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Dr. James E. Campbell
Intera Environmental Consultants, Inc.
3000 Youngfield Street, Suite 285
Lakewood, Colorado 80215

Dear Dr. Campbell:

Thank you for lending me the reprints of the articles on fracture flow by Grisak and Pickens. I found them very interesting. However, it appears that their method would be difficult to extend to cases where the medium contains many fractures of various sizes and direction.

Your copies are enclosed.

Best regards.

Sincerely,

ORIGINAL SIGNED BY

Stewart A. Silling, Project Manager
High-Level Waste Licensing
Management Branch
Division of Waste Management

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Solute Transport Through Fractured Media
2. Column Study of Fractured Till

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A tracer solution containing Cl and Ca was passed through a large intact cylindrical sample of fractured clayey glacial till obtained from a depth of 5 m in a fresh excavation. The sample was intersected by two orthogonal sets of fractures oriented parallel to the long axis of the column. Breakthrough curves for Cl and Ca show that these species were significantly retarded in relation to the average fracture flow water velocity as they passed through the column. The retardation is attributed to the effect of diffusion of the solutes from the fractures into the porous matrix of the till. The relative positions of the Ca and Cl breakthrough curves are attributed to the combined influence of a smaller effective diffusion coefficient for Ca than for Cl and adsorption of Ca in the matrix during the diffusion process. Relatively good agreement with the experimental data was achieved in mathematical simulation using the finite element solute transport model described by Grisak and Pickens (1980). Effective diffusion coefficients for Cl and Ca in the till matrix were found to be 5.0×10^{-7} and 1.9×10^{-7} cm^2/s, respectively. The lack of total continuity between fracture sets was accounted for in the model by using an effective fracture spacing and effective aperture width based on the concepts of flow in planar fractures in sets of simple geometry.

INTRODUCTION

This paper describes a laboratory investigation of tracer migration through a large cylindrical sample of fractured clay-loam till and presents an analysis of the experimental data using the finite element model described by *Grisak and Pickens* [1980] in part 1. The fractured till has two transport domains: the fractures in which advection and dispersion of solutes predominates and the porous matrix in which molecular diffusion, in response to concentration gradients, is important. Diffusion occurs through the tortuous pore spaces in the very low permeability matrix. This process is termed matrix diffusion and the diffusion coefficients that govern the process are termed matrix diffusion coefficients. To interpret the results of the tracer experiment, it was necessary to employ average flow velocities and effective fracture aperture widths obtained using concepts based on the principles of flow in planar fractures in simple networks.

This study was conducted to gain insight into the behavior of solutes and environmental isotopes in fractured clayey deposits of the type that are common in the Northern Plains Region. The results are applicable to a wide range of hydrogeologic phenomena. Because most groundwater samples from fractured media are derived mainly from the fractures, they provide only a part of the information required to interpret the geochemistry, water ages, or flow velocities within a groundwater system. It may be possible to reconcile discrepancies between apparent hydraulic regimes and measured groundwater ages or tracer velocities [*Day*, 1977] by employing matrix diffusion concepts.

The sampling methodology, laboratory apparatus, and test conditions described are not of the same nature as those of normal laboratory column tracer experiments. The degree of control obtained on test conditions in the laboratory is considered well beyond that possible in a field situation for this type of material, but because of the extremely large size and weight of the sample the controls are clearly not as precise as column tracer experiments conducted on small samples. The experimental conditions are, however, compared to smaller-scale column studies, and difficulties are discussed and quantified when possible.

FIELD SITE AND SAMPLING PROCEDURE

The sample of fractured till was obtained from the vicinity of the low-level radioactive waste management area at the Whiteshell Nuclear Research Establishment (WNRE), Manitoba. *Cherry et al.* [1971, 1973], *Grisak and Cherry* [1975], *Grisak* [1975], and *Grisak et al.* [1976] described the hydrogeology of the area and the hydraulic properties of the fractured till, as interpreted from field data and laboratory consolidation tests. The sequence of glacial deposits from which the sample was obtained overlie granitic bedrock on the western edge of the Canadian Precambrian Shield. In order of decreasing depth at the sampling site the deposits consist of a sandy confined aquifer (4-m thickness) on the bedrock surface, a clay-loam till (7-m thickness) with a layer of clay-bound Precambrian cobbles and boulders at the base, and a lacustrine (Lake Agassiz) clay unit (1.5-m thickness) with numerous carbonate pebbles and clasts of till. The sample was obtained from the clay-loam till unit. The clay fraction in the till is predominately interstratified mica-montmorillonite (55%) with some illite (34%) and other clay minerals (11%) [*Mills and Zwarich*, 1970]. The cation exchange capacity, bulk density, and porosity of the unfractured matrix are approximately 12 meq/100 g [*Mills and Zwarich*, 1970], 1.7 g/cm^3, and 30 to 35%, respectively [*Grisak and Cherry*, 1975]. The matrix hydraulic conductivity estimated from consolidation tests is approximately 6×10^{-9} cm/s [*Grisak and Cherry*, 1975].

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Solute Transport Through Fractured Media
1. The Effect of Matrix Diffusion

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Solute transport through fractured media is described by numerically combining advective-dispersive transport, which is dominant in the fractures, and diffusive transport, which is usually dominant in the unfractured matrix. Transport is considered in a manner conceptually similar to 'double-porosity' or 'intra-aggregate' transport models. A finite element model is developed for simulating nonreactive and reactive solute transport by advection, mechanical dispersion, and diffusion in a unidirectional flow field. The effect of the value of the solute diffusion coefficient in the matrix (termed the matrix diffusion coefficient) is illustrated by solute breakthrough curves and concentration profiles in the fracture as well as in the matrix. The illustrated conditions are similar to the laboratory tracer study on fractured till described in the accompanying paper (Grisak et al.). The effects on solute transport of fracture aperture size, water velocity in the fracture, matrix porosity, matrix distribution coefficient, and dispersivity in the fracture are illustrated with breakthrough curves and concentration profiles. The net effect of large matrix diffusion coefficients and/or large distribution coefficients in the matrix is to reduce significantly the effective solute velocity in the fracture. Reduction in the effective solute velocity can also be seen to be possible in materials with low matrix porosities such as crystalline rocks. The aperture size, matrix porosity, matrix diffusion coefficient, and distribution coefficient, all are important in determining the relative amounts of solute transported in the fracture and stored in the matrix. Implications with regard to aquifer recharge, groundwater chemistry, contaminant transport, tracer tests, and groundwater age dating in fractured media are discussed. The numerical model and the laboratory tracer test data provide considerable insight into the processes controlling solute transport in fractured media.

INTRODUCTION

The objective of this paper is to describe the processes important in the transport of solutes through fractured media and to illustrate the effect of various parameters on the concentration history and concentration profiles of reactive and nonreactive solutes in a fracture. Emphasis will be placed on demonstrating the effects of (1) solute diffusion into the matrix from the fracture, (2) aperture size and water velocity, (3) dispersivity, (4) porosity, and (5) distribution coefficient. It will be shown that in fractured media these factors can be of considerable importance in evaluation of contaminant transport and interpretation of groundwater ages based on movement of a chemical species such as tritium or carbon 14.

The role of diffusion in solute transport through geologic media has been recognized in many areas of research. *Garrels et al.* [1949] conceptually illustrated that diffusion from a fracture source into a porous matrix could be invoked as an important ore depositional process, and *Peck* [1967] suggested that diffusive fluxes may have been the principal factor in the deposition and leaching of many ore deposits. *Golubev and Garibyants* [1971] present a comprehensive discussion of geochemical migration due to diffusion in geologic materials, and *Freeze and Cherry* [1979] give a qualitative assessment of the concept of solute transport through fractures with diffusion into a porous matrix. Intra-aggregate solute transport, which includes diffusion into a 'second porosity' adjacent to the primary pores, has been the subject of several papers in the soils literature [e.g., *Green et al.*, 1972; *van Genuchten and Wierenga*, 1976].

Foster [1975] illustrated, with a one-dimensional analytical solution, that the tritium profile in the unsaturated part of the chalk aquifer in England could be a consequence of tritium diffusion from the fractures into the porous blocks. The application of this analytical solution was, however, of limited value, since empirical corrections were necessary to allow for the effect of matrix porosity. *Young et al.* [1976] used similar reasoning to Foster's in their interpretation of the nitrate profile in the unsaturated zone of the chalk aquifer. In a simulation of solute transport through the chalk, *Oakes* [1977] assumed that only 15% of the surface input of nitrates and tritium traveled with the infiltrated water to the water table and did not interact with the matrix pore water. Most of the tritium and nitrate have remained shallow and have not reached the water table along with the bulk of the recharge water because of solute storage in the unfractured chalk blocks. When the fractures are unsaturated, the tritium and nitrate remain virtually trapped in the blocks.

The order of magnitude of diffusion coefficients of solutes in uncompacted materials with large porosities, such as clays and sands, is fairly well documented [*van Schaik et al.*, 1966; *Olsen and Kemper*, 1968; *Ellis et al.*, 1970; *Turk*, 1976] and has been the subject for over a decade of a continuing series of papers in the *Journal of Soil Science*. The tritium and stable isotope profiles in the fractured surficial clays and tills in many parts of Canada have been interpreted on the basis of solute transport in the fractures and matrix diffusion [*Day*, 1977; *Cherry et al.*, 1979]. In these types of deposits, where solute diffusion coefficients are relatively large, matrix diffusion has an overwhelming effect on the net solute transport through the fractures.

Diffusion coefficients in compacted clays or consolidated sediments such as shales and sandstones [*Stoessel and Hanor*, 1975] and in crystalline rocks [*Norton and Knapp*, 1977] are less well documented. The diffusion process within the limited pore spaces of indurated and crystalline rocks and the magnitude of the effective diffusion coefficient for crystalline rocks

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