

## LABORATORY MODELING OF TWO-DIMENSIONAL DIFFUSIVE AND ADVECTIVE-DIFFUSIVE CHLORIDE TRANSPORT THROUGH SILT AND CLAY\*

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**Abstract**– Two-dimensional diffusive and advective-diffusive chloride transport through clay and silt, respectively, was investigated using laboratory models. The observed chloride concentration plumes in the soil samples as well as the chloride concentration-versus-time profiles in the source reservoirs were predicted using the computer code MIGRATEv9. Equivalent horizontal and vertical chloride diffusion coefficients reasonably predicted the observed concentration plumes and concentration-versus-time indicating that soils were homogeneous and isotropic. The predicted diffusion coefficients were in the range of the reported values for similar soils. The effect of downward Darcy flux in the advection-diffusion tests on the chloride concentration plumes was assessed by comparing the shapes of the plumes with those in the pure diffusion tests. The downward Darcy flux caused the concentration plumes in the advection-diffusion tests to migrate further in the vertical direction compared to that in the horizontal direction. All plumes spread symmetrically with respect to the vertical axis of symmetry of the silt samples, and the applied horizontal base flow had no significant effect on the symmetrical shape of the plumes in the advection-diffusion tests. Overall, the existing two-dimensional advective-diffusive-dispersive contaminant transport theory as implemented in the computer code MIGRATEv9 reasonably predicted the chloride migration through silt and clay.

**Keywords**– 2-D laboratory modeling, diffusion, advection-diffusion, clay, silt

### 1. INTRODUCTION

Many regulatory authorities now require the use of liners beneath waste disposal sites to control pollutant migration [1-5] and this often involves separating the landfill from any underlying aquifer by a relatively impervious natural fine grained layer such as silt or clay or a compacted clay liner. Accordingly, the geotechnical and geochemical properties and contaminant migration through liners have been investigated extensively [6-13]. The movement of pollutants through relatively impermeable soils is slow; however, significant pollution may still occur in the long term such that designing disposal sites to prevent possible contamination of groundwater in both the short term and the long term is important [14].

The primary factors that govern contaminant migration are advection, diffusion, and chemical reaction. For many applications, advective transport may be small compared with that due to diffusion [15-19], but this relative difference cannot be generalized for all applications.

Rowe and Booker [14, 20] developed a one-dimensional analysis that takes into account the decrease in the concentration of leachate in the landfill as leachate is transported into the underlying soil and subsequently into a more permeable underlying stratum (aquifer) beneath the soil deposit. The one-dimensional analysis may be adequate provided the width of the landfill is large compared with the depths

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of the underlying soils such that transport is predominantly unidirectional. If, however, the plan dimensions of the landfill are comparable with the depth of the underlying soils, both horizontal and vertical transport may occur [21-24].

This study considered the case of single solute (chloride) migration from a landfill into an underlying fine grained layer of finite depth under 2-D conditions using laboratory models. The objectives of this investigation were as follows: (1) 2-D diffusion tests on clay were performed to investigate how the observed concentration plumes in clay could be predicted by an analytical 2-D transport model and whether equivalent horizontal and vertical chloride diffusion coefficients could predict the observed concentration plumes and concentration-versus-time and to examine whether the soils are homogeneous and isotropic, (2) 2-D advection-diffusion tests through silt were performed with a test configuration consisting of a downward Darcy flux through silt and a horizontal base flow underneath the silt (in the modeled aquifer) to observe the concentration plumes through silt; the use of equivalent horizontal and vertical diffusion coefficients in silt, in theoretical predictions, was investigated, (3) by comparing the predicted and observed concentration plumes, an assessment was made of how well the existing 2-D advective-diffusive-dispersive transport theory predict 2-D chloride migration through clay and silt layers.

## 2. MATERIALS, LABORATORY MODELS AND TEST METHODS

### a) Characteristics of the soil samples

The clay and silt samples were obtained from the vicinity of the Urmia City landfill site, Urmia, Iran. Various tests performed on these samples indicate that these samples are silt with low plasticity (ML) and clay with low plasticity (CL). The words M, C, and L, refer to silt, clay, and low plasticity, respectively. Table 1 shows the important properties of the soil samples.

Table 1. Characteristics of the soils used in the experiments

Property	Standard	Silt	Clay
Liquid limit (%)	ASTM D4318	22	22
Plastic limit (%)	ASTM D4318	14	8
Unified soil classification	ASTM D2487	ML	CL
Specific gravity	ASTM C128	2.71	2.73
Optimum water content (%)	ASTM D698	13.6	12.9
Maximum dry density (g/cm <sup>3</sup> )	ASTM D698	1.91	1.96

### b) Two-dimensional diffusion tests

Figure 1 shows the schematic view of the experimental setup used to perform the diffusion tests. The apparatus has 32 cm height, 42 cm width, and 5.6 cm thickness. The available space for the soil sample has 20 cm height, 30 cm width, and 3.8 cm thickness, as shown in Fig. 1. There is a compartment on the top in the middle of the soil sample for source contaminant reservoir (NaCl chloride solution in this study). This reservoir with a 5 cm width simulates a landfill on top of the natural or compacted soil layer. As shown in Fig. 1, the water tightness was achieved by sealing washers and the apparatus was assembled using nuts and bolts.

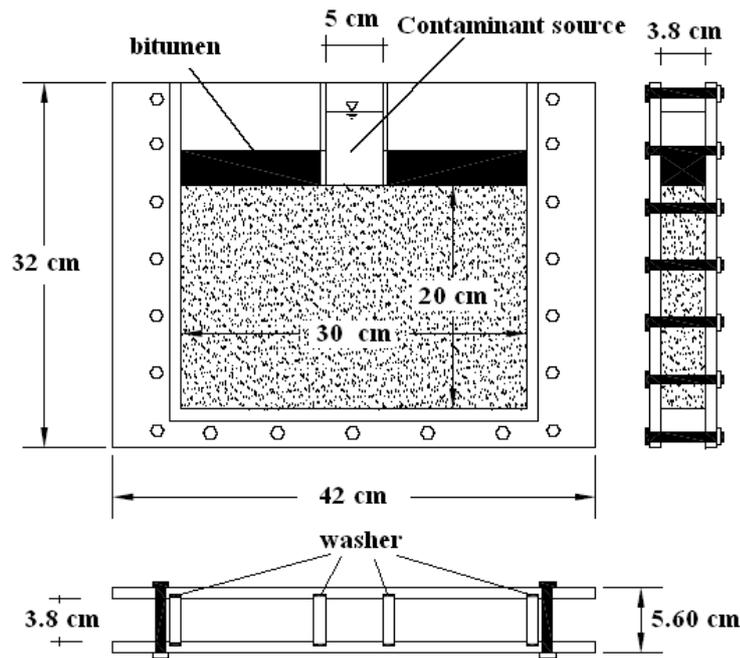


Fig. 1. Schematic of 2-D diffusion tests

The clay sample was air dried, pulverized, and passed through a No. 4 sieve. The sample was mixed with tap water. The wetted sample was placed inside the model and was compacted in 7 layers of 3 cm thickness to simulate the standard Proctor method of compaction. Care was taken to obtain a homogenous soil layer after compaction by applying equal compaction energy on the soil surface. Once the desired 20 cm height of the sample was achieved, a layer of bitumen was applied on top of the soil on both sides of the source reservoir to obtain a zero flux boundary on top of the soil and also to prevent change of soil water content and drying of the surface of the soil sample during test. The sodium chloride solution of known concentration was poured inside the source reservoir compartment and the 2-D clay diffusion test started. Two identical tests were performed on clay to insure the repeatability of the test results. These tests were referred to as Tests CD-1 and CD-2 with the test durations of 40 days and 42 days, respectively. Similar results were obtained for both tests and the data for both tests and the figures for Test CD-2 are only presented for the sake of brevity.

The NaCl samples were collected from the centre source reservoir on a daily basis to observe the chloride concentration change during the test. To keep the source solution height inside the source reservoir constant during the test, the same volume of distilled water was added to the reservoir to replace the volume of extracted solution. Before and after sampling from the source reservoir, the solution was stirred manually by a spoon to keep uniform concentration of solution inside the reservoir during the test. After termination of the test, the final source sample was collected from the source reservoir and the reservoir was drained. The collected source reservoir samples were then analyzed for their chloride concentrations and plotted against elapsed time (duration of the diffusion test). The model was placed horizontally on the table and was disassembled. The front and side Plexiglas sheets of the model were removed. A chess type sketch was drawn on the surface of the soil as a guide and the sample was sliced in 54 cubes of 3 cm by 3.3 cm dimensions, as shown in Fig. 2. A pneumatic soil pore water squeeze apparatus was used to obtain the contaminated pore water from the sliced soil samples and the chloride concentrations of the extracted pore water samples were measured. The observed chloride concentrations

were plotted in the centre points of the cubical soil samples against  $x$  (width) and  $z$  (height) dimensions of the soil. The selected observed concentration plumes were then plotted by interpolating between the plotted concentrations in the centre point of the samples and were compared with the predicted concentration plumes which will be discussed later. All tests were performed at  $23 \pm 2^\circ\text{C}$  room temperature.



Fig. 2. Slicing the soil samples after termination of the 2-D diffusion tests

### c) Two-dimensional advection-diffusion tests

The 2-D diffusion model was modified to perform the 2-D advection-diffusion tests on the silt sample. The schematic of the model is shown in Fig. 3. At the bottom of the model a space with 4 cm height was provided to create a receptor reservoir to simulate an aquifer at the bottom of the soil layer. A perforated sheet with a filter paper on top separated the bottom reservoir from the overlying soil. The inlet and outlet openings with valves at the left and right side of the reservoir were created to apply a horizontal base flow at the bottom reservoir. The horizontal flow was created using a peristaltic pump connected to the inlet at the left opening. A water tank containing the distilled water was considered as a source of water for the peristaltic pump. The outflowing water through the right opening was collected and the horizontal base velocity ( $v_b$ , as will be discussed later) was calculated based on the volume of outflowing water.

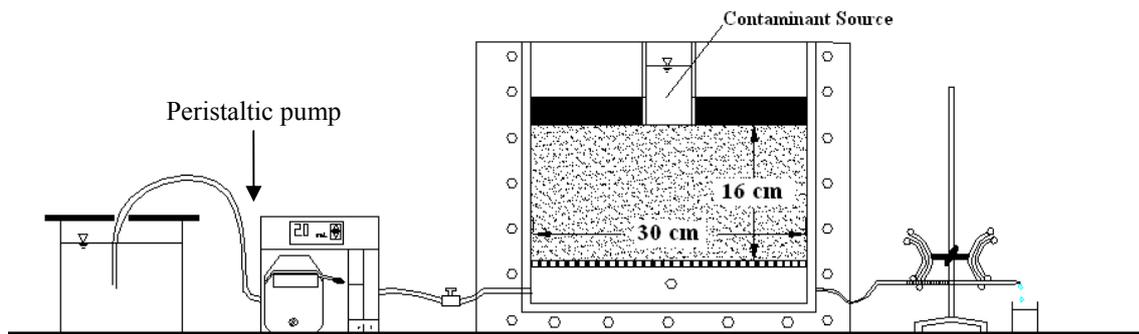


Fig. 3. Schematic of the 2-D advection-diffusion tests

The silt (ML, Table 1) was selected as a soil sample to accelerate the advective process of transport through the soil and avoid longer test duration. To set up the advection-diffusion test, the model was assembled and the bottom receptor reservoir was filled with water. The silt sample was prepared, placed and compacted in the model, using the same method described earlier for 2-D clay diffusion tests. Care

was taken to create a homogenous and isotropic soil layer after installation. The peristaltic pump was turned on and a horizontal base flow through the bottom receptor reservoir (the simulated aquifer) was initiated. The applied flow and the base velocity were 2 mL/min and 0.13 cm/min, respectively, in two conducted tests. After installation of the silt sample, application of the bitumen, and applying the base flow, the NaCl solution of known concentration was poured inside the source reservoir on top of the silt, and the test was started. The source solution samples and the receptor reservoir samples were collected on a daily basis for the observation of the concentration change with time during the test. The collected samples were analyzed for chloride concentrations and were plotted against elapsed time (for the duration of the tests).

At the end of the tests, source and receptor reservoirs were drained and the silt was sliced using the same method described earlier for 2-D clay diffusion tests. The method of silt pore water extraction, chloride concentration measurement, and plotting the selected observed chloride plumes were similar to those described earlier for 2-D clay diffusion tests. Two identical tests were performed which were referred to as Tests AD-1 and AD-2 with the test durations of 20 days and 30 days, respectively. The data for both tests and the figures for Test AD-1 are only presented for the sake of brevity.

### 3. THEORY

Rowe and Booker have described and given solutions to the governing equations of 2-D advective-diffusive-dispersive transport [22]. The transport of substances through soil can often be approximated by Fick's law [25], having the form:

$$f_x = nc v_x - nD_{xx} \frac{\partial c}{\partial x}$$

$$f_z = nc v_z - nD_{zz} \frac{\partial c}{\partial z}$$
(1)

where  $n$  is the porosity of the soil layer;  $D_{xx}$ ,  $D_{zz}$  are the coefficients of hydrodynamic dispersion (incorporating the effects of molecular diffusion and mechanical dispersion) in the  $x$ - and  $z$ -direction, respectively;  $v_x$ ,  $v_z$  are the horizontal and vertical component of seepage velocity;  $f_x = f_x(x, z, t)$  = the flux in the  $x$ -direction;  $f_z = f_z(x, z, t)$  = the flux in the  $z$ -direction.

The coefficients of hydrodynamic dispersion  $D_{xx}$ ,  $D_{zz}$  are commonly defined as the sum of the coefficient of mechanical dispersion,  $D_{xx(md)}$ ,  $D_{zz(md)}$  and effective molecular diffusion coefficient in the porous medium,  $D_{xx(e)}$ ,  $D_{zz(e)}$  viz,

$$D_{xx} = D_{xx(md)} + D_{xx(e)}$$
(2)

$$D_{zz} = D_{zz(md)} + D_{zz(e)}$$

$$D_{xx(e)} = \tau_{xx} D_o$$
(3)

$$D_{zz(e)} = \tau_{zz} D_o$$

and  $\tau_{xx,zz} = f_n(\theta)$  is the tortuosity of the soil and  $D_o$  is the diffusion coefficient of the ion of interest in the free solution. It is known that the effective diffusion coefficients,  $D_{xx(e)}$ ,  $D_{zz(e)}$  vary with the volumetric water content (e.g. Porter et al. [26], Kemper and Van Schaik [27]). Many researchers attribute the decrease in the rate of diffusion as the water content decreases to the increased tortuosity of the pathway for diffusion. It has

been reported that there is a linear (or approximately linear) relationship between the effective diffusion coefficients,  $D_{xx(e)}$ ,  $D_{zz(e)}$  and the volumetric water content of the soil,  $\theta$ . The relationships read as follows [18, 19]:

$$D_{XX(e)} = \frac{\theta}{\theta_{ref}} \cdot D_{XX(e-ref)} \quad (4)$$

$$D_{ZZ(e)} = \frac{\theta}{\theta_{ref}} \cdot D_{ZZ(e-ref)}$$

where  $D_{xx(e)}$ ,  $D_{zz(e)}$  are the effective diffusion coefficients in the soil at a volumetric water content  $\theta$ ,  $\theta_{ref}$  is the volumetric water content at full saturation (i.e. total porosity), and  $D_{xx(e-ref)}$ ,  $D_{zz(e-ref)}$  are the effective diffusion coefficients in soil at full saturation.

Consideration of mass balance shows that:

$$\frac{\partial f_x}{\partial x} + \frac{\partial f_z}{\partial z} + n \frac{\partial c}{\partial t} + g = 0 \quad (5)$$

where the quantity  $g$  takes account of the possibility of some of the contaminants being adsorbed onto the soil skeleton. For equilibrium-controlled ion exchange where the concentration of the exchange ion is relatively low, the adsorption of this species may be approximated by a linear relationship of the form:

$$g = \rho K_d \frac{\partial c}{\partial t} \quad (6)$$

where  $\rho$  is the bulk density of solid and  $K_d$  is the distribution coefficient. The distribution coefficient  $K$  may often be estimated from the results of a laboratory column test [28]. It should, of course, be determined over a representative range of concentrations reflecting the likely field variations. For conservative species such as chloride ion, the  $K_d$  value is zero.

For a soil in which the pore-fluid velocity is uniform, equations (1) and (5) can be combined to give:

$$\frac{\partial}{\partial x} \left( nD_{xx} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial z} \left( nD_{zz} \frac{\partial c}{\partial z} \right) - \frac{\partial}{\partial x} (nv_x c) - \frac{\partial}{\partial z} (nv_z c) = (n + \rho K_d) \frac{\partial c}{\partial t} \quad (7)$$

The problem under consideration is illustrated schematically in Fig. 4, which shows a typical section through a landfill of width  $L$  overlying a uniform soil layer of thickness  $H$  [22]. Thus the following may be adopted:  $c = c(x, z, t)$  is the concentration at any point  $(x, z)$  within the soil layer ( $0 \leq z \leq H$ ) at time  $t$ ;  $c_T = c(x, 0, t)$  is the concentration at the top of the clay layer ( $z = 0$ );  $c_b = c(x, H, t)$  is the concentration in the aquifer beneath the clay layer ( $z = H$ );  $c_{LF}$  is the concentration of contaminant within the landfill.

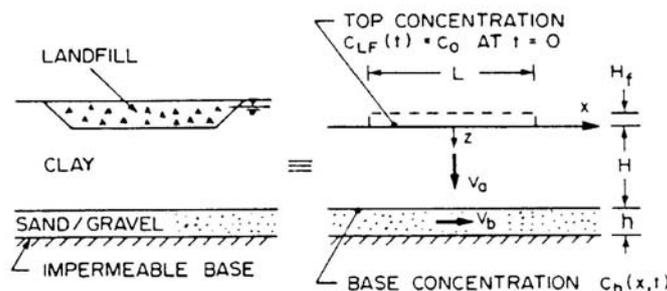


Fig. 4. Typical section through a landfill problem idealization (not to scale) [22]

It will be assumed that the concentration of the contaminant in the landfill  $c_{LF}$  is spatially homogeneous but may vary with time as leachate is transported into the soil; outside the landfill the surface concentration of contaminant will be assumed to be zero so that at the interface of landfill and soil ( $z = 0$ ):

$$\begin{aligned} c_T &= c_{LF}(t), & |x| < L/2 \\ c_T &= 0, & |x| > L/2 \end{aligned} \quad (8)$$

Consideration of conservation of mass within the landfill gives:

$$LH_f c_{LF}(t) = LH_f c_0 - \int_0^t \int_{-L/2}^{L/2} f_z(x, 0, \tau) dx d\tau \quad (9)$$

where  $H_f$  is the equivalent height of leachate which is defined as the volume of leachate per unit plan area of the landfill and  $c_0 = c_{LF}(0)$  is the initial leachate concentration in the landfill. Equation (9) simply states that the mass of contamination in the landfill at time  $t$  is equal to the initial mass of contaminant ( $LH_f c_0$ ) at  $t = 0$  less the mass transported into the soil over the width of the landfill ( $-L/2 \leq x \leq L/2$ ) between time  $\tau = 0$  and time  $\tau = t$ . Equation (9) may be rewritten as:

$$c_{LF}(t) = c_0 - \frac{1}{LH_f} \int_0^t \int_{-L/2}^{L/2} f_z(x, 0, \tau) dx d\tau \quad (10)$$

Now suppose that the soil layer is underlain by a more permeable stratum of thickness  $h$  and porosity  $n_b$ . If there is vertical advective transport into the aquifer, then, strictly speaking, continuity requires that the base velocity in the aquifer should vary with horizontal position. However, if the vertical superficial velocity  $v_a = nv_z$  in the soil layer is small compared with horizontal superficial velocity in the aquifer, then, as a first approximation, the base velocity  $v_b$  may be assumed to be uniform and horizontal.

It is also assumed that the concentration in the aquifer is uniform across its thickness, then consideration of conservation of mass in an element of the aquifer between  $x$  and  $x + dx$  gives:

$$c(x, H, t)hn_b dx = \int_0^t f_z(x, H, \tau) d\tau dx - h \int_0^t [f_z(x + dx, H, \tau) - f_x(x, H, \tau)] d\tau \quad (11)$$

which follows from the observation that the mass of contaminant contained in this element at time  $t$  is equal to total mass transported into the element from the overlying soil less the total mass transported out of the element by horizontal advection and dispersion. Dividing throughout by  $hn_b dx$ , taking the limit as  $dx$  tends to zero, and assuming that mass transported is governed by Ficks law gives:

$$c_b = c(x, H, t) = \int_0^t \left[ \frac{f_z(x, H, \tau)}{hn_b} - \frac{v_b}{n_b} \frac{\partial c(x, H, \tau)}{\partial x} + D_H \frac{\partial^2 c(x, H, \tau)}{\partial x^2} \right] d\tau \quad (12)$$

where  $D_H$  is the coefficient of hydrodynamic dispersion in the horizontal ( $x$ ) direction in the permeable aquifer.

The solution to equations outlined above has been given by Rowe and Booker [22] and has been implemented in the computer code MIGRATEv9 [29]. This code was used to predict the experimental observations in 2-D model tests conducted in this study which will be described later.

## 4. RESULTS AND DISCUSSION

### a) Two-dimensional diffusion tests

The results from 2-D diffusion tests on clay are summarized in Table 2. The data listed in Table 2 comprises the tests physical, chemical, and geometrical data as well as the predicted chloride diffusion coefficients in  $x$  and  $z$  directions in the clay. The computer code MIGRATEv9 was used for the

theoretical analysis (predictions)[29]. The selected predicted concentration plumes were plotted by interpolating between the calculated concentrations in the centre point of the samples and were compared with the observed concentration plumes. Figures 5a to 5d show the selected observed and predicted concentration plumes of 430 mg/L, 180 mg/L, 95 mg/L, and 84 mg/L in 2-D clay diffusion Test CD-2. As shown in Table 2, the equivalent horizontal and vertical chloride diffusion coefficients of  $4.75 \times 10^{-10} \text{ m}^2/\text{s}$  (Test CD-1) and  $5.23 \times 10^{-10} \text{ m}^2/\text{s}$  (Test CD-2) were used in the analyses to predict the concentration plumes in clay in both tests. These equivalent diffusion coefficients for the clay reasonably predicted the observed concentration plumes (and concentration-versus-time, as discussed in Fig. 6) indicating that soils were homogeneous and isotropic in both tests. The selection of the diffusion coefficients are based on a theoretical trial and error analysis with MIGRATE. The analyses are repeated with different diffusion coefficients until a best fit of theoretical and observed concentrations were achieved. The diffusion coefficients are in the range of the reported values for similar soil [6, 7, 13, 18, 19, 30, 31, 32].

Table 2. Results for 2-D clay diffusion tests

Parameter	Test CD-1	Test CD-2
Soil dimensions (height x width) (cm)	20.0 x 30.0	20.0 x 30.0
Source solution height (cm)	6.8	6.8
Soil average volumetric water content ( $\text{cm}^3/\text{cm}^3$ )	0.3	0.3
Soil average degree of saturation (%)	98.0	98.5
Soil average water content (%)	15.8	16.3
Soil chloride background concentration (mg/L)	78	78
Initial source chloride concentration (mg/L)	3550	3490
Soil dry density ( $\text{g}/\text{cm}^3$ )	1.89	1.87
Duration of test (days)	40	42
Chloride diffusion coefficients ( $D_{xx} = D_{zz}$ ) $\times 10^{10} (\text{m}^2/\text{s})$	4.75	5.23

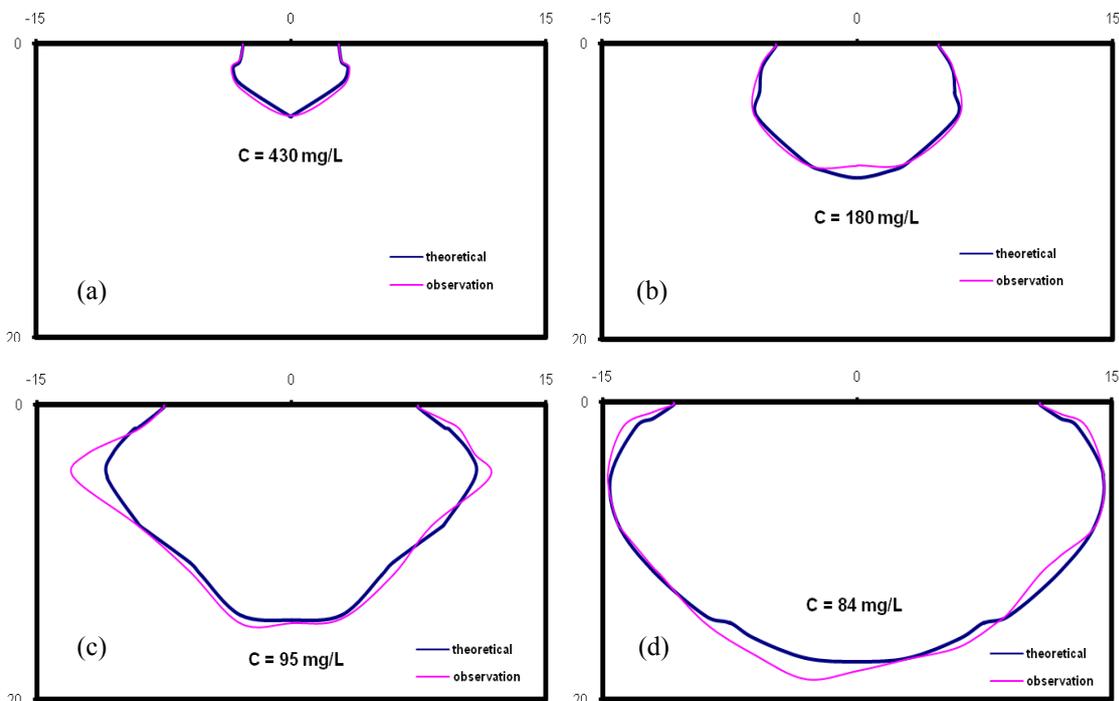


Fig. 5. Observed and predicted chloride concentration plumes in 2-D clay diffusion Test CD-2: (a) 430 mg/L concentration plume, (b) 180 mg/L concentration plume, (c) 95 mg/L concentration plume, and (d) 84 mg/L concentration plume

Figure 6 shows the observed and predicted change in chloride concentrations with elapsed time in the source reservoir during Test CD-2. The chloride concentrations decreased with time in the source reservoir when the chloride ion migrated into clay in two dimensions. As shown in Fig. 6, there is a good agreement between the observed and predicted profiles.

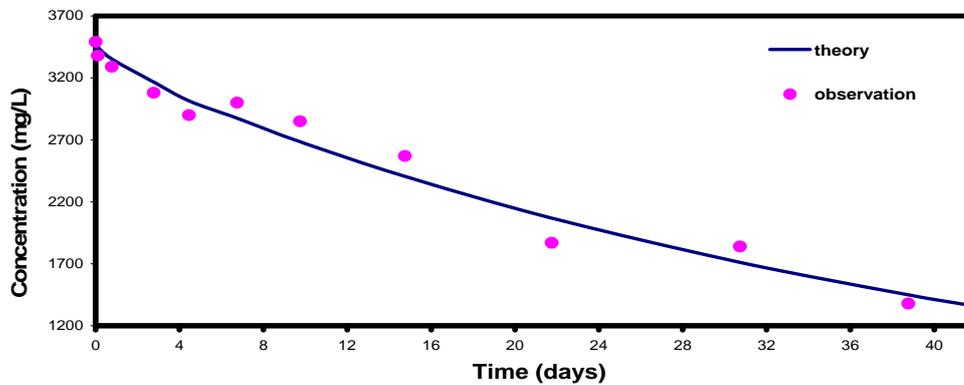


Fig. 6. Observed and predicted chloride concentrations versus elapsed time in 2-D clay diffusion Test CD-2

#### b) Two-dimensional advection-diffusion tests

The results from 2-D advection-diffusion tests on silt are summarized in Table 3. The data listed in Table 3 comprises the physical, chemical, and geometrical data as well as the observed downward Darcy velocity through the silt ( $v_a$ ), horizontal base velocity ( $v_b$ ) in the bottom receptor reservoir, and predicted chloride diffusion coefficients in  $x$  and  $z$  directions in the silt. Figures 7a to 7d show the observed and predicted 940 mg/L, 580 mg/L, 354 mg/L, and 162 mg/L chloride concentration plumes in the silt in Test AD-1. The downward Darcy flux was calculated by dividing the observed volume of infiltrated solution from the source reservoir, into the plan area of the soil in contact with the solution, and into the elapsed test duration. The observed downward Darcy flux through silt,  $v_a = 1.54 \times 10^{-8}$  m/s = 0.73 m/a (Test AD-1) and  $2.31 \times 10^{-8}$  m/s = 0.487 m/a (Test AD-2) were in the upper range of the values usually encountered through landfill liner systems [13]. The applied base velocity in the bottom receptor reservoir which simulated an aquifer underneath the compacted liner,  $v_b = 2.18 \times 10^{-5}$  m/s, in both tests, is also in the range of the values usually observed in permeable aquifers [33, 34].

The effect of downward Darcy flux in silt on the chloride concentration plumes could be verified by comparing the shape of the plumes with those in pure diffusion tests. The downward Darcy flux has caused the concentration plumes in advection-diffusion tests to penetrate more in vertical direction compared to horizontal direction. As shown in Fig. 7, all plumes have spread symmetrically with respect to the vertical axis of symmetry of the soil sample and the horizontal base flow has no significant effect to alter the symmetrical shape of the plumes. Based on the results, due to the applied base velocity, the migrated chloride ions into the bottom receptor reservoir were washed out by the base flow and minimal concentrations were observed inside the base reservoir during the test.

Figure 8 shows the chloride concentration profile versus elapsed time in Test AD-1. The concentrations decreased with time as the chloride ions migrated into the soil. There is good agreement between the observed and predicted profiles.

Table 3. Results for 2-D silt advection-diffusion tests

Parameter	Test AD-1	Test AD-2
Soil dimensions (height x width) (cm)	16.0 x 30.0	16.0 x 30.0
Source solution height (cm)	5	5
Soil average volumetric water content (cm <sup>3</sup> /cm <sup>3</sup> )	0.34	0.32
Soil average degree of saturation (%)	97.9	99.0
Soil average water content (%)	18.8	17.0
Soil chloride background concentration (mg/L)	130	130
Initial source chloride concentration (mg/L)	4500	4500
Soil dry density (g/cm <sup>3</sup> )	1.78	1.85
Downward Darcy velocity, $v_a$ (m/s)	$2.31 \times 10^{-8}$	$1.54 \times 10^{-8}$
Horizontal base velocity, $v_b$ (m/s)	$2.18 \times 10^{-5}$	$2.18 \times 10^{-5}$
Test duration (days)	20	30
Chloride diffusion coefficients ( $D_{xx}=D_{zz}$ ) $\times 10^{10}$ (m <sup>2</sup> /s)	6.43	5.86

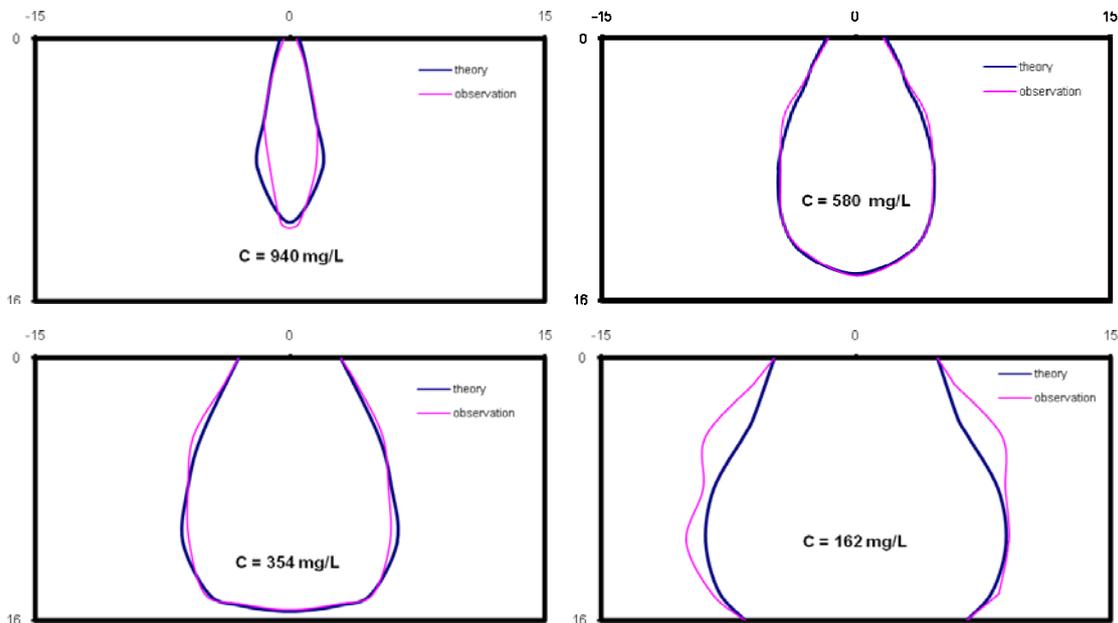


Fig. 7. Observed and predicted chloride concentration plumes in silt 2-D advection-diffusion Test AD-1: (a) 940 mg/L concentration, (b) 580 mg/L concentration, (c) 354 mg/L concentration, and (d) 162 mg/L concentration

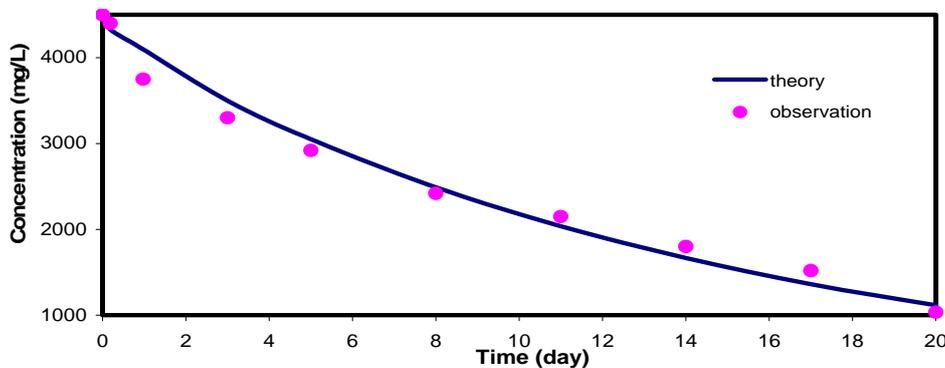


Fig. 8. Observed and predicted chloride concentrations versus elapsed time in 2-D silt advection-diffusion Test AD-1

To verify the effect of downward advective flux in chloride concentration distribution in the vertical axis of symmetry of silt in the case of no downward advective flux (pure diffusive flux), at the end of Test AD-1 the observed chloride concentrations in the vertical axis of symmetry of silt were compared with the calculated concentration profile with no advection. Figure 9 shows both profiles. The dashed line in Fig. 9 is the silt background concentration profile. To calculate the pure diffusive concentration profile through silt, the data of Test AD-1 was used except that the downward Darcy velocity was set to zero (zero advection or pure diffusion) and the base velocity was also set to zero. As can be verified from Fig. 9, downward advective flux causes more chloride migration into silt, and hence lowers concentration in the source reservoir at the end of the test compared to pure diffusive flux. Due to a relatively high base velocity, there is no significant difference in the base reservoir concentrations in both cases.

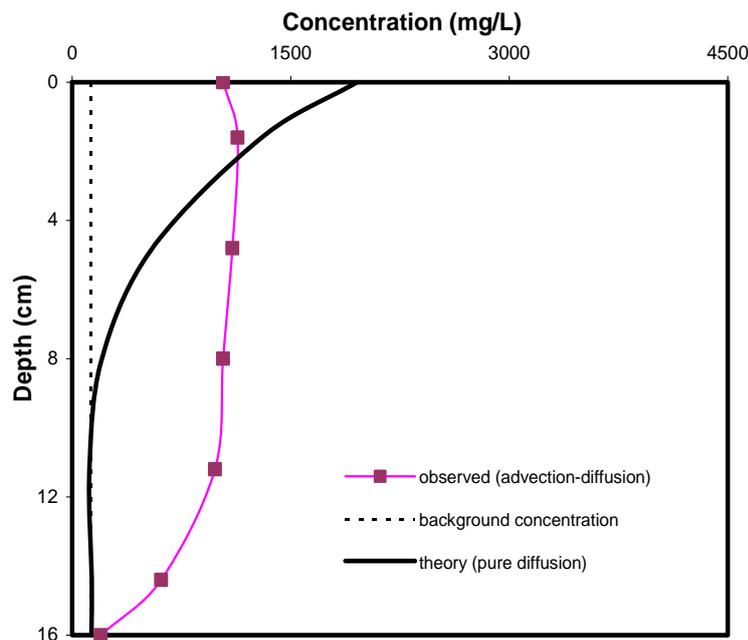


Fig. 9. Comparison of the effect of advective-diffusive and pure diffusive flux in chloride concentration distribution in vertical axis of symmetry of silt in Test AD-1

## 5. SUMMARY AND CONCLUSIONS

The laboratory two-dimensional diffusive and advective-diffusive chloride transport experiments through clay and silt, respectively, were performed to simulate simplified landfill scenarios consisting of (1) a contaminant source (landfill) underlain by a compacted clay liner through which the chloride ion in the landfill migrates two-dimensionally into the underlying soil by pure diffusive mechanism, and (2) a contaminant source underlain by a silt layer and an aquifer, through which the chloride ion in the landfill migrates two-dimensionally into the underlying soil by advective-diffusive mechanisms, and reaches the underlying aquifer with horizontal base flow. A laboratory two-dimensional model was designed and fabricated to perform 2-D pure diffusion tests and then, by simple modification of the same model, to perform 2-D advection-diffusion tests. The computer code MIGRATEv9 was used to predict the observed data of the tests. The observed and predicted chloride concentration plumes were plotted by interpolating the data at the centre points of the soil cubical mesh blocks. The observed chloride concentrations in the source reservoir during the tests were also plotted and compared with the predicted profiles.

In 2-D clay diffusion tests, equivalent horizontal and vertical chloride diffusion coefficients reasonably predicted the observed concentration plumes and concentration-versus-time indicating that soils were homogeneous and isotropic. The chloride diffusion coefficients were in good agreement with the reported values on similar soil.

In 2-D silt advection-diffusion tests, using the tests physical, chemical, and geometrical data, as well as equal horizontal and vertical chloride diffusion coefficients of  $D_{xx} = D_{zz} = 6.43 \times 10^{-10} \text{ m}^2/\text{s}$  and  $D_{xx} = D_{zz} = 5.86 \times 10^{-10} \text{ m}^2/\text{s}$  in the silt, resulted in good agreement between the observed and predicted chloride concentration plumes in silt, as well as the chloride concentration versus time profiles in the source reservoirs. The above diffusion coefficients for chloride in silt are in the range of the reported diffusion coefficients for similar soil. By comparing the shape of the concentration plumes in 2-D silt advection-diffusion and pure diffusion tests, it was concluded that the downward Darcy flux in advection-diffusion tests caused the concentration plumes to penetrate more in the vertical direction compared to horizontal direction. All plumes spread symmetrically with respect to the vertical axis of symmetry of the soil samples and the applied horizontal base flow had no significant effect to alter the symmetrical shape of the plumes in 2-D advection-diffusion tests. By comparing the predicted (theoretical) chloride concentrations in vertical axis of symmetry of silt in 2-D advection-diffusion test (with downward Darcy flux) and pure diffusion case at the same test (with no downward Darcy flux), it was verified that downward advective flux caused more chloride migration into the silt and hence, lower concentration in the source reservoir, compared to pure diffusive flux.

By comparing the observed and predicted chloride concentration plumes in the clay and silt samples and concentration profiles in the source reservoirs, an assessment was made of how well existing two-dimensional advective-diffusive-dispersive contaminant transport theory implemented in the computer code MIGRATEv9, predicted the 2-D chloride migration through silt and clay.

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