ISSN (Online) : 2319 - 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization, Volume 2, Special Issue 1, December 2013

Proceedings of International Conference on Energy and Environment-2013 (ICEE 2013)

On 12th to 14th December Organized by

Department of Civil Engineering and Mechanical Engineering of Rajiv Gandhi Institute of Technology, Kottayam, Kerala, India

EVALUATION OF CRITICAL FRACTURE SKIN POROSITY FOR CONTAMINANT MIGRATION IN FRACTURED FORMATIONS

Vinish V. Nair

Associate Professor, RIT Kottayam, Kerala, India

ABSTRACT

Most of the studies reported in literature on fluid flow and mass transport in fractured formations are based on the assumption that fractures control the overall conductivity of the rock and the porous matrix just provides storage. However, field observations of rock fractures at many locations have shown that fractures in the field can be rather very complex. Observations at some sites have revealed that the portion of the rock matrix adjacent to many open fractures, referred to as the fracture skin, have different transport properties compared to that of the undisturbed rock matrix. This, in turn, is likely to influence the transport of solutes through these formations. To perform modelling in this situation, a numerical model is developed in the present study based on triple continuum approach incorporating the fracture skin as the third continuum. The numerical model is based on the finite difference method and employs a fully implicit formulation. An attempt is made to evaluate the critical fracture skin porosity for crystalline fractured formations.

1. INTRODUCTION

Understanding flow and contaminant transport in fractured formations is of considerable importance from the point of view of exploitation and preservation of groundwater resources. Fractures are geometrically complex structural discontinuities which significantly influence the dynamics of flow through geological formations. They generally offer a path of least hydraulic resistance for the transport of hydrothermal fluids, water and contaminants in groundwater systems, and oil and gas in petroleum reservoirs. Fractures also form critical pathways through otherwise impermeable or low permeability rocks, as they may enable radioactive and toxic industrial wastes to escape from underground storage repositories and reach the biosphere.

Some recent investigations have revealed that the portion of the rock matrix adjacent to many open fractures, referred to as the fracture skin, can have different sorption and diffusion properties compared to those of the undisturbed rock matrix and this may influence the retardation and transport of solutes. Fracture skins are ubiquitous in nature and are especially noticeable in fractured formations or doubly porous rocks where there is an interchange of fluids and solutes between the fracture and the matrix [1].

This interchange causes precipitation, typically, of iron and manganese oxides [2] or calcite [3-4] and may dramatically alter the transport properties of the formations at the interface between the fracture and the matrix. Fracture skins include the zones of altered rock abutting the fracture and coatings of by infiltered debris precipitated minerals and organic matter on the fracture surfaces [1]. Moench [5] studied the influence of fracture skins on flow of groundwater in a fractured aquifer. Robinson et al. [1] presented an analytical solution for the problem of contaminant transport in a finite set of parallel fractures with fracture skin. Zimmerman et al. [6] investigated the effect of sorption of organic solutes on fracture surfaces using an experimental fracture-flow apparatus and observed increase in the amount of solute sorbed with decreasing flow rate and decreasing compound solubility. Garner and Sharp [7] analyzed solute migration in granitic rocks with fracture skin at two climatically different field sites. Nair and Thampi [8] analysed the influence of solute velocity on the transport of contaminant in fractures with fracture skin. Literature review reveals that, till date, very few numerical models have been developed to investigate the effect of fracture skin on contaminant transport through fractured formations. In this study, a numerical model based on the triple continuum approach is developed to simulate reactive solute transport in a fractured formation. The concentration profiles along the fracture are computed for a constant solute concentration source at the inlet boundary. The numerical model employs a fully implicit finite difference method based numerical scheme. Sensitivity analysis is carried out to determine the most critical fracture skin parameters affecting contaminant transport in a fractured formation. An attempt is also made to evaluate the critical fracture skin porosity for contaminant transport in crystalline fractured formations.

TABLE 1. DATA USED IN THE BASE CASE FOR CONSERVATIVE SOLUTE TRANSPORT (GARNER AND SHARP 2004)

Parameters	Values
Average flow velocity in the fracture	1.0 m/d
Dispersion coefficient in the fracture	0.001 m^2/d
Diffusion coefficient of skin	8.64×10^{-7} m^2/d
Diffusion coefficient of matrix	8.65×10^{-10} m^2/d
Porosity of skin	0.09
Porosity of matrix	0.024
Half fracture aperture	0.000565 m
Skin thickness, $(d\text{-}B)$	0.0207 m
Retardation coefficient of fracture surface	1
Retardation coefficient of skin	1
Retardation coefficient of matrix	1
Coefficient of radioactive decay	1×10^{-12} d^{-1}
Fracture spacing	13.1 m

2. MATHEMATICAL MODEL

The schematic diagram of the fracture-skin-matrix system considered in this study is presented in Fig.1. It consists of a set of identical fractures, whose axes are parallel and equally spaced, the fracture skin being of constant thickness. The following transport processes have been considered in the present work: 1) advective transport along the fracture, 2) hydrodynamic dispersion within the fracture in the direction of the fracture axis, 3) diffusion-limited solute transport at the fracture-skin interface, 4) adsorption onto the fracture wall, 5) adsorption within the skin, 6) diffusion within the fracture skin, 7) adsorption within the matrix, 8) effective diffusion within the matrix, and 9) radioactive decay.

The following assumptions are made regarding the system geometry and the hydraulic properties influencing solute transport in fractured formations.

(1) The length of the fracture is much larger than its width.

(2) Transverse diffusion and dispersion within the fracture ensure complete mixing across fracture width at all times.

(3) Permeability of the fracture skin and the matrix is very low and the transport within the skin and the matrix occurs mainly by effective molecular diffusion.

(4) Transport along the fracture is much faster than transport within the fracture skin and the matrix. Local equilibrium is assumed for the mass partition mechanisms in the fractured system throughout the flow domain as an approximation at the macroscopic scale. Local equilibrium assumption can be used if the contaminant sorption onto or desorption from the fracture surface is sufficiently fast relative to the convective transport. In the fracture, velocity is assumed to be constant with time and uniform in space and the water flow is assumed to be laminar. Solute transport processes in the fracture-skin-matrix system can be described by coupled one-dimensional equations, coupling being provided by the continuity of fluxes and concentrations at the interface. The differential equation for the fracture is based on mass balance for an element in the fracture. Solute transport processes in a fracture-skin-matrix system can be described by coupled one-dimensional equations, the coupling being provided by the continuity of fluxes and concentrations at the interface. The governing differential equations for the fracture is given by

$$\frac{\partial^2 C_f}{\partial z^2} - \frac{v}{D}\frac{\partial C_f}{\partial z} - \lambda \frac{R_f}{D} C_f + \frac{\varphi D}{BD}\frac{\partial C_s}{\partial x}\bigg|_{x=B} = \frac{R_f}{D}\frac{\partial C_f}{\partial t} \qquad (1)$$

The corresponding differential equation for the fracture skin is as follows:

$$\frac{\partial^2 C_s}{\partial x^2} - \lambda \frac{R_s}{D_s} C_s = \frac{R_s}{D_s}\frac{\partial C_s}{\partial t} \qquad (2)$$

The differential equation for the matrix can be written as

$$\frac{\partial^2 C_m}{\partial x^2} - \lambda \frac{R_m}{D_m} C_m = \frac{R_m}{D_m}\frac{\partial C_m}{\partial t} \qquad (3)$$

where subscripts *f, s* and *m* denote the fracture, skin and matrix respectively, *C* is the concentration of the solute, *R* is the retardation factor, *v* is the average linear groundwater velocity in the fracture, *B* is the half fracture aperture, *D* is the hydrodynamic dispersion coefficient, φ is the porosity and λ is the coefficient of

radioactive decay.

3. NUMERICAL MODEL

In this study, the fracture-skin-matrix system, described by the set of coupled partial differential equations, is solved using a numerical model based on the finite difference method. A fully implicit numerical scheme is employed in the numerical model. The advection part in equation (1) is handled using an upwind implicit approach. The resulting system of equations is solved using the Thomas algorithm. To satisfy the continuity of fluxes at the fracture–skin interface, the solution is iterated at each time step. A smaller grid size at the fracture-skin interface helps to accurately simulate the concentration flux into the fracture skin. The maximum value of Courant number is fixed at 0.2. For validation of the numerical model, concentration profiles along a fracture were computed for a constant concentration inlet boundary condition with the data given in Table 1. The concentrations of contaminant along the fracture at the end of 500 days, 1000 days and 5000 days were computed using the numerical model and the computed results were compared with the corresponding concentration profiles derived using the analytical solutions of Robinson et al. (1998). It is observed that the computed results are in good agreement with the analytical solution (Fig. 2).

4. RESULTS AND DISCUSSION

The numerical model developed in this study is used to compute contaminant concentrations along the fracture, fracture skin and matrix at the end of 500 days. The length of the parallel fractures is taken as 350m. Other data used in the simulations are presented in Table 1. A detailed sensitivity analysis was conducted to evaluate the critical fracture skin properties affecting contaminant migration in fractured media.

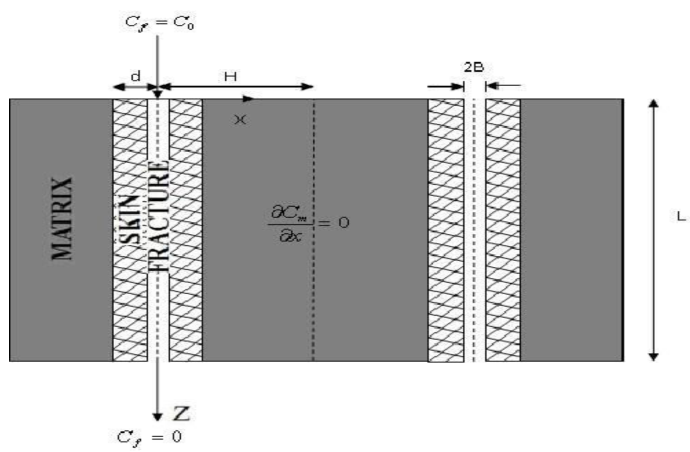

FIG. 1 IDEALISATION OF THE FRACTURE-SKIN- MATRIX SYSTEM

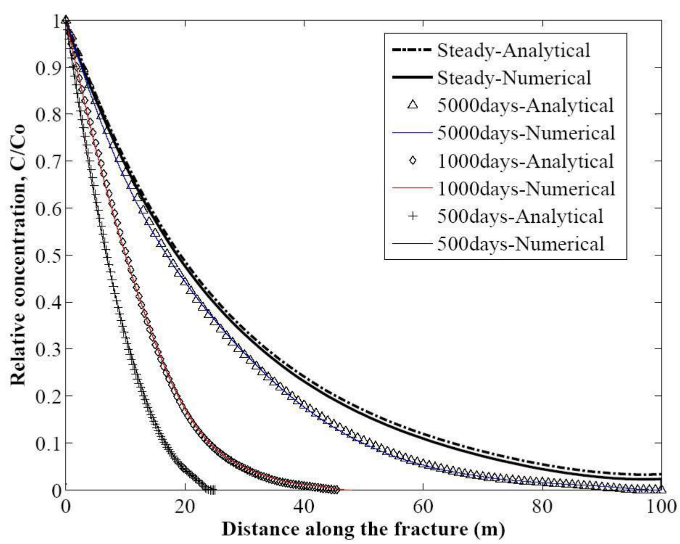

FIG. 2 COMPARISON OF NUMERICAL SOLUTION WITH THE ANALYTICAL SOLUTION OF ROBINSON ET AL. (1998)

It is very important to evaluate the critical fracture skin porosity beyond which the use of triple continuum models is warranted in the analysis of contaminant transport in fractured formations.

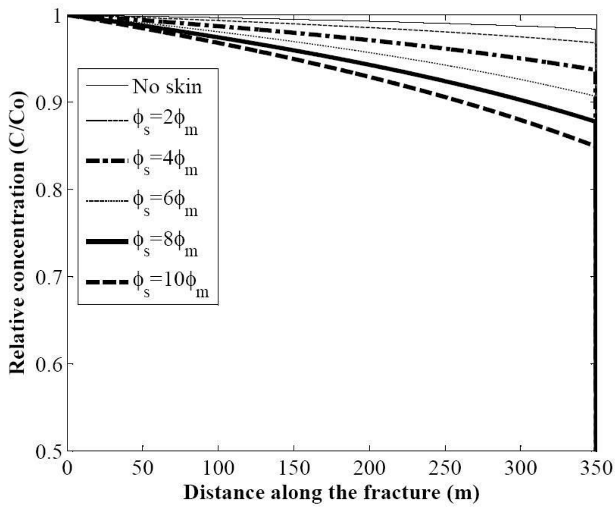

FIG. 3 INFLUENCE OF SKIN POROSITY ON SOLUTE TRANSPORT

Most of the open fractures in the field possess a fracture skin [1] and measurement of the transport properties of the skin is extremely difficult. In order to evaluate the critical skin porosity, other transport properties (diffusion coefficient and retardation coefficient) of the fracture skin are set equal to that of the rock matrix and the porosity of the fracture skin is increased in steps up to 10 times the porosity of the matrix. The resulting concentration profiles along the fracture are computed for different matrix porosities ranging from 0.01 to 0.1. The concentration profiles obtained from various simulations are plotted. The concentration profile for the base case is presented in Fig. 3. It is clear from the computed concentration profiles that the change in relative concentration is within 5% of that for the no skin condition up to a skin porosity equal to four times the matrix porosity.

5. CONCLUSION

A numerical model is developed to describe contaminant transport in fractured formations with fracture skin, using the triple continuum approach. The model incorporates advection and longitudinal dispersion in the fracture, sorption onto the fracture wall, diffusion-limited solute transport normal to the fracture-skin interface, sorption and diffusion within the fracture skin, sorption and diffusion within the matrix and radioactive decay. Simulations were performed with a constant input source concentration at the inlet boundary of the fracture to investigate the effect of various transport parameters of fracture skin on contaminant migration in fractured formations. Results indicate that skin porosity and skin diffusion coefficient are the most critical fracture skin properties affecting contaminant transport in fractured formations. The critical skin porosity and critical diffusion coefficient values are evaluated for different rock porosities. It is observed that the critical skin porosity for crystalline rocks with small diffusion coefficients is about four times the matrix porosity. The critical skin diffusion coefficient depends on fracture skin porosity. Variation in contaminant concentrations along the fracture is small from the case with no fracture skin at low skin porosities. The results of this work are useful in characterization studies of solute spread in crystalline fractured rock formations with fracture skin and have implications on the management of waste disposal in such formations. The ability of the present numerical model to predict the fate and transport of contaminant in fractured media and to understand the transport processes in these systems would be of great economic benefit for planning and implementation of the remediation of contaminated fractured sites.

REFERENCES

[1] Robinson, N.I., Sharp, J.M., and Kreisel, I., 1998. "Contaminant transport in sets of parallel finite fractures with fracture skins". *J. Contaminant Hydrol.*, 31(1–2), pp. 83–109.

[2] Fu, L., Milliken, K. L., and Sharp, J. M. Jr., 1994. "Porosity and permeability variations in the fractured and liesegang-banded Breathitt sandstone,Middle Pennsylvanian, eastern Kentucky: Diagenetic controls and implications for modelling dual porosity systems". *J. Hydrol.*, 154, pp. 351–3

[3] Antonellini, M., and Aydin, A., 1994. "Effect of faulting on fluid flow in porous sandstones:
Petrophysical properties". *Am. Assoc. Petroleum Geologists Bull.*, 78, pp. 355–377.

[4] Kreisel, I., and Sharp, J.M. Jr., 1996. Fracture skins in the Brushy Canyon Formation. In: DeMis W D, Cole A G (ed) *The Brushy Canyon Play in Outcrop and Subsurface: Concepts and Examples*, PBS-SEPM No. 96-38, Midland,

[5] Moench, A.F., 1995. "Convergent radial dispersion in a double-porosity aquifer with fracture skin Analytical solution and application to a field experiment in fractured chalk". *Water Resour. Res.,*31, pp. 1823–1835.

[6] Zimmerman, M.D., Bennett, P.C., and Sharp, J.M. Jr. et al., 2002. "Experimental determination of sorption in fractured flow systems". *J. Contaminant Hydrol*., 58(1-2), pp. 51-77.

[7] Garner, T.T., and Sharp, J.M. Jr., 2004. Hydraulic properties of granitic fracture skins and their effect on solute transport. In: *Proc. 2004 U.S. EPA/NGWA Fractured Rock Conference: State of the science and measuring success in remediation*,Maine, 2004

[8] Nair, V.V.,and Thampi, S. G., 2011. "Numerical modelling of contaminant transport in sets of parallel fractures with fracture skin". *J. Porous Media*, 15(1), pp. 95-100.