured as follows: First, a solute transport model is introduced. Next, the results are discussed. The application of a graphical method to characterize rock matrix block size distribution is presented, followed by concluding remarks.

2. Description of the problem and mathematical model

Fig. 1 shows a schematic of the physical system under consideration. It is assumed that the fractured aquifer has a constant thickness with impermeable top and bottom boundaries. A tracer is injected into a fully penetrated vertical well in which a divergent radial flow with steady state hydraulic head distribution exists. The injected fluid is assumed to be a single phase, fully miscible

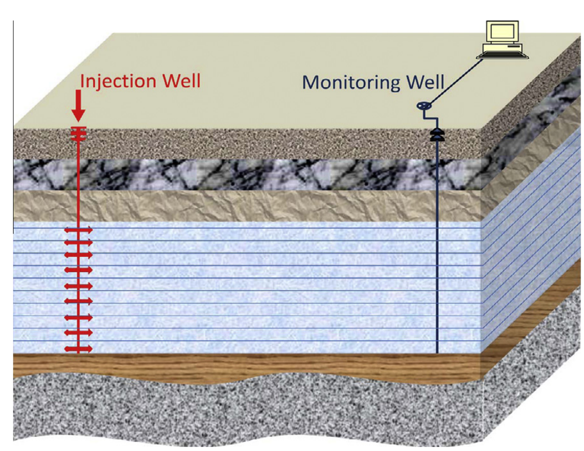

Fig. 1. Schematic of the physical system of a divergent radial flow for the characterization of rock matrix block size distribution in fractured aquifers.