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Tracer Experiments Conducted at a Shallow Depth in a discrete fracture in a Shale and Dolostone Formation

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TRACER EXPERIMENTS CONDUCTED AT A SHALLOW DEPTH IN A DISCRETE FRACTURE IN A SHALE AND DOLOSTONE FORMATION

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INTRODUCTION

The study of contaminant transport in fractured bedrock is a relatively new but increasingly important endeavour. Over the past few years a significant number of sites contaminated by heavy organic compounds that mix poorly with water (dense non-aqueous phase liquids, or DNAPLs) have been found to have contamination in the groundwater circulating through fractures in the underlying bedrock. Attempts to predict contaminant migration and design remedial plans have been frustrated by the shortcomings in our fundamental understanding of the transport processes in these environments.

One of the most representative methods for investigating solute transport in groundwater systems is the tracer experiment where a tracer of known concentration is introduced into flowing groundwater in a well-defined fashion and the subsequent progress of migration monitored and interpreted. In fractured rock, the methodology involved in conducting tracer experiments is complicated by the sometimes unknown flow geometry, difficulties in establishing well-defined source conditions, and complications in the monitoring of tracer migration due to the large amount of water stored in the monitoring boreholes relative to the amount of water in the formation.

In this paper, tracer experiments conducted under conditions of forced advection and ambient flow are described and interpreted. The experiments were conducted using new techniques which alleviate the problems related to the source condition and monitoring. The purpose of the experiments was to test a conceptual model of conservative solute transport in a discrete fracture. The experiments were conducted in a discrete horizontal fracture which pervades a shale and dolostone formation of Cambrian age at a depth of approximately 10 m.

CONCEPTUAL MODEL

Although fractures are often assumed to be planar features, it is well-known that fracture surfaces are rough and undulating, and have numerous asperities, some of which form points of closure in the flow domain (Brown, 1987). The roughness features potentially act to disperse contaminants in the direction of groundwater flow. The points of closure act as obstructions to flow around which the contaminants must pass. In addition, solute travelling in the fracture may diffuse under a concentration gradient into the surrounding unfractured rock mass.

To account for these processes when interpreting tracer experiments by simulation, it is assumed that the roughness features and the aperture width (the fracture opening) vary smoothly in all spatial directions such that continuum averaging can be used. Thus, a lumped parameter, referred to as dispersivity (α_L), is used to account for the spreading processes due to fracture roughness, a tortuosity factor (τ) accounts for the extended pathways that arise during negotiation around asperities, and matrix porosity (θ_m) is used to govern the rate of mass loss to the unfractured rock as a result of diffusion. Macroscopic velocity during both the natural and forced gradient experiments is assumed to be a function of the mean fracture aperture.

ADVECTIVE TRACER EXPERIMENTS

After a large number of preliminary experiments, it was determined that the best method for conducting advective tests was based on a divergent flow field for which steady conditions had been established. This method allows for monitoring of the arrival of a single tracer at many observation wells during a single experiment. The experiment was conducted using a mixing system in the source borehole by which the tracer was introduced into the fracture in a mathematically well-defined manner. The experiment was conducted using a conservative tracer which was injected into the source borehole as a spike of concentration. Arrival of tracer was monitored in an array of 13 boreholes intersecting the fracture over a square area of approximately 30 m on a side. The arrival was monitored using recently-developed sampling packers in which the standing volume of water in a monitoring borehole is eliminated. The arrival of tracer was detected in 11 of the 13 boreholes. Simulation of the transport process using a semi-analytical model which accounts for dispersivity, matrix diffusion, mixing in the source borehole and for tortuosity suggests that matrix diffusion may play a predominant role in the migration of solutes. Contrary to previously published results, the relative influence of dispersivity was found to be increasingly diminished with increasing scale. Fracture apertures determined from the results of the tracer experiment were found to be in general agreement with apertures calculated from independent hydraulic tests. The individual advective processes that contribute to dispersivity remain unresolved on the basis of this experiment. A more detailed description of the experimental method and results can be found in Novakowski and Lapcevic (1994).

NATURAL GRADIENT TRACER EXPERIMENTS

Although the information obtained from the radial divergent experiments is very useful, the validity of these results under conditions of ambient flow can be questioned. Also, advective tracer experiments reveal nothing about the natural velocity field within the plane of the fracture. Thus, two tracer experiments were conducted at the same site as that described above, under conditions of natural gradient. In addition, several point dilution experiments were conducted to provide independent measurements of local groundwater velocity. A new source condition was developed for the tracer experiments in which a disk of uniform concentration is established around the source well. A conservative tracer was injected into a corner borehole in the borehole array and the results show that a uniform concentration was achieved. Monitoring of the transport process was undertaken using the same sampling devices as used for the advective experiments. The tracer was observed to arrive at 7-9 boreholes of the borehole array. A preliminary interpretation of the arrival of tracer at one of the observation boreholes was conducted using a one-dimensional model which accounts for matrix diffusion and tortuosity. A fit to the field data was obtained using sensible values of the governing parameters, however, because transverse dispersion is not considered, it is difficult to qualify the validity of these values. The influence of transverse dispersion is evident at down-gradient observation wells where more than 4 m of lateral spreading is observed over only about 15 m of travel distance down-gradient. Velocity estimates determined from the tracer experiments also agree poorly with measurements of velocity obtained from point dilution and that predicted using the cubic law. The difference between the velocity estimates obtained from the tracer experiment versus those obtained from point dilution can be attributed either to the retarding effect of matrix diffusion or to temporal variations in the local velocity field. Novakowski et al. (1994) describes further the results and interpretation of these experiments.

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