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Journal of Hazardous Materials A73 (2000) 1–15

**Journal of  
Hazardous  
Materials**

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# One-dimensional solute transport in stratified sands at short travel distances

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Received 29 July 1999; received in revised form 18 October 1999; accepted 25 October 1999

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## Abstract

This paper presents laboratory-scale experimental observations on the migration of a non-reactive pollutant, sodium chloride, through stratified sands at short travel distances under one-dimensional flow conditions. Sand stratifications, perpendicular, parallel and inclined to the main flow direction, were used and contrary to most other published research work, flow was forced through the stratifications at a constant mean pore water velocity. The paper therefore examines the isolated effects of the different dispersion properties and particle size distribution of the sands used on their dispersion behaviour in different stratification configurations under the specified flow conditions. The initial part of the work on homogeneous sands produced differences in the dispersion which was found to be particle size distribution- and volume-dependent. For the stratified configurations and for the same volume of soil, the results showed different dispersion behaviour at the outflow position depending on the type of stratification and the sequence of the sands within each stratification. The paper presented a picture of the effect of various soils and flow conditions imposed on the transport of the solute and provided useful data on the profile of solute concentration for remediation purposes. © 2000 Elsevier Science B.V. All rights reserved.

*Keywords:* Solute migration; Stratified sand; Laboratory models; Dispersion parameters

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## 1. Introduction

Most sites, whether consisting of natural soils or made ground, have heterogeneities. Such sites commonly consist of an essentially unknown assemblage of strata having

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different hydraulic and chemical properties. The ability to predict and quantify contaminant migration in such heterogeneous soils, in terms of arrival time and spatial patterns, is essential for risk assessment, for the determination whether and where remediation is required and in the selection of the most appropriate treatment method. Consequently, the numerous complex issues related to site heterogeneities in terms of soil, contaminant and flow conditions have recently become a major part of much of the research work being carried out on contaminated ground. The complexity of site heterogeneities and the complexity of their effects mean that a simplified problem is usually investigated so that the effect of individual factors can be isolated and established. The most common simplification form of soil heterogeneity is the use of stratified soil. Soil stratifications in the form of soil layers positioned perpendicular, parallel and inclined to the main flow direction have been considered [1–4]. Soil stratification perpendicular and inclined to the main flow direction is applicable to landfill liners and to vertical infiltration of contaminants through the ground. Soil stratification parallel and inclined to the main flow direction is applicable to natural ground conditions with horizontal groundwater flow. The most common flow condition is that of one-dimensional flow through the full soil stratifications [2]. Other flow conditions have also been considered including one-dimensional flow through selected strata and pulse input [5–7]. Most published work has concentrated on long travel distances corresponding to long time periods after the introduction of a contaminant into the groundwater system. This paper concentrates on short travel distances represented in a short tank in which the mixed zone is of the same order of magnitude as the distance travelled in the direction of the flow hence representing early travel times.

Numerical solutions for contaminant transport problems have been developed to provide prediction models. Limited numerical solutions for specific soil stratifications have been proposed [2,8,9]. These are usually complex and problem-specific that most reported research work, whenever possible, still relies on the approximate applicability of the solution of one-dimensional flow in homogeneous isotropic soil [10,11]. Different solutions are obtained for different boundary conditions, but ordinarily, when the porous medium is long compared to the mixed zone, all solutions give almost identical results. For the problem of a large mixing zone compared to the length of the porous medium, different solutions emerge depending on the boundary conditions imposed [12].

This paper presents laboratory results of the dispersion behaviour and time development of concentration profiles of a non-reactive solute in stratified sands in short travel distances under one-dimensional flow conditions. The sands were stratified perpendicular, parallel and inclined to the main flow direction. Different to most other research work in which the effect of heterogeneity is reflected in dealing with different flow velocities in the different permeability soil layers, the mean pore water velocity was maintained constant throughout all stratifications. Hence, the purpose was to examine the isolated effect on the dispersion properties and particle size distribution of the individual sands in the presence of other sands of different dispersion properties which could exist in practice. The behaviour was examined in terms of mean contaminant velocity, dispersion coefficients and concentration isochrones. Where appropriate, the results were compared with numerical predictions using the computer program POLLUTE [8].

It has become well established that the dispersion behaviour of porous media is dependent on the scale of the experiment. This was demonstrated by studies which showed that the dispersivity of homogeneous soil in small-scale column experiments, was usually similar to the mean particle size, while in the field, the dispersivity is two to three orders of magnitude greater [2,13]. The values presented here were therefore used for comparison purposes only and should not be translated directly to full-scale problems without establishing the appropriate correlations between the two.

## 2. Theoretical background

The equation describing the transient concentration distribution for a non-reactive solute in saturated, homogenous, isotropic porous medium under one-dimensional steady-state uniform flow can be written as:

$$\frac{dC}{dt} = D_L \frac{d^2C}{dx^2} - v_f \frac{dC}{dx} \quad (1)$$

where  $C$  is the concentration,  $t$  is the time,  $x$  is the distance travelled,  $D_L$  is the longitudinal hydrodynamic dispersion coefficient and  $v_f$  is the mean pore water velocity, equal to  $v/n$ , where  $v$  is the discharge velocity and  $n$  is the porosity.

For a step input of solute, Ref. [11] gave the following solution:

$$\frac{C}{C_o} = \frac{1}{2} \left[ \operatorname{erfc} \left( \frac{L - v_f t}{2\sqrt{D_L t}} \right) + \exp \left( \frac{v_f L}{D_L} \right) \operatorname{erfc} \left( \frac{L + v_f t}{2\sqrt{D_L t}} \right) \right] \quad (2)$$

where  $C_o$  is the input concentration,  $L$  in the case investigated is the length of the tank and  $\operatorname{erfc}$  is a complementary error function. When  $L$  is sufficiently large, the second term in Eq. (2) becomes small compared to the first term and can be neglected [11], giving:

$$\frac{C}{C_o} = \frac{1}{2} \operatorname{erfc} \left( \frac{L - v_f t}{2\sqrt{D_L t}} \right) \quad (3)$$

The dispersion coefficient may then be calculated from the breakthrough curve using the following equation [11]:

$$D_L = \frac{1}{8} \left[ \frac{L - v_f t_{0.16}}{\sqrt{t_{0.16}}} - \frac{L - v_f t_{0.84}}{\sqrt{t_{0.84}}} \right]^2 \quad (4)$$

For short travel distances under the same conditions, the following solution in terms of the number of effluent pore volume,  $U$ , [12] is commonly used [2]:

$$\frac{C}{C_o} = \frac{1}{2} \left[ \operatorname{erfc} \left( \frac{1 - U}{2(UD_L/v_f L)^{1/2}} \right) \right] \quad (5)$$

Brigham recommended plotting effluent relative concentration,  $C/C_0$  versus  $\gamma = [(U - 1)/U^{1/2}]$  on linear probability paper. If the data fit a straight line, then the dispersion coefficient can be calculated from the slope of the line using:

$$D_L = \frac{v_f L (\gamma_{0.84} - \gamma_{0.16})^2}{8} \quad (6)$$

where  $\gamma_{0.84}$  and  $\gamma_{0.16}$  correspond to the relative concentrations  $C/C_0$  of 0.84 and 0.16, respectively.

The longitudinal hydrodynamic dispersion coefficient,  $D_L$ , is assumed to be the sum of two parts. The first is the mechanical dispersion coefficient which is a linear function of the mean pore water velocity  $v_f$  and is equal to  $\alpha_L v_f$ , where  $\alpha_L$  is the longitudinal dispersivity, which is commonly considered to be a soil characteristic. The second is the molecular diffusion coefficient of the solute in the porous medium,  $D^*$ , so that:

$$D_L = \alpha_L v_f + D^* \quad (7)$$

In the problem investigated here, the Peclet number ( $v_f d_{50}/D^*$ , where  $d_{50}$  is the mean particle size) values were found to be between 50 and 100 and hence mechanical dispersion was far more dominant than molecular diffusion [14] and meant that  $D_L$  is simplified to:

$$D_L = \alpha_L v_f \quad (8)$$

from which the dispersivity can then be calculated.

A noticeable difference between the movement of a miscible contaminant in short and long columns is that in short columns, because of the higher concentration gradient, the displacing fluid flows faster than the displaced fluid [12] and hence on a breakthrough curve, the time for the arrival of 50% concentration ratio  $C/C_0$  does not take place at one pore volume, but at a smaller fraction. The actual value is governed by the ratio  $\beta = v_f L/D_L$ , where the smaller this ratio is, the lower the pore volume at 50% relative concentration. Hence, the mean contaminant velocity ( $v_c$ ) calculated using  $L/t_{0.5}$  is always greater than the mean pore water velocity ( $v_f$ ) calculated from  $v/n$ . Values of  $\beta$  between 125 and 500 have been reported to be considered sufficient to ensure long travel distances. The value used in the experiments reported here was around 10 corresponding to short travel distances.

The general solution to Eq. (1) for a layered soil developed by Rowe and Booker was implemented into a computer code POLLUTE [8]. The program uses semi-analytical techniques to solve Eq. (1) in homogeneous and layered strata of finite depth.

### 3. Materials and experimental procedure

The experimental work was carried out in a rectangular laboratory-scale perspex tank 0.45 m long, along which the main flow was imposed, 0.38-m-wide and 0.25-m-high. One inlet and three outlet flow ports were used as shown schematically in Fig. 1. These ports were screened with fine wire mesh to eliminate possible clogging by the soil and were adjusted such that flow in and out of the tank could be fixed at predetermined rates. A peristaltic flow pump, located at the inflow position was used to provide the

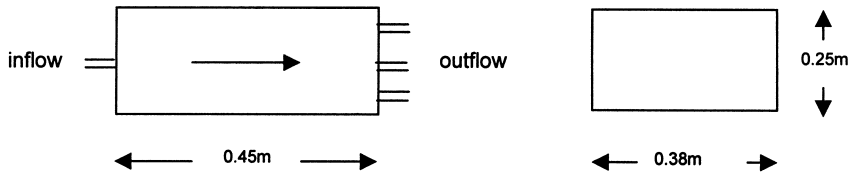


Fig. 1. Schematic diagram of the tank used in the experiments.

inflow water and contaminant solution into the soil tank. The one-dimensional flow condition was imposed using porous plastic sheets placed along the required cross-sectional areas of flow.

A sodium chloride solution containing 8 g/l (0.137 M) concentration was used as the non-reactive contaminant. This is a typical landfill leachate concentration of  $\text{Cl}^-$  and typical collective concentration of  $\text{Na}^+$  and other similar ions such as  $\text{K}^+$  [15]. The concentration of sodium chloride was measured at the outflow position using a conductivity meter. All experiments were conducted at an ambient temperature of approximately 24°C.

Three gradings of sand were used: fine to medium (FMS), medium (MS) and coarse (CS) as shown in particle size distribution curves in Fig. 2. All three sands were placed at a constant porosity of 40% in all the experiments. The sands were placed under water to ensure saturation and all sand layers were maintained saturated throughout the experiments. Uncontaminated water was initially permeated through the tank to ensure steady state conditions were achieved before the saline solution was introduced and to establish the required outflow conditions at each port to maintain constant velocity. The discharge velocity used in all the experiments was around  $4.5 \times 10^{-5}$  m/s similar to values used in similar reported experimental work [2]. The tests were terminated after one pore volume of flow.

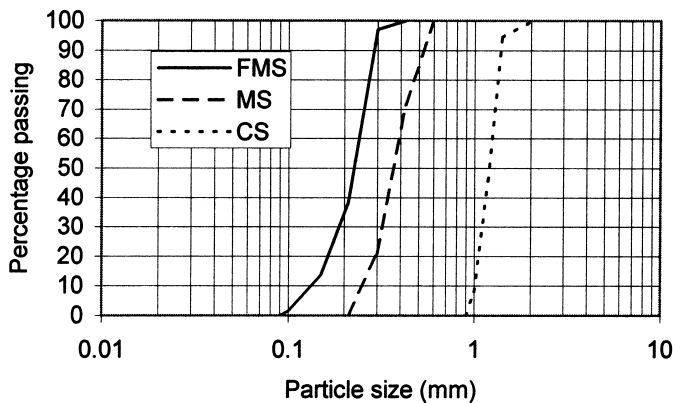


Fig. 2. Particle size distribution curves for the three sands used.

Table 1  
Dispersion properties of the homogeneous sand layers

Test	Sand type	$D_{10}$ and $C_u$	Thickness (m)	$K$ ( $\times 10^{-3}$ m/s)	$v_c = L/t_{0.5}$ ( $\times 10^{-5}$ m/s)	Calculated $D_L$ (Eq. (6)) ( $\times 10^{-6}$ m <sup>2</sup> /s)	Calculated $D_L$ (Eq. (4)) ( $\times 10^{-6}$ m <sup>2</sup> /s)	Predicted $D_L$ (POLLUTE) ( $\times 10^{-6}$ m <sup>2</sup> /s)
H1a	Fine-medium (FMS)	0.14	0.08			4.1		
H1b		1.52	0.18	0.24	14.3	4.8	3.7	4.2
H1c			0.25			5.5		
H2a	Medium (MS)	0.26	0.08	0.62	23.4	6.0		
H2b		1.36	0.18	0.62	17.1	7.1	6.9	5.8
H2c			0.25	0.62	14.3	8.1		
H3a	Coarse (CS)	1.0	0.08			7.3		
H3b		1.2	0.18	13.0	19.8	8.6	8.3	6.6
H3c			0.25			9.8		

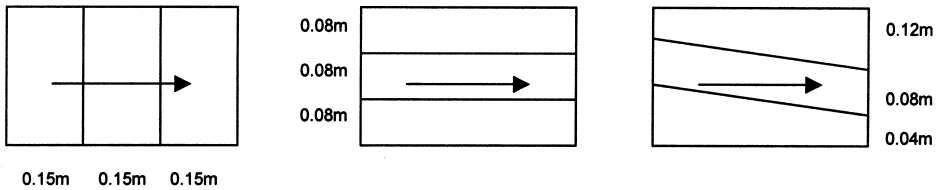


Fig. 3. Schematic diagram of the three sand stratification configurations used in relation to the main flow direction: (a) perpendicular, (b) parallel and (c) inclined.

The first set of experiments was to test the three sands individually in homogeneous configurations designated H1, H2 and H3 as shown in column 1 of Table 1. The second set of experiments was that of the perpendicular to flow soil stratification configurations, designated PR1 to PR4 in which three sections of sand were used, each 0.15 m long as shown in Fig. 3(a). The sands used in each section are as shown in Table 2. The third set was of the parallel to flow direction soil stratification configurations, designated PL1 to PL5 in which three layers of sand, each 0.08-m-thick, were used as shown in Fig. 3(b). The sand used in each layer is as detailed in Table 3. The fourth and final set of tests was of the inclined to the flow direction soil stratification configurations, designated INC1 and INC2, in which the inclination of soil layers to the horizontal was  $10^\circ$  as shown in Fig. 3(c). The sand used in each layer is as detailed in Table 4. Constant head permeability tests [16] were carried out on the three sands at the same porosity of 0.4 and the permeability values are shown in Table 1.

#### 4. Results and discussion

Each of the four sets of experiments are presented and discussed separately first and then compared with each other and with the numerical POLLUTE predictions where appropriate. The results are presented in terms of dispersion properties in tabulated form. Relative concentrations were plotted against the pore volume term  $[(U-1)/U^{1/2}]$  on probability paper and all the results presented here are from those which produced a straight line. Some of the results, those of the parallel and inclined stratifications, are also presented in terms of concentration isochrones to show the distribution profile of the solute concentration in the centre of each of the three sand layers.

Table 2  
Dispersion behaviour of the perpendicular sand stratifications

Test	Sand stratification configuration	$v_c$ ( $\times 10^{-5}$ m/s)	Calculated $D_L$ ( $\times 10^{-6}$ m <sup>2</sup> /s)	Predicted $D_L$ ( $\times 10^{-6}$ m <sup>2</sup> /s)
PR1	FMS–FMS–CS	14.9	4.02	5.35
PR2	FMS–CS–FMS	15.4	4.54	5.10
PR3	CS–CS–FMS	19.4	5.25	5.98
PR4	CS–FMS–CS	18.7	7.13	6.20

Table 3  
Dispersion behaviour of the parallel sand stratifications

Test	Sand type	$v_c$ ( $\times 10^{-5}$ m/s)	Calculated $D_L$ ( $\times 10^{-6}$ m <sup>2</sup> /s)
PL1	FMS	14.5	4.33
	MS	16.6	6.02
PL2	FMS	15.1	4.43
	FMS	14.5	5.16
	CS	19.5	6.86
PL3	FMS	13.8	5.44
	MS	15.2	6.06
	CS	19.1	7.50
PL4	MS	15.2	6.13
	CS	19.1	6.80
	MS	16.7	6.72
PL5	CS	19.4	7.12
	CS	19.6	6.84
	FMS	16.2	5.91
	CS	20.1	6.73

The advection–dispersion behaviour can be assessed from the breakthrough curves by the closeness of the curve to the  $y$ -axis at the 50% relative concentration point, measured in terms of the mean contaminant advective flow velocity ( $v_c$ ). It can also be assessed in terms of the spreading of the ‘S’-shaped curve about the 50% relative concentration point giving an indication of the degree of dispersion, quantified in the longitudinal dispersion coefficient ( $D_L$ ).

All the breakthrough curves related to the results presented here displayed the classical ‘S’-shaped curve. It was observed in all the tests that the mean contaminant velocity ( $v_c$ ), measured as  $L/t_{50}$ , was always greater than the mean pore water velocity ( $v_f$ ). In other words, the time for  $C/C_0$  to reach 50% at the outflow position ( $L = 0.45$  m) was always shorter than that required for the advective front travelling at the mean pore water velocity ( $v_f$ ) to reach the same position. This is the characteristic behaviour

Table 4  
Dispersion behaviour of the inclined sand stratifications

Test	Sand type	$v_c$ ( $\times 10^{-5}$ m/s)	Calculated $D_L$ ( $\times 10^{-6}$ m <sup>2</sup> /s)
INC1	FMS	12.1	2.77
	CS	15.3	7.32
	FMS	15.0	3.23
INC2	CS	16.1	6.38
	FMS	18.2	2.19
	CS	15.5	7.10



in short columns [12] for which the Brigham solution is recommended and was used here in calculating the dispersion coefficients [2].

#### 4.1. Homogeneous configurations

The dispersion behaviour of the three sands in homogeneous configurations was investigated in 0.18-m-thick layers and for the medium sand only in 0.08- and 0.25-m-thick layers in addition. This provided a direct comparison between the three sands and an assessment of the effect of the volume of soil used. All the tests were carried out at the same discharge velocity ( $v$ ) of around  $4.5 \times 10^{-5}$  m/s giving a mean pore water velocity ( $v_f$ ) of  $11.25 \times 10^{-5}$  m/s for  $n = 0.4$ . The results are shown in Table 1. The table shows three sets of values for the dispersion coefficient in the last three columns. The first shows the calculated  $D_L$  values using the Brigham method (Eq. (6)) which are the appropriate values for the experimental setup used with a margin of accuracy of up to  $\pm 5\%$ . The next column shows the calculated  $D_L$  values from the classical expression (Eq. (4)) which applies to the problem of a long column or large travel distances, with a margin of accuracy of up to  $\pm 10\%$ . The last column gives the predicted  $D_L$  values using the numerical programme POLLUTE. These values were produced using the experimentally determined dispersivity (calculated from Eq. (8) and using  $D_L$  calculated from Eq. (6)) and the appropriate flow properties.

Table 1 shows that the arrival time for 50% relative concentration is shortest for the coarse sand and hence the mean contaminant velocity ( $v_c$ ) is highest. Comparing the three sands for the same layer thickness shows that the coarser the sand, the higher the dispersion coefficient and hence the greater the spreading of the solute. All other factors being equal, the cause of the different dispersion behaviour is the difference in the particle size distribution. The results for different sand layer thicknesses carried out on the medium sand showed that the dispersion behaviour is governed by the volume of soil tested and not simply by its length. The mean contaminant velocity decreased and the dispersion coefficient increased as the volume of soil tested increased, which is probably indicative of the increased microscopic heterogeneity as the volume of soil tested is increased. This increase is, however, relatively small in that doubling the cross-sectional area of the soil tested caused an increase of 18% in the value of  $D_L$ . The values in italic for the fine-medium sand and coarse sand are calculated using the medium sand results to give the same ratio of the dispersion coefficient between the different thicknesses for each sand. The  $\alpha$  values that would be obtained from Table 1 (Eq. (8)) are much higher than the mean particle size [17] which is in line with other similar published work [18,19].

In addition to carrying out tests on the homogeneous configurations using the discharge velocity specified above, tests were carried out using half and double that velocity. The results produced roughly half and double the dispersion coefficients giving a direct correlation between the two. Table 1 shows that the effect of permeability on the dispersion behaviour is insignificant in that the permeability of the coarse sand is over 20 times greater than that of the medium sand, but the dispersion coefficient is only 20% greater.

Table 1 also shows that the  $D_L$  values calculated from Eq. (4) are lower than those produced using Eq. (6) indicating that Eq. (4) underestimates the dispersion in short columns. Also, the predicted  $D_L$  values using POLLUTE are also lower than those calculated from Eq. (6). This is a reflection of the differences between an 'ideal' homogeneous soil and experimental homogeneity indicating that experimentally, dispersion is always greater than predicted theoretically.

#### 4.2. Perpendicular stratifications

Four different sand stratification configurations perpendicular to the main flow direction were tested as detailed in Table 2 together with the calculated dispersion coefficients, using Eq. (6), and predicted, using POLLUTE. All the tests contained two sands only; namely the fine-medium sand (FMS) and coarse sand (CS). Tests PR1 and PR2 have the FMS/CS ratio of 2:1 with the CS section being at the end and middle, respectively. Tests PR3 and PR4 have the same arrangement, but with the FMS/CS ratio reversed. As was observed with the homogeneous configurations, the observed mean contaminant velocities were greater than the mean pore water velocity.

Comparison between tests PR1 and PR2 and similarly between PR3 and PR4 shows different results indicating that the positioning of the layers in the perpendicular configurations affects the dispersion behaviour, although the change is relatively small. The trend predicted using POLLUTE was the reverse for tests PR1 and PR2 to what was observed experimentally.

Comparing the perpendicular configurations containing two-thirds of one sand with the homogeneous configuration of the same sand, hence comparing PR1 and PR2 with H1c, shows that the presence of coarser sand in one-third of the fine-medium sand sample has decreased the dispersion coefficient of the combined configuration by up to 27%. Comparing PR3 and PR4 with H3c shows the same effect in that the presence of the fine-medium sand in one-third of the coarse sand sample has reduced the dispersion coefficient, but the reduction is greater and up to 47%. This can be explained by the combined effect of each of the layers being shorter than its corresponding homogeneous layer and the different in dispersion properties of the two sands. The former produces less dispersion in both cases because at very short travel distances, the spreading is limited and increased with distance [17]. The latter increases the dispersion in tests PR1 and PR2 and decreases it in tests PR3 and PR4. Hence, in tests PR1 and PR2, the effects of the two factors are of the opposite sign and since the observed overall effect is a small decrease, this means that the reduction is greater than the increase. In the case of tests PR3 and PR4, both factors cause a decrease and hence the combined effect is a large decrease overall. A look at the POLLUTE predicted results and comparing them with those predicted for the homogeneous configuration shows a similar trend.

#### 4.3. Parallel stratifications

Five different sand stratification configurations parallel to the main flow direction (horizontal) were investigated. These are detailed in Table 3 together with the results

giving the dispersion properties of each layer separately. All five test configurations consisted of a layer of one sand sandwiched between two layers of a different sand. Hence, the middle layer was either more dispersive, tests PL1 to PL3, or less dispersive, tests PL4 and PL5, than the surrounding layers. The objective in those tests was to observe the degree of change in the dispersion behaviour of one sand layer due to the presence of adjacent sand layers with different dispersion properties and mean contaminant flow velocity, but under the same imposed mean pore water velocity. The difference in the dispersion behaviour between the top and bottom layers in each test being the same sand confirms the margin of accuracy of the experimental results being up to  $\pm 5\%$ .

A visual description of the dispersion behaviour during two of the tests is presented in terms of concentration isochrones showing relative concentration in the middle of the three layers at various time intervals, and equivalent pore volume, is shown in Fig. 4(a) and (b) for tests PL2 and PL5, respectively. The concentration isochrones show that the solute concentration in the coarse sand is greater than that in the fine-medium sand up to a pore volume of 0.63 and hence the concentration profile reverses in shape when the sands are reversed. It can also be seen that the solute concentration in the fine-medium sand is roughly half that in the coarse sand up to a pore volume of 0.27. This observation was used in subsequent work to investigate the feasibility of the treatment of such heterogeneous contaminated sand by cement grouts [20].

The results of tests PL1 and PL2 in Table 3 show that the presence of a higher dispersivity soil in the middle layer has caused the dispersion coefficient of the two outer layers to increase compared to their corresponding value in the homogeneous configurations in Table 1. The dispersion coefficient of the middle layer itself reduced slightly. Such increase is attributed to lateral dispersion from the more dispersive layer into the less dispersive adjacent layers. The dispersion behaviour of the more dispersive sand remained roughly the same. This applies to both cases when the middle layer is either more dispersive or less dispersive than the surrounding layers. A comparison between PL1 and PL2 shows that the bigger the difference in the dispersivity between the adjacent layer, the greater the increase in the dispersivity of the less dispersive layer. The same observation can be seen in the reverse stratification when the middle layer is less dispersive. It can also be seen that as the difference between the dispersivities increase, the increase in the dispersivity of the middle layer is increased even further compared to the reverse sand stratifications as can be seen by comparing tests PL2 with PL5. This is because the middle less permeable layer is subjected to lateral dispersion from both sides, being sandwiched between two more dispersive layers.

#### *4.4. Inclined stratifications*

Two different soil stratification configurations inclined at  $10^\circ$  to the horizontal were investigated as detailed in Table 4 together with the dispersion results. These tests are the same stratification configurations as two of the parallel stratifications detailed in Table 3, namely PL2 and PL5, respectively. Typical concentration isochrones are shown in Fig. 5(a) and (b) for tests INC1 and INC2, respectively. The first observation that can be made from both Table 4 and Fig. 5 is that the difference in the dispersion coefficients

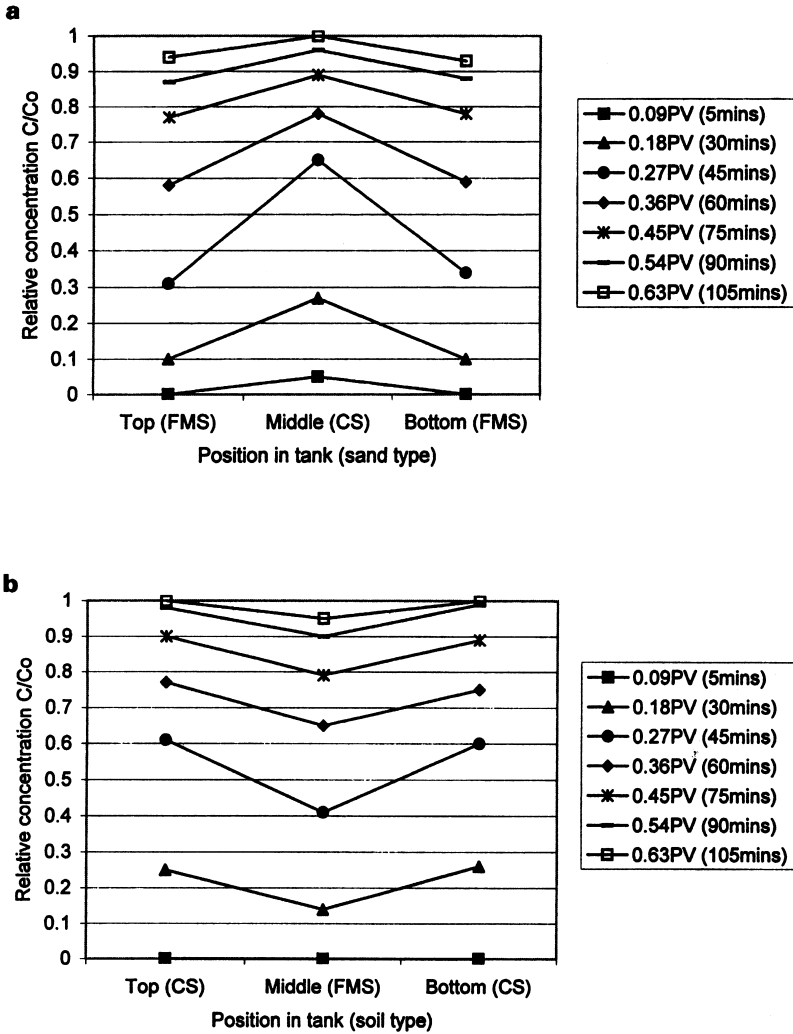


Fig. 4. Concentration isochrones for the parallel sand stratification configurations in tests PL2 and PL5.

and solute concentration between adjacent layers is bigger than was observed in the corresponding parallel stratification tests. This indicates that flow inclined to stratification causes more spreading of the solute and hence more dispersion.

Comparison between tests INC1 and PL2 show that the  $D_L$  values of the fine-medium sand layers in the inclined configurations are lower than those in the parallel stratifications and the opposite is correct for the coarse sand. This shows that, although the experimental setup was such that the flow was imposed in the horizontal direction at the same mean pore water velocity throughout in both the parallel and inclined stratification tests, the dispersion behaviour was different. Comparing tests PL5 and INC2 with

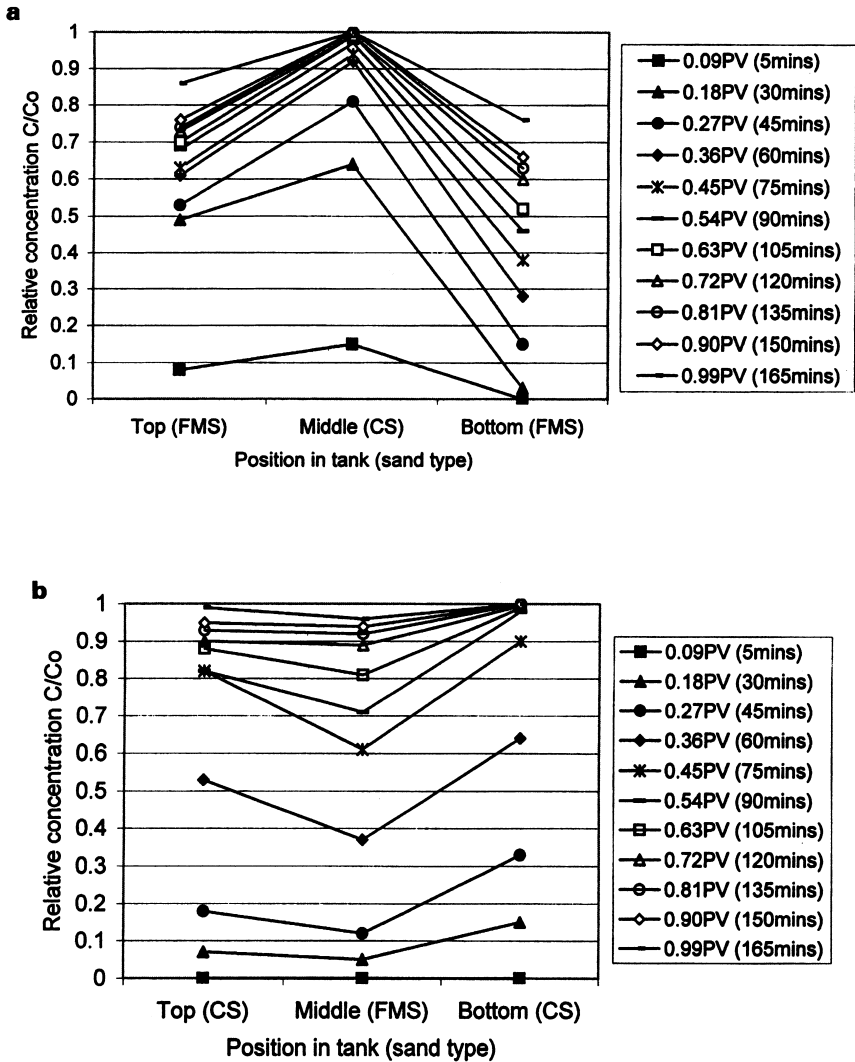


Fig. 5. Concentration isochrones for the inclined sand stratification configurations for tests ICN1 and INC2.

fine-medium sand layer sandwiched between two coarse sand layers in parallel and inclined configurations, respectively, shows the same effect mentioned above and shows that the  $D_L$  value of the fine-medium sand roughly halved, while that of the coarse sand increased slightly.

The concentration isochrones show that a pore volume of around 1.0 was required to achieve consistent solute concentration between adjacent layers and that up to a pore volume of 0.5, the concentration in the coarse sand was about twice that in the fine-medium sand.

## 5. Conclusions

The migration of a non-reactive pollutant in three types of sand at short travel distances was studied. The results show that under one-dimensional flow conditions in both homogeneous and stratified configurations, the mean contaminant velocity is always greater than the mean pore water velocity, being highest for the coarsest sand. The three sands produced different dispersion behaviour, being produced by different particle size distribution in the presence of the same porosity. The dispersion behaviour was also found to be volume-dependent such that as the volume increased, the microscopic heterogeneity increased and hence the dispersion coefficient increased.

In the perpendicular sand stratifications, the dispersion coefficient reduced compared to the value of the homogeneous dominant sand. In the parallel sand stratifications, the dispersion coefficients of the less dispersive sand increased in the presence of a more dispersive sand. In the inclined sand stratifications at  $10^\circ$  to the main flow direction, a higher level of dispersion was observed compared to the parallel stratifications.

The concentration isochrones showed that at early time intervals, for example, pore volumes of 0.27 and 0.5 for the parallel and inclined stratifications, respectively, the concentrations of the solute in the fine-medium sand was always roughly half that of the coarse sand. Subsequently, it was at pore volume of 0.6 and 1.0, respectively, that the concentrations became more or less similar. The results of this work present a picture of the degree of contaminant heterogeneity under such soil, contaminant and water flow conditions and provides useful data on the profiles of solute concentrations for remediation purposes. These soil and contaminant heterogeneities were used in a subsequent study which dealt with the treatment of such contaminated soils with cement grouts [20].

## Acknowledgements

The authors gratefully acknowledge the assistance of the technical staff in the School of Civil Engineering at the University of Birmingham.

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