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Solute transport in a single fracture involving an arbitrary length decay chain with rock matrix comprising different geological layers

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ABSTRACT

A model is developed to describe solute transport and retention in fractured rocks. It accounts for advection along the fracture, molecular diffusion from the fracture to the rock matrix composed of several geological layers, adsorption on the fracture surface, adsorption in the rock matrix layers and radioactive decay-chains. The analytical solution, obtained for the Laplace-transformed concentration at the outlet of the flowing channel, can conveniently be transformed back to the time domain by the use of the de Hoog algorithm. This allows one to readily include it into a fracture network model or a channel network model to predict nuclide transport through channels in heterogeneous fractured media consisting of an arbitrary number of rock units with piecewise constant properties. More importantly, the simulations made in this study recommend that it is necessary to account for decay-chains and also rock matrix comprising at least two different geological layers, if justified, in safety and performance assessment of the repositories for spent nuclear fuel.

1. Introduction

In many countries such as Canada, Japan, Switzerland, Finland and Sweden, research programs have been studying radionuclide transport in crystalline rocks for more than thirty years. One important reason for this is that these countries are seriously considering constructing final repositories for radioactive wastes in such environments, at depth from a few tens of meters, for low and intermediate level wastes, to five hundred meters or more for high level wastes (Bear et al., 1993; SKB, 2011). As a consequence, it is of great importance to have a rational understanding of the fundamental mechanisms that govern radionuclide transport in fractured media and to develop models that can readily be applied for this practical matter.

In general, it has been conceived that in fractured rocks, groundwater flows mostly through open fractures due to the very low permeability of the rock matrix compared to the fractures. The open fractures offer, then, an effective pathway, via so-called flowing channels, for nuclide transport to the biosphere (Mahmoudzadeh et al., 2013). The porous rock matrix containing relatively immobile groundwater can potentially store a portion of the radionuclides, via the so-called matrix diffusion, which makes the porous rock accessible for up-taking and storing the nuclides (Neretnieks, 1980; Sudicky and Frind, 1984).

As an important mechanism that could affect removal of nuclides from the flowing channels, matrix diffusion has long been verified and studied in cases where the rock matrix has been taken as an infinite homogeneous medium (Davis and Johnston, 1984; Grisak and Pickens, 1980; Neretnieks, 1980; Sudicky and Frind, 1982; Tang et al., 1981). In reality, however, it has a more complex structure than that assumed, as it commonly consists of not only the intact wall rock but also an altered zone (Cvetkovic, 2010; Löfgren and Sidborn, 2010; Piqué et al., 2010). More recently, Mahmoudzadeh et al. (2013) showed that the altered parts of the rock could strongly affect the transport

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of solutes in fractured media because they have significantly different diffusive and adsorptive properties than the intact wall rock (Selnert et al., 2009).

On the other hand, in the case of radioactive wastes, multi-decay chains need to be considered as well to get more realistic results. With this understanding, the work presented in the paper attempts to extend our previous model (Mahmoudzadeh et al., 2013) that considered transport of a single nuclide in a conductive fracture where the rock matrix was assumed to be composed of several geological layers with different properties. It accounted for the fact that solute could also diffuse from the flowing channel into the stagnant water zone occupied in part of the fracture and then from there into and out of the rock matrix layers adjacent to the stagnant water zone. In this study, we will expand the model to also account for an arbitrary length radionuclide decay-chain along a fracture situated in porous rock matrix, aiming to illustrate how the decay-chain process and/or the altered zone of the rock matrix can influence transport of radionuclides through a single fracture. For simplicity, however, we will ignore the effect of the stagnant water zone at this stage by assuming that it is absent. The novelty of this work is the presentation of an analytical solution that simultaneously accounts for any number of rock matrix layers and arbitrary length decay-chains. This analytical solution may be used to validate numerical codes that model multiple layers of rock matrix and decay-chains of arbitrary length in fractured media.

The paper is organized as follows. In Sections 2 and 3 the model is formulated in detail, both conceptually and mathematically. Then, the analytical solution to the solute concentration at the outlet of a flowing channel is derived, in the Laplace domain, in Sections 4 and 5. Following this, a series of simulations are made in Section 6 to illustrate the relative importance of the decay-chain and also the rock matrix layers in retarding solute transport in fractured rocks. Conclusions follow in Section 7.

2. Conceptual model

As schematically shown in Fig. 1, the system considered is an idealization of the basic building block of a network of intersecting fractures with distributions of lengths, orientations, and positions (Gylling et al., 1999; Moreno and Neretnieks, 1993). It is assumed that the flow takes place between two parallel flat surfaces separated by a distance $2b$, forming a rectangular channel of width $2W$, with a constant mean velocity, u. The rock matrix adjacent to the flowing channel is considered to consist of m layers with different thicknesses of δ^j, $j = 1,2,\ldots,m$; the layers close to the fracture surface consist of the altered zone, which may be composed of fault gauge, cataclasite, altered rock, etc. (Mahmoudzadeh et al., 2013), while the last one is the intact wall rock.

Furthermore, a complete mixing of the solute across the flowing channel has been postulated, since the width of the channel is often much smaller than the transport distance (Buckley and Loyalka, 1993) so that it is unnecessary to take the transverse dispersion in the flowing channel into account. Likewise, the longitudinal dispersion is also neglected as it is generally dominated in fractured media by the differences in the residence times of solutes transported along different flow paths and hence it does not need to be treated on the level of individual flow channels (Gylling, 1997). Nevertheless, the general procedure for combining longitudinal dispersion with any retention model could be included (Painter et al., 2008).

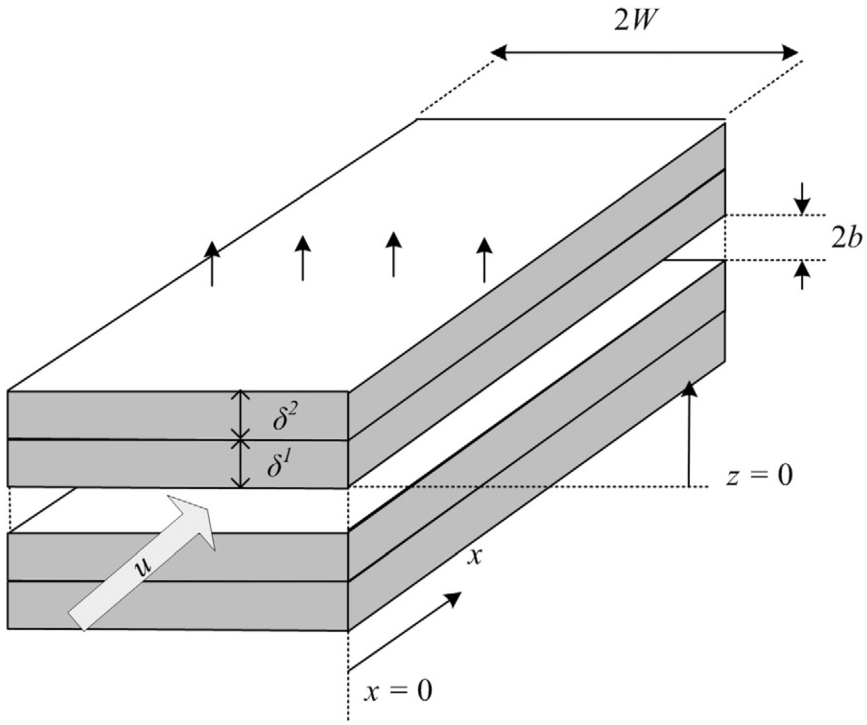

Fig. 1. Flow in a channel in a fracture from which solute diffuses into rock matrix layers.