

COMPARISON OF FLUX AND RESIDENT CONCENTRATION BREAKTHROUGH CURVES IN STRUCTURED SOIL COLUMNS

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ABSTRACT

In many solute transport studies, either flux or resident concentration has been used. Choice of the concentration mode was dependent on the monitoring device in solute displacement experiments. It has been accepted that no priority exists in the selection of concentration mode in the study of solute transport. It would be questionable, however, to accept the equivalency in the solute transport parameters between flux and resident concentrations in structured soils exhibiting preferential movement of solute. In this study, we investigate how they differ in the monitored breakthrough curves (BTCs) and transport parameters for a given boundary and flow condition by performing solute displacement experiments on a number of undisturbed soil columns. Both flux and resident concentrations have been simultaneously obtained by monitoring the effluent and resistance of the horizontally-positioned TDR probes. Two different solute transport models namely, convection-dispersion equation (CDE) and convective lognormal transfer function (CLT) models, were fitted to the observed breakthrough data in order to quantify the difference between two concentration modes. The study reveals that soil columns having relatively high flux densities exhibited great differences in the degree of peak concentration and travel time of peak between flux and resident concentrations. The peak concentration in flux mode was several times higher than that in resident one. Accordingly, the estimated parameters of flux mode differed greatly from those of resident mode and the difference was more pronounced in CDE than CLT model. Especially in CDE model, the parameters of flux mode were much higher than those of resident mode. This was mainly due to the bypassing of solute

through soil macropores and failure of the equilibrium CDE model to adequate description of solute transport in studied soils. In the domain of the relationship between the ratio of hydrodynamic dispersion to molecular diffusion and the pecllet number, both concentrations fall on a zone of predominant mechanical dispersion. However, it appears that more molecular diffusion contributes to the solute spreading in the matrix region than the macropore region due to the nonlinearity present in the pore water velocity and dispersion coefficient relationship.

Key word: flux concentration, resident concentration, convection-dispersion equation, convective lognormal transfer function, travel time, hydrodynamic dispersion, molecular diffusion, pecllet number, matrix region, macro region, breakthrough curve.

요 약 문

구조토양에서의 침출수와 잔존수농도의 파과곡선에 관한 비교연구

오염물질 이동현상 연구에서는 침출수 혹은 잔존수농도 형태가 사용되는데 이의 선택은 모니터링 방법에 의존하게 된다. 파과곡선 실험에서 모니터링 농도 형태에 관한 선택은 임의적이며, 각 농도 형태에서 얻어진 운송 파라미터들은 동등하며 다공성매질의 수리적 특성을 각각 대표하는 것으로 알려져왔다. 그러나, 현장상태의 구조적 발달을 보이는 토양에서는 농도 형태별 운송계수의 동등성이 의문시 된다. 본 연구에서는 불교란 현장시료(직경 20cm, 높이 20cm)에 대하여 두가지 농도 형태에 의한 파과곡선 실험을 시행하므로써 모니터링 방법에 따른 농도 형태와 그에 따른 운송 파라미터들을 비교분석하였다. 침출수 농도와 잔존수 농도는 토양상부에서 20cm와 10cm 떨어진 지점에서 EC-meter와 TDR을 이용하여 각각 측정하였다. 연구결과, 침출수 농도는 잔존수 농도보다 침투농도가 훨씬 높게 그리고 침투농도의 운송시간이 짧게 나타났음을 알 수 있었다. 따라서 침출수농도곡선으로부터 추정된 운송파라미터들은 잔존수농도곡선으로부터 추정된 수치들과 상당한 차이를 보였으며 그 차이는 CLT 모델보다 CDE 모델에서 더 크게 나타났다. 특히 CDE 모델에서는 침출수곡선으로부터 도출된 계수값들이 잔존수곡선으로부터 도출된 계수값들보다 훨씬 크게 나타났다. 이는 구조토양내에 존재하고 있는 대공극을 통한 오염물질 우회통과와 평형조건에서의 CDE 모델이 연구대상 토양에서의 오염물질 이동현상을 표현하는데 부적합하였기 때문인 것으로 사료된다. 분자 분산에 대한 동수리학적 확산의 비와 Peclet number와의 상관관계를 나타내는 도표영역에서 두가지 농도는 모두 역학적 확산이 오염물질 운송을 좌우하는 영역에 속하였다. 그러나 분자분산은 토양내 대공극부분보다 matrix 부분에서의 오염물질 확산에 더 많은 기여를 하는 것으로 나타났으며 이는 공극유속과 확산계수사이에 존재하는 비선형성에 기인하기 때문인 것으로 사료된다.

INTRODUCTION

In recent years studies on solute transport

behaviour in soils have drawn increasing attention because of ever-growing concerns about environmental hazard of applied agrochemicals

and nuclear waste disposals on land and water quality. Among them most important issues have been on how the applied solutes move along the vadose zone and permeate to the ground water. Several attempts were made on the use of existing model or development of new model to describe the solute transport mechanism. Validation of transport models, before anyone undoubtedly uses any model, would be a necessary procedure. A common approach used for model validation among many soil scientists was to conduct a breakthrough experiment at either laboratory or field scale in order to obtain necessary information on the movement of chemicals.

Two different expressions of solute concentration, i.e., flux and resident concentrations, exist for both theoretical equations and monitoring techniques. It has been shown that use of either concentration mode results in an identical equation describing solute movement (Parker and van Genuchten, 1984), and that for known transport properties either of them is easily transformed into the other. A limiting factor in the solute transport study was monitoring data rather than model developing. Depending on the mode of concentration detected by measuring device, each model type for transport mechanism was chosen. No priority exists on the choice of the concentration mode so that if anyone detects either mode of concentration then he/she uses a corresponding type of model or equation and reports results of studies. This means that there exists a complete equivalency in the solute transport parameters between two concentration modes.

A number of laboratory-scale solute displacement experiments have been conducted on disturbed or undisturbed soil columns by detecting either flux concentration (Khan and Jury, 1990; Li and Ghodrati, 1994; Ma and Selim, 1994) or resident concentration (Vanclouster *et al.*, 1993; Mallants *et al.*, 1994; Ward *et al.*, 1994) using time domain reflectometry (TDR). So far, no detailed solute transport study has been conducted based on simultaneous measurements of both type concentrations except for theoretical consideration (Parker and van Genuchten, 1984). In this study, we investigate how they differ and affect the transport parameters by monitoring flux and resident concentrations and performing parameter estimation of the observed breakthrough curves (BTCs) based on two solute transport models, convection-dispersion equation (CDE) and convective log-normal transfer function (CLT).

MATERIALS AND METHODS

Solute Displacement Experiment

The site where the structured soil columns were taken was being used as grass land. Soil is classified as Stagnic Podzoluvizol (FAO clas-

Table 1. Basic soil properties of the structured soil.

Depth (cm)	Textural fractions(%)			Organic (%)	CEC (meq/100g)
	Sand	Silt	Clay		
15	14.72	66.41	18.87	1.7	10.06
35	15.12	66.56	18.32	0.9	8.03
50	15.45	61.27	23.28	0.4	14.51
70	20.33	56.06	23.59	0.5	9.28
90	19.68	56.18	24.14	0.1	10.17

sification) with indication of eluviation of clay and minerals and influence of seasonally perched groundwater table. Soil profile showed 5 distinct horizons with strong structural development: Ap (0-30), E (30-40), Btg1 (40-60), Btg2 (60-90) and C (90 cm). Soil type was silt loam with varying clay percent over different horizons (Table 1). Undisturbed soil columns with a diameter and height of each 20 cm were collected at 12 discrete locations in a 40 m long transect and at 4 different depths per location.

Prior to the breakthrough experiment, the saturated hydraulic conductivity (K_s) and the near saturated hydraulic conductivity were measured using a constant head and crust method (Bouma *et al.*, 1972). From the results of hydraulic conductivity, significant variability of K_s were found among soils at the same horizon with difference in several orders of magnitude. It was believed that this was due to the existence of macropores in the soil. Step application of solute in a soil having macropores has been confronted with difficulties in obtaining a stable resistance of TDR at equilibrium due to bypassing the soil matrix domain and thus requiring an enormous amount of solute. Therefore we decided to use a pulse input of solute.

Both flux and resident concentrations were simultaneously monitored using an EC-meter for the effluent leaving the bottom boundary and soil resistance by positioning 15 cm long and 2.5 cm wide parallel TDR probes in the middle of the soil column. A steady state condition was imposed on each column in a period of 15 days before application of solute. During the steady state condition, soil moisture content

and resistance were measured by TDR. Solute was applied with ponding condition on top of the soil column in a 1 cm depth of CaCl_2 solution (10 g/l) as a tracer. After application of solute, ponding condition was again imposed on top boundary to leach the solute plume downward while a free drainage condition was imposed on bottom boundary by installation of a perforated PVC disk to collect the effluent. The effluent (CaCl_2) concentration was determined by an EC-meter. In order to investigate a possible existence of soil macropores in the columns, a dye experiment was conducted at the end of solute displacement experiment by applying methylene blue of 4 liter solution with concentration of 1 g/l to the top of soil columns under ponding condition which exhibited typical BTC of macropore flow with fast movement of solute.

Calibration of TDR Measurements

For determination of TDR-measured resident concentration, soil columns at the end of BTC experiment were saturated with the same CaCl_2 concentration as input solution to obtain the calibration coefficient (Mallants *et al.*, 1994; Ward *et al.*, 1994) from the TDR resistance at the equilibrium between the input concentration and soil solution in the TDR-detecting region. Since almost no changes in TDR readings were found with only saturation after even a considerable period, advective flow was induced to accelerate the equilibrium by imposing a hydraulic gradient using a matriotte system. The step increase of solute concentration results in a zero gradient of TDR impedance at a large time

for a given depth. At this time, one may assume that the impedance corresponds to the input concentration, C_o , so that

$$C_o = \beta_z \left[\frac{1}{R(z, t_F)} - \frac{1}{R(z, t_i)} \right] \quad (1)$$

where β_z is the calibration coefficient at depth z , $R(z, t_F)$ is the TDR measured impedance of depth z at a large time and $R(z, t_i)$ is the initial impedance of depth z before application of step input. Once the calibration coefficient is obtained, the solute concentration at depth z and time t , $C(z, t)$, in response to addition of solute with the concentration, C_o , can be determined by:

$$C(z, t) = \beta_z \left[\frac{1}{R(z, t)} - \frac{1}{R(z, t_i)} \right] \quad (2)$$

The electrical conductivity of flux concentration as measured by the EC-meter was calibrated using the following relationship between EC (dS/m) and C (g/l) obtained from

measurements of EC in solutions of known concentrations:

$$EC = 1.341 C + 0.76 \quad (r^2 = 0.98) \quad (3)$$

Parameter Estimation

Since the monitored flux and resident concentration data are in the form of time-series for a given depth, the monitored data were first time-normalized after calibration. Time-normalization has been performed by dividing the concentration with the time integral of time-series flux or resident concentration. The time-normalized travel time probability density functions (*pdfs*) of either flux or resident concentration of a solute is given by:

$$f(l, t) = \frac{C(l, t)}{\int_0^t C(l, t') dt'} \quad (4)$$

where $C(l, t)$ is flux or resident concentration at depth l at time t .

Table 2 summarizes the time-normalized flux

Table 2. Summary of flux and resident pdfs of CDE and CLT model.

	CDE	CLT
Flux	$f'(z, t) = \frac{z}{2\sqrt{\pi Dt^3}} \text{Exp} \left[-\frac{(z - Vt)^2}{4Dt} \right]$	$f'(z, t) = \frac{1}{2\pi\sigma^2 t} \text{Exp} \left[-\frac{\ln(t/z) - \mu}{2\sigma^2} \right]$
Resident	$f^r(z, t) = \frac{V}{\sqrt{\pi Dt}} \text{Exp} \left[-\frac{(z - Vt)^2}{4Dt} \right] - \frac{V^2}{2D} \text{Exp} \left(\frac{Vz}{D} \right) \text{Erfc} \left[\frac{z + Vt}{\sqrt{4Dt}} \right]$	$f^r(z, t) = \frac{1}{z} \frac{1}{\sqrt{2\pi\sigma^2}} \text{Exp} \left[-\frac{(\ln(t/z) - \mu) - \frac{\sigma^2}{2}}{2\sigma^2} \right]$

Table 3. Time moments of solute travel times of time-series flux and resident pdfs for the CDE and CLT model.

	CDE		CLT	
	Flux	Resident	Flux	Resident
T_1	$\frac{z}{V}$	$\frac{1}{V} \left(\frac{D}{V} + z \right)$	$\left(\frac{z}{l} \right) \text{Exp} \left(\mu + \frac{\sigma^2}{2} \right)$	$\left(\frac{z}{l} \right) \text{Exp} \left(\mu + \frac{3\sigma^2}{2} \right)$
T_2	$\frac{z^2}{V^2} + \frac{2Dz}{V^3}$	$\frac{1}{V^2} \left(\frac{4D^2}{V^2} + \frac{4Dz}{V} + z^2 \right)$	$\left(\frac{z}{l} \right)^2 \text{Exp} (2\mu + 2\sigma^2)$	$\left(\frac{z}{l} \right)^2 \text{Exp} (2\mu + 4\sigma^2)$
Var	$\frac{2Dz}{V^3}$	$\frac{1}{V^2} \left(\frac{3D^2}{V^2} + \frac{2Dz}{V} \right)$	$\left(\frac{z}{l} \right)^2 \text{Exp} (2\mu + \sigma^2) \left[\text{Exp} (\sigma^2) - 1 \right]$	$\left(\frac{z}{l} \right)^2 \text{Exp} (2\mu + 3\sigma^2) \left[\text{Exp} (\sigma^2) - 1 \right]$

and resident *pdfs* of both the CDE and CLT models for a narrow pulse of mobile, non-volatile and nonreactive solute applied uniformly onto the soil surface under steady state water flow. Least squares optimization (Jury and Sposito, 1985) was used for the *pdfs* to estimate the transport parameters of both models. In order to compare the result of parameters of CDE and CLT pdf, pore water velocity (v) and dispersion coefficient (D) were computed from CLT model parameters, μ , and time moments given by:

$$T_N^f = \int_0^\infty t^N f^f(z,t) dt \quad (5a)$$

$$T_N^r = \int_0^\infty t^N f^r(z,t) dt \quad (5b)$$

where T_N is the Nth time moments of solute travel times for each concentration mode and superscript f , r denote flux and resident concentration mode. Variance of travel times can be computed by:

$$Var(t) = \int_0^\infty (t-T_1)^2 f(t) dt = T_2 - T_1^2 \quad (6)$$

where Var is the variance of solute travel times and T_1 , T_2 are the first and second time moments. Time moments were analyzed in 4 different cases according to both concentration modes and model types and listed in Table 3.

The pore water velocity was obtained by dividing the travel distance with mean travel time corresponding to the parameter, μ . Derivation of dispersion coefficient from the time moments of CLT pdf was done based on the dispersion of travel time defined by Jury and Sposito (1985) for flux concentration:

$$Dispersion\ of\ f^f(t) = \frac{Z^2}{2} \frac{Var}{T_1^3} \quad (7)$$

$$\text{with } Var = T_2 - T_1^2$$

and by Kim *et al.* (1996a) for resident concentration:

$$Dispersion\ of\ f^r(t) = \frac{Z^2}{(T_1 - Var)^2} \quad (8)$$

$$\text{with } \hat{Var} = \sqrt{T_2} - T_1$$

where T_1 and T_2 are the first and second time moments.

Prediction of Flux *pdf* in Macro Domain

Meaningful comparison between resident and flux concentration was achieved by predicting the flux concentration from the resident concentration using CLT model parameters since each type of concentration was detected at different depths. Prediction was done using the parameters of CLT model estimated from the resident concentration in the flux pdf. In case of a large difference in the measured and predicted flux concentrations, an attempt was made to es-

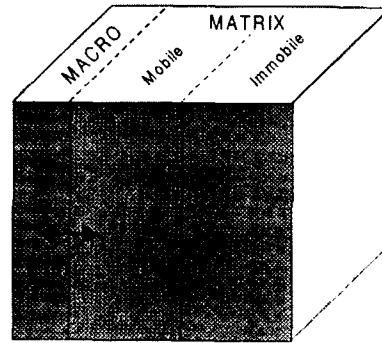


Fig. 1. Schematic representation of macro and matrix regions in a macroporous soil. Solute interchange (I) and (II) corresponds to the model of non-equilibrium CDE (van Genuchten and Wierenga, 1976) with mobile and immobile zones and a dual porosity model (Gerke and van Genuchten, 1993) applicable to fractured porous media.

estimate the flux concentration in the macro region from the measured flux concentration of effluent representing the concentration of whole region. Fig. 1 shows a schematic representation of two different regions with subdivision of the matrix region into mobile and immobile zone in a macroporous soil. Assume that the macro region represents the region of fast moving and the matrix the region of slow moving. The concentration (C_f) and transport volume (V) in each region for a certain mass, M , can be given as:

$$C^{f_{mac}} = \frac{M_{mac}}{V_{mac}} \tag{9a}$$

$$C^{f_{mat}} = \frac{M_{mat}}{V_{mat}} \tag{9b}$$

where , are the concentrations of macro and matrix region and , the M_{mac}, M_{mat} the masses of each region. The effluent concentration consists of flux concentrations in both soil macro and matrix regions:

$$C^{f_{eff}} = \frac{M_{mac} + M_{mat}}{V_{mac} + V_{mat}} \tag{10}$$



Fig. 2. Evidence of macropores in a soil column from the dye experiment.

When V_{mac} is much larger than V_{mat} , Eq. (10) can be given as the following form:

$$C^{f_{eff}} = C^{f_{mac}} + C^{f_{mat}} \frac{V_{mat}}{V_{mac}} \tag{11}$$

The ratio of the two transport volumes is equivalent to that of pore water velocities in two different regions for a steady water flow. In case that the pore water velocities are known, the flux concentration in the macro region can be easily estimated using Eq. (11).

RESULTS AND DISCUSSIONS

Comparison of BTC Type

Most of the monitored BTCs in both the flux and resident concentration showed distinct features in peak concentration and travel time of peak concentration for different flux densities of effluent, and presence of bimodal shape. The BTCs are grouped into 4 different types. Table 4 shows the result of BTC types and the criteria of grouping. Type 1 represents the BTCs having much higher and earlier peak in flux con-

Table 4. Formulation of BTC type according to mean water flux rate, peak concentration and travel time of peak concentration.

BTC Type	Flux rate (cm/hr)	Peak Conc.	Peak Travel Time	Number of Sample
1	0.127 (0.013)*	$C'_p > C_p^r$	$t'_p < t_p^r$	8
2	0.682 (0.109)	$C'_p > C_p^r$	$t'_p \approx t_p^r$	14
3	0.358 (0.078)	$C'_p \approx C_p^r$	$t'_p \approx t_p^r$	15
4	0.022	$C'_p > C_p^r$	$t'_p > t_p^r$	1

* Standard deviation of flux rate

centration than resident. In type 2, the flux concentration shows still much higher concentration peak but the peak travel time almost equals to that of resident concentration. Type 3 shows the BTCs having the same magnitude of both the peak concentration and peak travel time in the flux and resident concentration. Type 4 corresponds to the BTC showing earlier and higher peak of resident concentration than flux concentration. In fact, this type was the one of our expectation to obtain from the column displacement experiment since the resident concentration was monitored at 10 cm from the inlet boundary and the flux at 20 cm. However, most of the BTCs have been found to be type 1, 2,

3 indicating the significant influence of macropores on the solute movement. The result of BTC type demonstrates that macropore flow in undisturbed soils is a rule rather than an exception. Existence of macropores is illustrated in Fig. 2 for a soil column that showed a high flux rate. Stained dye spots clearly indicate the position of macropores.

The representative BTCs for each type listed in Table 4 are shown in Fig. 3. The BTCs of type 1, 2, 3 show earlier breakthrough of flux than resident concentration. A few important features can be noted from the comparison of dif-

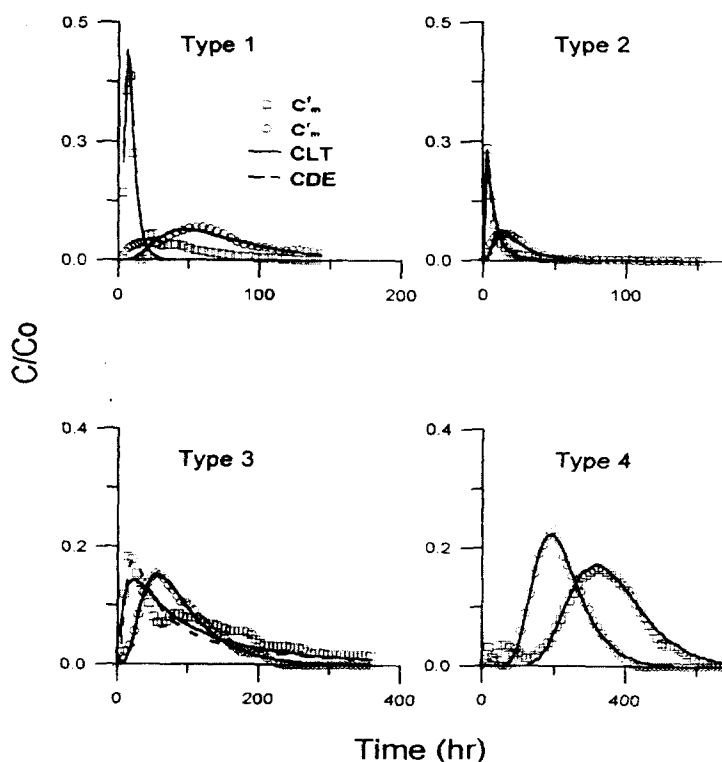


Fig. 3. Illustration of 4 different types of measured and fitted BTCs in flux and resident concentrations C_m^f and C_m^r denote the measured flux and resident concentrations respectively. In most cases the dashed line fitted by CDE model was overlapped by the solid line representing the CLT model fitting.

ferent BTC types. The BTC of type 1 shows a great difference between the measured flux and resident concentration. It seems that most of solutes moves preferentially along the macropores and only a small part of the applied solutes enters into the soil matrix region. Occurrence of peak travel time in both the flux and resident BTCs appears to greatly differ for type 1 whereas it almost coincides for type 2. From this, two possible explanations may be given such that either the preferential movement through the macro region in type 1, consisting of the main component of flux concentration, is

unlikely detected by the probe bypassing the TDR-detecting volume or that even if any of macropores is located in the TDR-detecting volume, the contribution of solutes in the macro region is so small in cross-sectional area compared to the matrix region. Comparison of the flux rates between type 1 (0.13 cm/hr) and type 2 (0.68 cm/hr) given in Table 4 implies that soils having higher flux rates are more likely to yield the same peak travel time in both the flux and resident BTC. This would be due to the increased chances of detecting the solutes by the probe on one hand and the increased area of macropores on the other hand since the number and area of macropores are proportional to the flux rate in the macro region. Another feature is related to the occurrence of bimodal peak in the flux concentration of the BTC. Note that the BTC of type 2 having the highest flux rate is in unimodal shape but the other types show bimodal BTCs. This is due to the fact that the solute interchange between the macro and matrix region is almost negligible during the storm flow through the macropores. However, chemical diffusion between the two regions are quite significant for soils having a rather moderate flux density because the solute interchange may occur during the relatively increased solute travel time. It is interesting to see that the type 3, having the intermediate flux density (0.36 cm/hr) between those of type 1 and 2, exhibits both the simultaneous travel time of peak concentration in flux and resident to a certain extent and a distinct bimodal shape in flux concentration. Type 4 shows the BTC obtained from a soil column without dominant ma-

cro pores since the flux density was very small with 0.02 cm/hr and the peak of resident concentration appears before that of flux concentration although the flux concentration shows a bimodal shape with the relatively low first peak.

An attempt was made to separate the flux concentration in the macro region from the measured effluent concentration using Eq. (11). The result is depicted in Fig. 4 for two other exemplary soil columns that are different from the 4 types shown in Fig. 3. Sample A has a bimodal peak but sample B does not. However, the magnitude of difference between the flux concentration in the macro and matrix regions is similar for both samples. The estimated flux concentration in the macro region appears slightly lower than the effluent concentration. In fact, the difference between the two concentrations

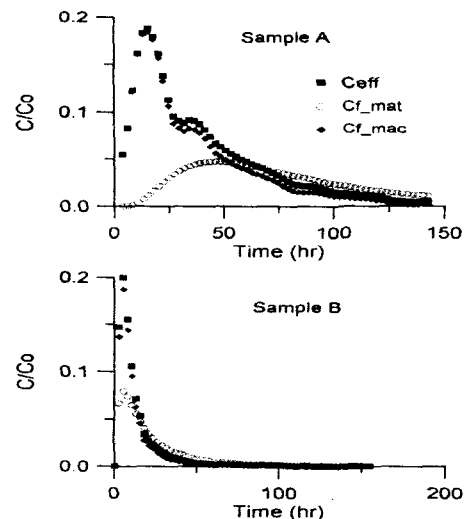


Fig. 4. Illustration of estimated flux concentrations (CF—mac) in the soil macro region, the ones (CF—mat) in the soil matrix region and the effluent concentration (Ceff) for two other soil columns.

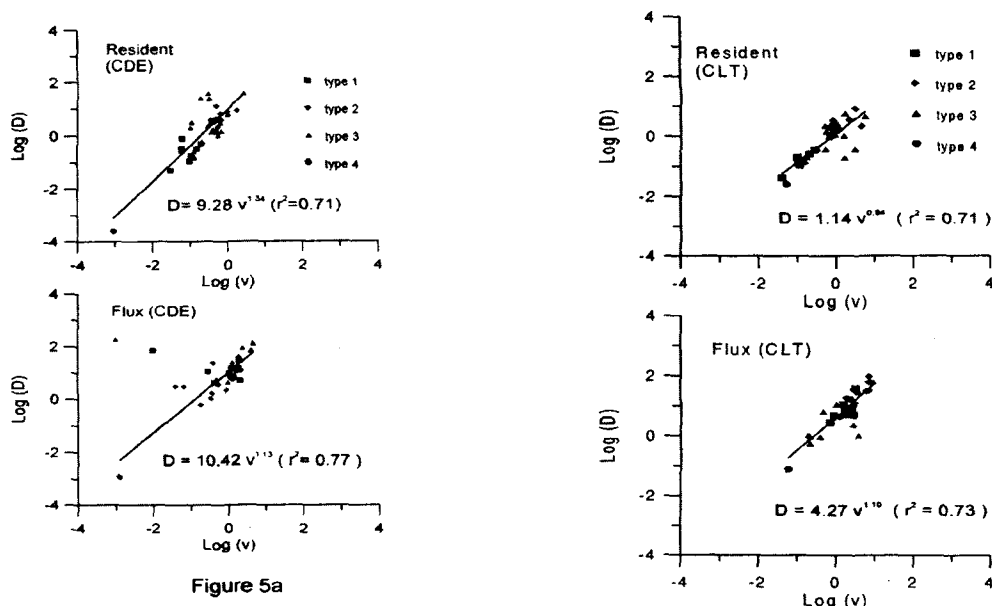


Fig. 5. Relationship between v and D of flux and resident concentrations in case of CDE (a) and CLT (b) model used for estimation of transport parameters.

largely depends on the ratio of pore water velocities in the matrix to the macro region. The higher ratio gives an almost identical result since the contribution of solute concentration from the matrix region becomes negligible. However, in a moderate ratio there would be a great difference between the two concentrations. In either case, the flux concentrations in two regions would be useful to increase the understanding of solute movement mechanism and interactions between the two regions in structured soils having various flow domains.

Comparison of Parameters

Fig. 5 shows the result of parameters estimated for the flux and resident concentrations using CDE and CLT model. For CDE model parameters (Fig. 5a), type 3 showed the highest D and type 4 the lowest v and D in both resi-

dent and flux concentrations. In flux concentration, two data points were far from the others. These data were obtained from the soil columns showing a typical storm flow of solute flux through the macro region with very early peak. In fact, application of the CDE model would fail to describe such behavior of solute movement as reported by others (Rao et al., 1980; Nkedi-Kizza et al., 1983). The extremely low values of v and high values of D were due to the inadequate model description to realize the behavior of solute transport in such soils. For this reason, the two data points were excluded for the regression analysis of the relationship between v and D . Parameters of CLT model expressed in v and D using Eq. (7) and (8) are shown in Fig. 5b for resident and flux concentrations. Large deviation of two data points with high values of D and low values of

v in flux concentration which was shown in CDE parameters, was disappeared shifting to the clustered data points. In addition, the data point of type 4 was closer to the other data points with the increase of v and D . Consequently, the relationship between v and D became more obvious in CLT than CDE. Since both models can equally give the almost perfect fitting to the measured data at a given depth, comparison of model parameter estimates should be based on other information. In this respect, we compared the results of both model parameters with flux rates. Contrary to the CDE model parameters, the order of magnitude in D especially in flux concentration was well compatible with the order of flux densities as the BTC type 2, 1, 3 and 4 had the value of D in a descending order. This indicates a tendency of increasing D with flux density. This result agrees to the large values of D for soils showing preferential movement obtained by others

(Parker, 1984; Seyfried and Rao, 1987; Li and Ghodrati, 1994). The dispersivity lengths obtained from CDE parameters showed generally higher values than those from CLT. This was due to the more contribution of molecular diffusion to the solute spreading than the mechanical dispersion in CDE model (Mallants et al., 1994). The flux concentration results in higher estimation of the dispersivity lengths than the resident because of predominant convective flow through macropores for both models. In case of CLT, the results of the dispersivity length (1.14 cm) were in a close agreement with the findings of Khan and Jury (1990) with 1.37 cm for flux concentration in loamy sand and Li and Ghodrati (1994) with 2.15 cm for flux concentration in silt loam but slightly higher than the field scale dispersivity length of resident concentration obtained by Kim et al. (1996b) which showed 1.53 cm at a depth of 15 cm in the same soil. The high values of disper-

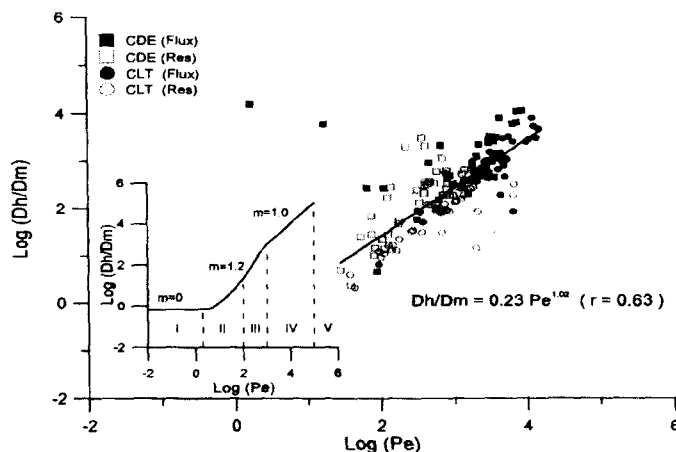


Fig. 6. Demonstration of estimated parameters from two different concentration modes and models in the domain of the ratio of molecular diffusion to hydrodynamic dispersion (D_h/D_m) and Peclet number (Pe).

sivity can be explained by the difference in the scale of measurements. For instance, sampling of a soil column in a smaller scale will create continuous macropores which otherwise would not exist at the field scale. The dispersion coefficients for CDE model are related to the pore water velocity with the power value of 1.13 for flux concentration and 1.34 for resident concentration. The higher value for resident concentration indicates more contribution of molecular diffusion to the solute spreading than

flux concentration.

Bear (1972) carried out a detail investigation on the dominant solute transport process in both experimental observations and theoretical aspects. According to the relationship between Peclet number (Pe) and the ratio (D_h/D_m) of hydrodynamic dispersion coefficient to the molecular diffusion coefficient, 5 different zones were distinguished. In this study, the relationship between Pe and D_h/D_m was investigated in a similar manner. The result of the relationship is shown in Fig. 6 for the flux and resident concentrations. Here, the Peclet number is defined as the ratio (vL / D_m) between the rate of transport by convection to the rate of transport by molecular diffusion (D_m). Obviously, most of soil columns studied showed a linear relation between Pe and D_h/D_m in a logarithm scale which falls on the zone 4. The value of power close to unity indicates that the dominant transport process in those soil columns was mainly mechanical dispersion with negligible molecular diffusion.

Summary and Conclusion

Solute displacement experiment was performed on structured soil columns in order to investigate the difference between flux and resident concentrations. Comparison of those concentrations revealed that the resident concentrations measured by TDR greatly differ from the flux concentrations measured by effluent. The difference was mostly found in peak concentration and travel time of peak with various flux rates. Based on these observations, 4 different types of breakthrough curves were dis-

tinguished. The first three types have shown earlier and higher peaks in flux than resident concentration indicating that the TDR-measured concentration represents only the solutes transport in soil matrix region.

Parameters of CDE and CLT model were obtained through least square optimization for both flux and resident concentrations. Separation of flux concentration in a macro region was attempted from the effluent concentration. Information on the parameters in both matrix and macro regions would be useful in modeling the solute transport in dual porosity media (van Genuchten and Wierenga, 1976; Gerke and Van Genuchten, 1993) and understanding of solute transport in macroporous soils (Skopp *et al.*, 1981; Hornberger *et al.*, 1990; Utermann *et al.*, 1990). Since both models can give equally a perfect fitting to the measured data for a given depth, a meaningful comparison was made by investigating the relationship between pore water velocity and dispersion coefficient. The CDE model resulted in overestimation of dispersivity length compared to the CLT model showing a nonlinear relationship between pore water velocity (v) and dispersion coefficient (D). The result of dispersivity obtained by CLT model parameters was compatible with the results of other studies. In certain cases, poor performance of CDE model was observed in estimation of parameters with extremely low values of pore water velocity and high values of dispersion coefficient for soil columns having high flux rates. This was attributed to the discrepancy between model assumption of complete solute mixing through different sizes of soil pores and

reality of preferential movement of solute through macropores. The higher estimation of dispersivity length in flux concentration than resident concentration and a linear relationship between v and D in the flux mode indicates that the solute dispersion is dominated by the mechanical dispersion rather than molecular diffusion. This was due to the convective flow through macropores with a high flux density. Expression of the dispersion characteristics in flux and resident concentrations from both CDE and CLT models in the domain of Peclet number and the ratio of hydrodynamic dispersion to molecular diffusion reveals that the dominant transport process in the studied soil columns is mechanical dispersion with negligible molecular diffusion.

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