96-94

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Interpretation of Field-scale Tracer Experiments Conducted Under Conditions of Natural Gradient in a Discrete Horizontal Fracture

By:
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96-94

MANAGEMENT PERSPECTIVE

Throughout Canada and the Eastern United States, there are a large number of contaminated sites which overlie fractured bedrock. Due to the presence of non-aqueous phase liquids which are denser than water, groundwater in the bedrock is often severely contaminated. Examples of sites such as this include the former PCB storage site in Smithville, Ontario and numerous sites in Niagara Falls, New York.

Our present understanding of the processes of contaminant transport in bedrock environments is very weak relative to that for porous media such as sands and gravels. It is now widely recognised that before we undertake to remediate contaminated groundwater in bedrock, we must better understand the fundamental physical processes of transport. The objective of this paper is to describe the interpretation of a tracer experiment conducted under conditions of natural groundwater flow. This type of experiment is, by a large margin, the most difficult type to conduct in fractured rock. To the authors knowledge, there are no other examples in the literature of a successfully completed test of this type. The results show that the tracer plume exhibits significant spreading in directions deviating away from the mean groundwater flow direction. Quantifying this lateral spreading will lead to better predictions of contaminant pathways and groundwater velocities in fractured rock

INTERPRETATION OF FIELD-SCALE TRACER EXPERIMENTS CONDUCTED UNDER CONDITIONS OF NATURAL GRADIENT IN A DISCRETE HORIZONTAL FRACTURE

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ABSTRACT: Fractures in low-permeability rock play a critical role in the contamination of groundwater resources by providing conduits for the transport of toxic contaminants. The development of conceptual models to describe the hydrogeology of sparsely fractured systems requires the characterization of the physical properties of discrete fractures at the field scale. A tracer experiment was conducted at a site instrumented with 27 boreholes within an 35 x 40 m area. Inflatable packers were used to isolate a horizontal fracture 10.5 m below ground surface in a shale-limestone bedrock. The results of hydraulic tests indicate that the fracture has a spatially variable aperture with a mean of 126 μm and standard deviation of 95 μm. The tracer experiment was initiated by injecting a radial disk of conservative tracer into the fracture plane. The appearance of tracer down-gradient was monitored using a sampling packer which minimizes the volume of groundwater withdrawn. Tracer breakthrough was observed in 8 boreholes at distances ranging from 11 to 41 m from the source borehole. The experiment was interpreted using a two-dimensional finite element transport model (LTGPLAN) which incorporates diffusion into the rock matrix, longitudinal and transverse dispersion and constant or spatially variable fracture aperture in the plane of the fracture. Results show that breakthrough curves interpreted using a constant aperture require large values of transverse dispersivity to account for deviations in groundwater velocity and the mean flow direction. At this scale there is no evidence for increased longitudinal dispersivity with distance. Simulations were also conducted using spatially correlated aperture distributions having the mean and standard deviation of the natural fracture. The results indicate that increasing correlation length leads to elongated plumes in areas of high aperture and greater deviation from the mean groundwater flow direction.

1 INTRODUCTION

The migration of contaminants in groundwater through fractures in both porous and non-porous rock is controlled by the physical properties of both the individual fractures and the surrounding host rock. The presence of sparse and discontinuous fractures in most rock types leads to groundwater flow systems which are highly complex.

Fluid flow in discrete fractures has traditionally been described using the parallel plate model where flow velocity is proportional to the square of the fracture aperture. Theoretical and experimental studies of both artificial and natural rock fractures at various scales and levels of normal stress have shown that the parallel plate approximation is sometimes inadequate in representing flow through natural fractures (eg. Tsang, 1984; Raven and Gale, 1985). Physical factors which lead to departure from the parallel-plate model include the roughness of the fracture surfaces, tortuosity of the flow paths and the presence of areas where the fracture surfaces are in contact and closed to flow. In addition to the advective and dispersive processes within the fracture plane, solute transport is also influenced by diffusion into the surrounding unfractured rock (Novakowski and Lapcevic, 1994). In the development of alternative conceptual models, it is generally assumed that fracture aperture can be characterized by a statistical distribution (normal, lognormal, gamma or power) and that the aperture is correlated spatially with the degree of correlation related to the scale of measurement (eg. Brown et al., 1986; Piggott, 1990; Brown, 1995). However, determining the spatial distribution and correlation of fracture aperture at the field scale (tens to hundreds of metres), is difficult if not impossible, due to the high cost required to obtain the data necessary for meaningful geostatistical interpretations.

Using stochastic theory for flow in a single fracture of variable aperture, a reexamination of field-scale tracer experiments was conducted for four different sites (Gelhar, 1987). Correlation scales were calculated assuming a log aperture variation to be on the order of a metre. Abelin et al. (1994) determined, from a detailed geostatistical analysis of apertures obtained from boreholes intersecting a single fracture, that no single variogram form described all the fractures adequately. Correlation lengths between 0.05 and 0.8 m were observed. However, at most field sites, interwell distances are greater than five m (eg. Raven et al., 1988: Shapiro and Nicholas, 1989; Abelin et al., 1991; Novakowski and Lapcevic, 1994) suggesting that aperture measurements obtained from the field setting will always be at a scale greater than the spatial correlation length of the aperture distribution and thus difficult to estimate.

A possible means by which to explore the structure of the aperture distribution and the influence on solute transport, is to conduct tracer experiments. Tracer experiments conducted under conditions of natural flow allow for study of transport processes at velocities and flow directions typical of natural systems. While large scale (on the order of hundreds of metres) tracer experiments have been conducted under conditions of natural gradient in unconsolidated aquifers (eg. Mackay et al., 1986), most tracer experiments in fractured rock are conducted under conditions of forced gradient (eg. Raven et al., 1988; Shapiro and Nicholas, 1989; Abelin et al., 1991; Novakowski and Lapcevic, 1994) due to practical constraints.

The purpose of this paper is to present the interpretation of a tracer experiment conducted in a single fracture under conditions of natural groundwater flow. The results of the experiment are interpreted using a two-dimensional numerical model which simulates the source condition, accounts for diffusion into the rock matrix, and both longitudinal and transverse dispersion in the fracture plane. The results are simulated using either a spatially constant aperture field or a spatially variable aperture field.

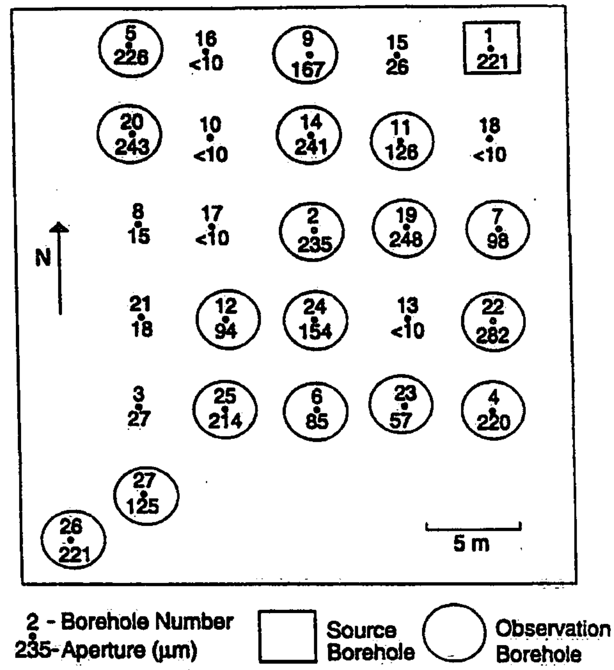

Fig.1 Site map showing source and observation boreholes used for tracer experiment

2 METHODS

2.1 *Tracer Experiment*

A tracer experiment was conducted under conditions of natural groundwater flow in a single horizontal fracture intersected by 27 boreholes within an area 35 x 40 m (Figure 1). The fracture occurs at a depth of 10.5 m below ground surface in Ordovician aged shale and limestone. Previous studies have determined the hydraulic aperture of this fracture to range between <10 µm (detection limit) and 282 µm (Lapcevic and Novakowski, 1993). Measurements of hydraulic head indicates the direction of predominant groundwater flow in the fracture is to the southwest with an hydraulic gradient of approximately 0.002. Each borehole was instrumented using pneumatic packers to isolate the fracture. Single packers which minimize mixing in the wellbore were used in the observation boreholes (Novakowski, 1992).

The tracer experiment was initiated by injecting a concentrated volume of the conservative tracer, Lissamine FF (0.17 L of 1000 mg/L solution), into a 3.3 L zone of the borehole located at the northeast corner of the grid (Figure 1). This method of tracer injection creates a 'disk' shaped source of known initial concentration centred at the borehole. The disk then migrates away from the well under conditions of natural flow. Subsequent movement of the tracer in the southwest direction was monitored in the fracture plane by obtaining groundwater samples at 17 of the 27 boreholes (Figure 1). The methodology used for the field tracer experiment is described in greater detail in Novakowski et al.(1995).

2.2 *Interpretation*

The breakthrough curves from the field experiment were interpreted using two, 2-D finite element codes: FLOW2D (Frind and Pinder, 1973) and LTGPLAN (Sudicky, 1990). FLOW2D was used to estimate the velocity field while LTGPLAN was used to simulate solute transport. LTGPLAN is based on the Laplace Transform Galerkin (LTG) technique where the advection-dispersion equation is solved in Laplace space using the Galerkin finite-element method. The Laplace-domain concentrations are transformed into real time values using a robust numerical inversion scheme. The LTG method avoids time stepping by solving for the concentration in Laplace space which is relatively smooth even in areas of widely contrasting velocities (Sudicky and McLaren, 1992).

Additionally, differences in time scale between the rapid advection of contaminants in the fracture versus much slower diffusion into the porous matrix poses numerical difficulties which are avoided with the LTG method (Sudicky and McLaren, 1992).

The field site was discretized by dividing the domain into a rectangular grid (x=35 m and y=42 m) of triangular elements having dimensions of 0.5 m in both the x and y directions. The y axis represents the N-S direction. The tracer breakthrough curves were simulated by manipulating aperture (2b), longitudinal dispersivity (α_L), transverse dispersivity (α_T) and matrix porosity (θ_m), in a systematic fashion. The hydraulic gradient (both magnitude and direction) was determined based on field measurements and assumed to be constant in time. Transmissivity at each nodal point was determined from aperture using the cubic law. A value of 1.8×10^{-10} m^2/s was used for the effective molecular diffusion coefficient based on the free water diffusion coefficient for Lissimine FF and a geometric factor.

The source condition was simulated using the numerical transport model in two steps. FLOW2D was used to determine the distribution of steady velocity with continuous injection at the source well. The calculated injection velocities were then used in LTGPLAN, and a steady release of tracer was applied at the source well to determine the spatial distribution of concentration at the end of a finite injection period. The nodal concentrations at the end of the injection period were used as input into the transport code to provide for an initial source condition. In this case, flow velocities were calculated under conditions of natural-gradient.

In the case where distributions of variable aperture were used, the distributions were simulated using a robust random field generator based on the discrete Fourier transform (Robin et al., 1993). In all simulations, an isotropic field with spatial correlation lengths equal in the x and y directions ($\lambda_x = \lambda_y$), and a exponential covariance model were used to generate two-dimensional aperture fields having a specified mean aperture (<2b>) and variance (σ^2). Boundary effects were eliminated by truncating a 256 x 256 array of generated apertures to a 141 x 169 array, thus accommodating the existing grid. A finer grid ($\Delta x = \Delta y = 0.25$ m) was used for the transport simulations conducted using variable apertures. The steady velocity field was determined for each simulation using FLOW2D assuming prescribed hydraulic head values around the grid boundaries. The values of prescribed head were defined to produce a mean groundwater flow direction and a total hydraulic head drop across the site which was consistent with the field data. The source condition for the transport simulations was incorporated in a manner similar to the constant aperture simulations.

3 RESULTS

Tracer was detected at distances ranging from 11 to 42 m in 8 observation boreholes (7, 19, 2, 22, 24, 6, 26 and 27) down-gradient from the source borehole. Peak concentration ranged over 4 orders of magnitude, between 5 μg/L to 4050 μg/L. Arrival times of the peak concentration ranged from 71 hr (borehole 19) to 269 hr (borehole 26). The duration of the experiment was approximately 1000 hr. The tracer plume at various times is shown in Figure 2. The contours of concentration are drawn based on 17 observation points and are very subjective.

The results of the interpretation of the breakthrough curves using a constant aperture are summarized in Table 1. The field curves were each interpreted independently, maintaining the hydraulic gradient and

Table 1. Summary of breakthrough curve interpretations using a constant aperture.

Bore-hole	Distance from Source (m)	v^1 (m/hr)	α_L (m)	α_T (m)	θ_m (%)	2b (μm)
7	10.8	0.20	0.1	0.08	1.37	200
19	11.8	0.20	0.1	0.01	1.33	200
22	15.9	0.25	0.1	0.08	1.35	220
24	19.1	0.24	0.1	0.03	1.60	215
6	23.7	0.22	0.1	0.08	1.32	210
27	34.8	0.25	0.1	0.10	1.80	220
26	41.2	0.25	0.1	0.20	2.20	220

[1]hydraulic gradient: 0.0024, flow direction: 206°N (except borehole 24 which was 201°N).

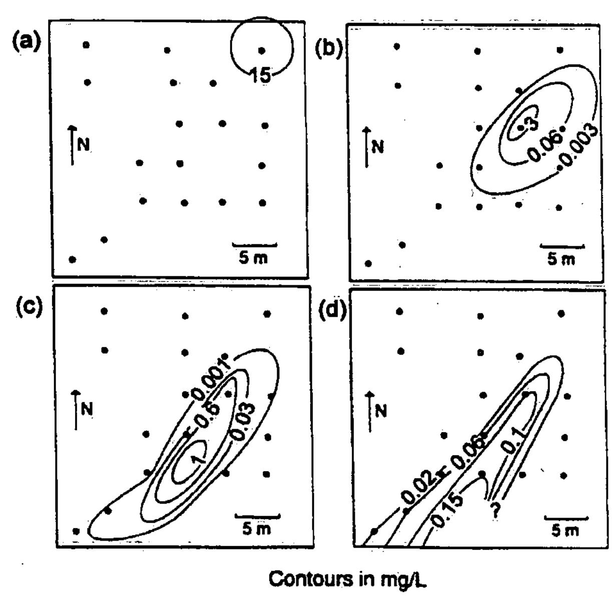

Fig. 2. Tracer plume at various times (a) t=0, (b) t=72 hr, (c) t=135 hr, (d) t=276 hr

flow direction as constant for all cases with the exception of borehole 24. Sharp fronts observed in the breakthrough curves at all distances indicate a small and constant longitudinal dispersivity (α_L). Matrix porosity ranged between 1.3 and 2.2 %. Transverse dispersivity (α_T) indicates a range of values between 0.01 and 0.20 m and aperture ranges from 200 to 220 μm. Figure 3 shows the model fit to the breakthrough data for borehole 6, which is 24 m down-gradient from the source. An increase in transverse dispersivity is required to simulate the results from observation boreholes at greater angles spatially from the mean flow direction and furthest from the source. This suggests that the plume has spread laterally due to variations in aperture not accounted for in the constant aperture model. The aperture values and velocity determined from the simulations increase slightly with distance from the source. This implies that pathways lengthen with distance as a result of tortuosity within the fracture plane. These observations are consistent with the results of forced gradient tracer experiments conducted previously in the same fracture plane (Novakowski and Lapcevic, 1994).

The observed aperture distribution in the fracture, based on the single-well hydraulic tests has a mean of 126 μm and a standard deviation of 95 μm. Geostatistical analysis of the hydraulic apertures indicated a spatial correlation length of 6 to 12 m when fit to exponential or spherical theoretical models. Variable aperture fields generated using this correlation structure were found to be unsuitable for the interpretation of the field experiment. This is because the number of samples used for the geostatistics is small, thus the actual spatial correlation length may be quite different from the estimate. While it is generally recognized that fracture apertures are spatially correlated at the laboratory scale and the correlation scales are small (eg. Brown et al., 1986), it is likely that the distances between the observation boreholes where the hydraulic measurements of aperture were made are too large to capture information on the spatial correlation structure of this fracture plane. In addition, the low number of measurement points (N=27), non-Gaussian distribution of apertures and the few available lag distances leads to poor geostatistical interpretation of the aperture field. Thus, to investigate the effects of spatially variable velocity fields due to variable aperture, simulations were conducted using the statistics of the hydraulic aperture distribution for a variety of correlation lengths. In addition, the centre of mass of the simulated plume was calculated at different points in time to compare the deviation of the plume due to aperture variations for a number of realizations.

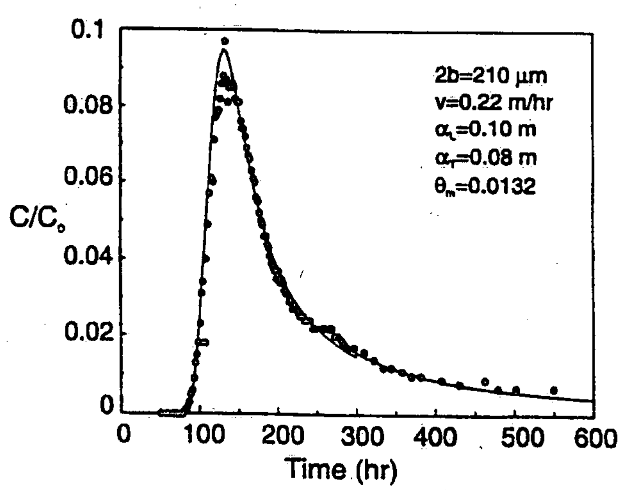

Fig.3 Field breakthrough curve match to numerical model using a constant aperture.

Figure 4 shows examples of the simulated tracer plume using input aperture distributions which have the same mean aperture (<2b> =125 μm) but different values of variance and spatial correlation length (λ_x=λ_y). One has a variance of 10,000 μm^2 and a spatial correlation length of 0.5 m (Figure 4a), the second has a variance of 10,000 μm^2 and correlation length of 5.0 m (Figure 4b), the third a variance of 2000 μm^2 and correlation length of 5.0 m (Figure 4c) and the fourth has a constant aperture of 125 μm (Figure 4d). In Figure 4a, the plume is observed to spread laterally in comparison to the constant aperture plume (Figure 4d), although the direction of mean flow appears to be unaffected. For a higher correlation length (Figure 4b) the deviation of the plume migration path about the mean flow direction is significant in comparison to Figure 4d. The lower variance of the aperture distribution used for the simulation shown in Figure 4c leads to a more uniform plume although with significant lateral spreading.

While the spatial correlation structure of the actual aperture distribution is unknown, the hydraulic aperture measurements do indicate a highly heterogeneous field with a variance of 9025 μm^2. Based on observational comparison between field-measured concentrations and the examples shown in Figure 4, it appears unlikely that a higher value of the correlation length can be characteristic of the aperture distribution for this fracture. Additional realizations having similar statistics illustrate that the transverse spreading shown in Figure 4b is typical.

The location of the centre of mass for each plume obtained from several realizations at spatial correlation lengths of 0.5 m and 5.0 m and variance σ^2=10,000 μm^2 are compared at two different times in Figure 5. This further illustrates the influence of high spatial correlation length in the widespread distribution of concentration. For lower correlation length, the centre of mass data show some deviation about the mean groundwater flow direction (Figures 5a and 5b).

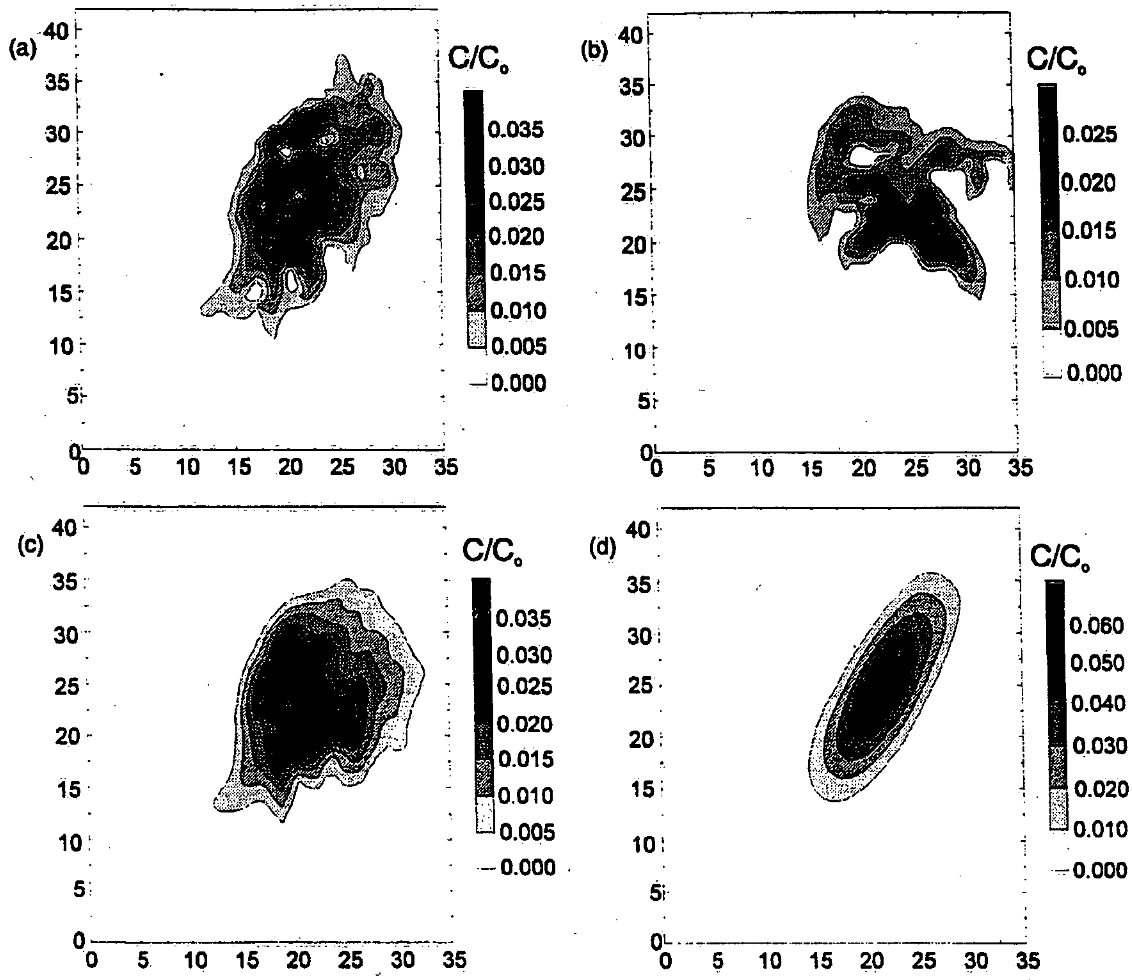

Fig.4 Example variable aperture plumes with $\langle 2b \rangle = 125\ \mu m$, $\alpha_L = 0.10$ m, $\alpha_T = 0.05$ m and $\theta_m = 0.01$: (a) $\sigma^2 = 10{,}000\ \mu m^2$, $\lambda_x = \lambda_y = 0.5$ m, (b) $\sigma^2 = 10{,}000\ \mu m^2$, $\lambda_x = \lambda_y = 5.0$ m, (c) $\sigma^2 = 2{,}000\ \mu m^2$, $\lambda_x = \lambda_y = 5.0$ m, (d) constant aperture

However at higher correlation length there is considerable longitudinal spreading in the centre of mass data and deviation from the mean flow direction (Figures 5c and 5d). While both the variance of the aperture distribution and the spatial correlation length have an effect on the behaviour of the tracer plume, higher correlation lengths lead to the largest spread in the plume dimension and to the greatest deviation away from the mean groundwater flow direction.

4 SUMMARY

The results of a tracer experiment conducted in a discrete fracture are interpreted using two conceptual models for fracture aperture; 1) constant aperture and 2) variable aperture having a known correlation structure. Interpretations of the field breakthrough curves using a constant aperture indicate a large spread in transverse dispersivity indicating lateral spreading of the two-dimensional plume. The data at this scale shows no evidence for increasing longitudinal dispersion as a function of increasing scale. A slight increase in aperture with distance suggests tortuous pathways within the fracture plane. Simulations with variable aperture fields show significant lateral spreading of the plume for correlation lengths between 0.5 and 5.0 m and high variance distributions. In addition, centre of mass calculations show a greater spread in deviations between the plume transport direction in relation to the mean flow direction at higher correlation lengths. The large spread in the location of the centre of mass values at the higher correlation length indicates that prediction of the plume movement using breakthrough at observation boreholes will be difficult. In addition, dispersion of the plume as a result of variable apertures suggests that the interpretations of field data using the constant aperture model might significantly overestimate the effects of matrix porosity and transverse dispersion. However, both of these observations are predicated on the assumption the large correlation lengths are common in discrete fractures. Based on the results of the interpretation using a constant aperture, this is not likely the case for the present field example.

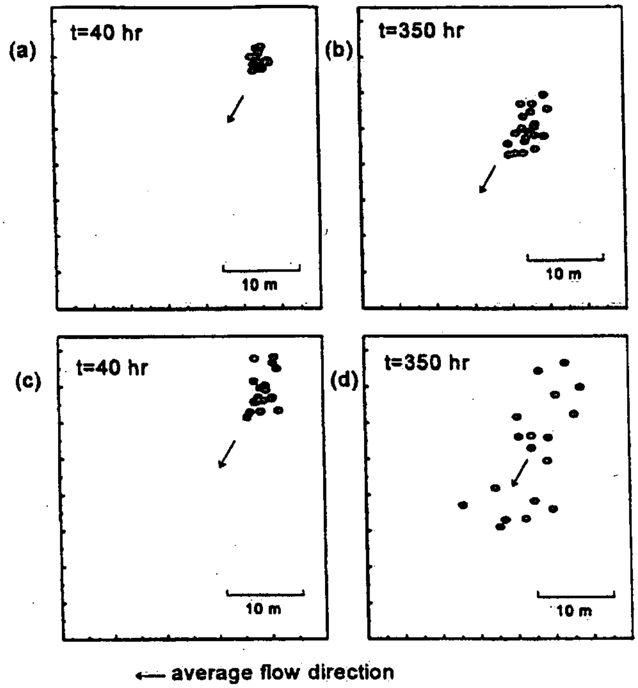

Fig. 5. Location of centre of mass for multiple realizations at two points in time: (a)&(b) <2b>=125 μm, σ^2=10,000 μm^2, $\lambda_x=\lambda_y$=0.5 m, (c) & (d) <2b>=125 μm, σ^2=10,000 μm^2, $\lambda_x=\lambda_y$=5.0 m

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