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A LABORATORY INVESTIGATION ON THE HYDRAULIC TRAP EFFECT IN MINIMIZING CHLORIDE MIGRATION THROUGH SILT*

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Abstract – The effect of the upward flow (the hydraulic trap effect) on advective-diffusive migration of chloride through silt under two different soil densities and Darcy velocity conditions was examined. Comparison on chloride concentrations in the receptor reservoirs beneath the silt samples in downward and upward flow tests showed that the hydraulic trap system could significantly reduce the concentrations in the soil and underlying receptor reservoirs and hence, the system could be used in solid waste landfill designs to minimize the contamination potential from landfill leachate. Effective chloride diffusion coefficients were measured on clay and silt samples from Urmia City landfill site in Iran, using the solid waste leachate from the same landfill. The experimental results were in good agreement with theoretical predictions in diffusive and advective-diffusive tests.

Keywords – Hydraulic trap, laboratory modeling, diffusion test, advection-diffusion test

1. INTRODUCTION

Advection and diffusion are two dominant controlling mechanisms for transport of contaminants from landfills to underlying aquifers. Diffusive transport is a dominant controlling mechanism in contaminant transport through compacted fine grained soils underlying landfills [1-3]. Diffusion coefficient of a chemical ion in a specific soil is a key parameter in evaluating the amount of contaminant flux transported by diffusion. Advection and diffusion can occur in the same direction when the height of the leachate mound at the base of the landfill is higher than the potensiometric surface of the underlying aquifer. Advection and diffusion can also occur in opposite directions when the potensiometric surface of the aquifer is higher than the height of the leachate at the base of the landfill. This phenomena is known as the "hydraulic trap" and has been implemented in landfill design at sites with high potensiometric surfaces in the aquifer [4, 5]. To investigate how the hydraulic trap could minimize the contamination potential from a landfill to the underlying aquifer, a laboratory model was designed so that diffusion and advection could be modeled in the same or opposite direction through a single soil layer.

The performance and evaluation of a hydraulic trap system in the Halton Landfill site (Halton, Canada) and in laboratory experiments has been reported [4]. The landfill was designed and constructed with a granular "sub-liner contingency layer" (SLCL) beneath the compacted liner. Laboratory experiments demonstrated that there can be diffusion away from a source, even with significant inward velocity. An existing theory was found to provide a good prediction of the observed concentration profile in these experiments. It is also shown that a pressurized air pocket below the clay effectively acts as a zero-flux boundary and hence, with respect to migration of chloride, could be conservatively neglected in the impact assessment.

The objectives of this investigation were as follows: The diffusion coefficients for chloride through silt and clay from the Urmia city landfill site were measured and determined using solid waste leachate from the same landfill. The transport parameter determined from the diffusion tests on silt was then used to predict

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advective diffusive transport through silt with downward and upward flow (hydraulic trap) configurations. The effect of the hydraulic trap on minimizing the chloride migration through silt from the upper source reservoir to the underlying receptor reservoir in advection-diffusion tests was also examined. Finally, the effect of soil density and Darcy velocity on chloride movement through silt was investigated.

By comparing the predicted and observed concentration profiles, an assessment was made of how well existing theory predicted chloride migration through silt layer. The Darcy velocities examined in the advection-diffusion tests were 55.5 m/yr, 38.2 m/yr, and 1.0 m/yr and thus exceed Darcy velocities commonly encountered through compacted fine grained soil liners in landfill sites [6, 7]. But there are many practical situations in developing countries where the landfills are not engineered and the solid wastes may be landfilled in a hydrological setting where the predominant soil types below the landfill base are fine grained soils such as silt with moderate or high hydraulic conductivity. The water table might be either at some depth below the base of the landfill or its potensiometric surface might be above the base of the landfill. In the later case, there will be upward flow from the aquifer to the base of the landfill. This phenomena known as "natural hydraulic trap" [8] could reduce the contamination potential from the solid waste leachate to the underlying aquifer. For the purpose of better understanding how well the hydraulic trap system could minimize the contaminant potential on the underlying receptor source, a laboratory model was designed to model both downward and upward flow (hydraulic trap) configuration through a single fine grained soil layer. This will be discussed in this paper.

2. APPARATUS AND TEST METHODS

a) Diffusion tests

To measure the diffusion coefficient of chloride in soil samples from the Urmia city landfill site, a simple laboratory model was used as shown in Fig. 1. The model consists of a polyethylene pipe with a height of 21-cm and an inside diameter of 10 cm, and a glass base glued to the pipe. Four soil samples were obtained from the Urmia city landfill site and the soil mechanical tests were conducted. Two samples (A and B) were identified as silt with low plasticity (ML) and the other two (C and D) as clay with low plasticity (CL). Table 1 shows the important characteristics of the soil samples.

The soil samples were air dried, pulverized, and passed through a No. 4 sieve (4.7-mm). The samples were then mixed with tap water to a 2-4 weight percent wet of optimum water content to obtain a minimum hydraulic conductivity after standard compaction [9]. The wet samples were then compacted inside the polyethylene pipe using the standard proctor method (ASTM D698 [10]) to a height of about 12-cm. Some wet samples were saved for chloride background concentration measurement. The leachate obtained from the landfill site was then applied on top of the soil sample inside the pipe (source reservoir) until the height was about 6 cm. The time was recorded and the initial leachate sample for initial chloride concentration measurement was collected from the source reservoir. The leachate samples were collected from the source reservoir on a daily basis to observe the chloride concentration change during the test. These samples were then analyzed for their chloride concentrations. To keep the source solution height constant during the test, the same volume of distilled water was added to the reservoir to replace the extracted leachate. After termination of the test, the final source sample was collected from the source reservoir and the leachate was drained. The glass base plate was detached from the pipe and the soil sample was extruded from the tube and sliced into 6 sublayers of approximately equal thickness. A pneumatic soil pore water squeeze apparatus was used to obtain contaminated pore water from the sliced soil samples and the chloride concentrations were measured. Two diffusion tests were conducted on each soil sample with a total of eight tests. These tests will be referred to as Tests DA1, DA2, DB1, DB2, DC1, DC2, DD1 and DD2. All tests were performed at 23 ± 2°C.

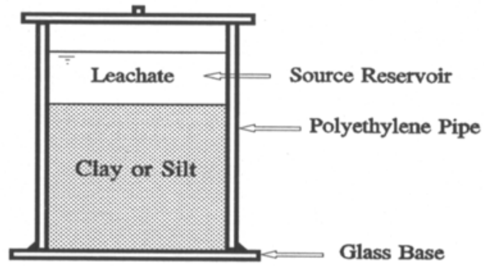

Fig. 1. Test set up for the diffusion tests on clay and silt

Table 1. Soil mechanical characteristics of soils used in the experiments

Properties	Soil A	Soil B	Soil C	Soil D
Soil Type	ML	ML	CL	CL
Liquid Limit (%)	18.5	22	20.75	22
Plastic Limit (%)	10	14	7	8
Specific Gravity	2.65	2.73	2.72	2.70
Optimum Water Content (%)	11.4	13.7	11.3	11.2
Maximum Dry Density (g/cm^3)	1.99	1.90	1.99	1.98
Field Dry Density (g/cm^3)	1.44	1.56	1.37	1.48

b) Advection-diffusion tests with downward flow

Figure 2 shows the test set up for the downward flow (advection and diffusion at the same direction). The polyethylene tube with a 22-cm height was used as the test column. A plexiglas ring was glued inside the tube to provide a support for a stainless steel porous plate. This plate separates the soil sample from the underlying receptor reservoir. There is a free space above the soil sample as a source reservoir. The soil sample B was used in the tests. The porous plate was placed in the tube and the dry sample was placed in the tube and compacted to a desired density using a small wooden hammer. The test tube containing the compacted soil was placed on top of a magnetic stirrer to mix the receptor reservoir solution during the test, using a magnetic bar located in the reservoir. The sample was saturated by allowing water to flow upwards through the sample for about 24 hours. After saturation, the water in the upper reservoir was drained and a pipette was attached to an outlet valve in the receptor reservoir to enable the replacement of distilled water with extracted solution from the reservoir during sampling. The elevation of the pipette was kept at soil top surface to prevent any displacement of the soil pore water during sampling. The sodium chloride solution was poured on top of the saturated soil. During the test, the source solution infiltrated downward through the soil sample and out-flowed through the pipette. The infiltrated solution from the source reservoir was continuously replaced by the same volume of distilled water using a peristaltic pump assembly as shown in Fig. 2. The solution samples from both source and receptor reservoirs were collected for chloride concentration measurement during the test. Sampling from the receptor reservoir was done through a septum port located in the test tube. At the termination of the test, source solution was drained, the base plate was detached from the bottom of the tube, and the soil sample was carefully extruded from the tube and sliced to approximately 6 equal thicknesses. The water content was measured in each slice and the soil pore water was squeezed from each slice using the soil pore water squeeze apparatus. The soil pore water samples obtained at test termination and the reservoirs solution samples obtained during the test were analyzed for chloride concentrations.

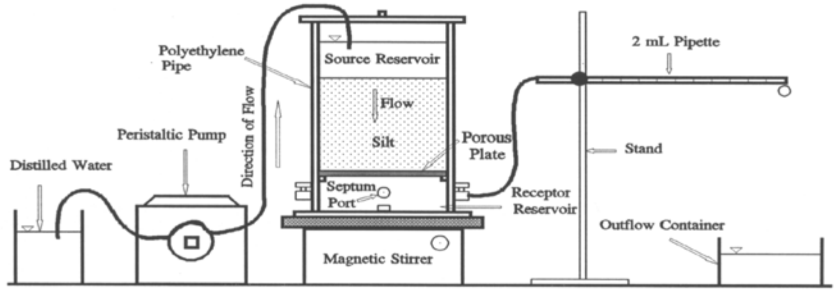

Fig. 2. Test equipment for downward flow advection-diffusion tests

To investigate the effect of soil density and Darcy flux on advective-diffusive transport through soil, three tests were conducted with silt (soil type B) with lower than field density (Test ADB1), at field density (Test ADB2) and higher than field density (Test ADB3). The duration of the tests was 26.5 hours, 24.9 hours, and 15 days, respectively.

c) Advection-diffusion tests with upward flow (hydraulic trap system)

Figure 3 shows the test set up for upward flow (advection upward and diffusion downward-The hydraulic trap configuration). Two tests were conducted which will be referred to as Tests ADB4 and ADB5 with test durations of 24 hours and 15 days, respectively. In the first test, silt with medium density (equal to its field density, dry density=1.56 g/cm^3) and in the second test silt with higher density (dry density=1.7 g/cm^3) were used to investigate the effect of soil density and Darcy flux as in tests ADB2 and ADB3. Due to the piping effect, the upward flow test with low-density silt (As in Test ADB1, dry density=1.36 g/cm^3) could not be performed. To model upward flow through the soil (hydraulic trap), a constant head reservoir was attached to the receptor reservoir. The out-flowing water from the constant head reservoir was replaced by the same amount of water using a peristaltic pump and a water tank as shown in Fig. 3. Another peristaltic pump was used to drain the incoming water to the source reservoir in order to maintain a constant head in the source reservoir. The flow rates for the two pumps were identical to maintain the continuity of flow through the system (inflow=outflow). The sampling procedure for source and receptor reservoir solutions and the soil pore water sampling were as described for Tests ADB1 to ADB3.

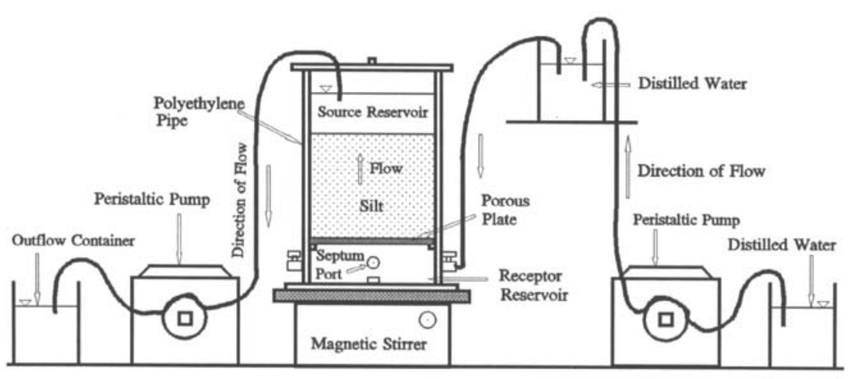

Fig. 3. Test equipment for upward flow (hydraulic trap) advection-diffusion tests

3. TEST ANALYSIS

It has been reported that the transport of contaminants through saturated clay can be described by the advection-diffusion equation [2, 7, 11-14] which can be written for one dimensional conditions as

$$(\theta + \rho K_d)\frac{\partial c}{\partial t} = \theta D \frac{\partial^2 c}{\partial z^2} - \theta v \frac{\partial c}{\partial z} \tag{1}$$

where c is the contaminant concentration at a depth z at time t; θ is the soil volumetric water content (θ=n, the soil porosity for saturated soil); v is the average linearized ground water velocity (seepage velocity); ρ is the dry bulk density of the soil, K_d is the distribution coefficient, $nv=v_a$ is the Darcy velocity, and D is referred to as the coefficient of hydrodynamic dispersion.

The coefficient of hydrodynamic dispersion D is commonly defined as the sum of the coefficient of mechanical dispersion, D_{md}, and effective diffusion coefficient in the porous medium, D_e, viz

$$D = D_{md} + D_e \tag{2}$$

where

$$D_e = \tau D_o \tag{3}$$

and $\tau = f_n(\theta)$ is the tortuosity of the soil and D_o is the diffusion coefficient of the ion of interest in free solution. It is known that the effective diffusion coefficient, D_e, varies with the volumetric water content (e.g. Porter et al. [15], Kemper and Van Schaik [16]). 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 coefficient $D_{e,}$ and the volumetric water content of the soil, θ. The relationship reads as follows [17, 18]

$$D_e = \frac{\theta}{\theta_{ref}} D_{e(ref)} \tag{4}$$

where D_e is the effective diffusion coefficient in the soil at a volumetric water content θ, θ_{ref} is the volumetric water content at full saturation (i.e. total porosity), and $D_{e(ref)}$ is the effective diffusion coefficient in soil at full saturation.

The boundary condition imposed by the source reservoir whose concentration $c_T(t)$ reduces with time due to the movement of chloride into the soil and also sampling, can be modelled [19, 8] by

$$c_T(t) = c_o - \frac{1}{H_f}\int_0^t f_R \, d\tau - \frac{q_o}{H_f}\int_0^t c_T(\tau)\, d\tau \tag{5}$$

where c_o is the initial concentration in the reservoir, H_f is the height of fluid in the source reservoir, q_o is the volume of fluid per unit area per unit time removed from the reservoir for chemical analysis during the test and replaced by distilled water, and f_R is the contaminant flux into the soil and is given by

$$f_R = \theta v c - \theta D \frac{\partial c}{\partial z} \tag{6}$$

where all the terms are as previously described.

When upward flow is a concern, (hydraulic trap), a negative sign is used for Darcy velocity in Eq. (7), i.e. ($f_R = -\theta v c - \theta D\, \partial c / \partial z$).

For the advection-diffusion tests with a fluid receptor, the concentration in the receptor at time t can be described by

$$c_b(t) = \int_0^t \left[\frac{f_b(\tau)}{h}\right] d\tau - \frac{q_b}{h}\int_o^t c_b(\tau)\, d\tau \tag{7}$$

where $f_b(\tau)$ is the flux entering the receptor at time τ, h is the thickness of the receptor, and q_b is the volume of fluid per unit cross sectional area of the soil per unit time removed from the receptor for chemical analysis during the test. For the diffusion tests, the source reservoir boundary was modelled by equation 4, while the bottom boundary was zero flux

$$f_b = \theta D \frac{\partial c}{\partial z} = 0 \tag{8}$$

A solution to Eq. (1) which allowed consideration of a finite mass of contaminant in the source, a reservoir receptor, and the replacement of sampled reservoir fluid by distilled water (i.e. the boundary condition given by Eq. (7)), or zero flux condition Eq. (8), has been given by Rowe and Booker ([19, 20]) and has been implemented in a computer program POLLUTE (Rowe and Booker [20, 21]). This program is used in this study to predict the observed data from the laboratory models discussed earlier.

4. EXPERIMENTAL AND MODELING RESULTS

a) Diffusion tests

The results from the diffusion tests are summarized in Table 2. The average degree of saturation for the silt samples in Tests DA1, DA2, DB1 and DB2 was 96 %, and for the clay samples in Tests DC1, DC2, DD1 and DD2 was 94 %. The chloride concentrations in the pore water and source reservoir were determined and normalized relative to the initial source solution concentration. Only the results for Tests DB1 and DB2 are presented as shown in Fig. 4. The solid lines in Fig. 4 represent concentration profiles predicted by modeling with POLLUTE. The observed water contents are plotted against soil depth as shown in Fig. 4c.

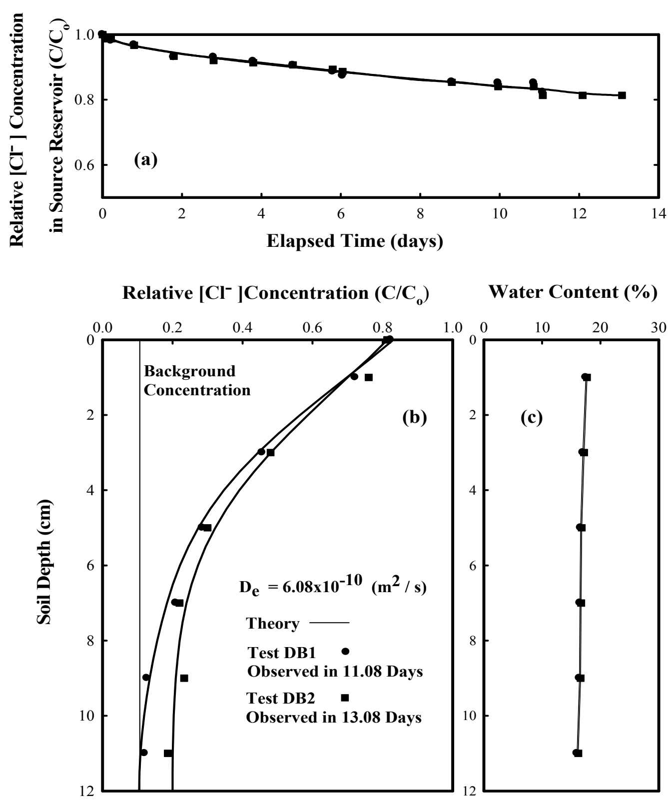

Fig. 4. Observed and modeled profiles of silt diffusion Tests DB1 and DB2: a) Relative Cl^- concentration in source reservoir versus elapsed time, b) Relative Cl^- concentration versus soil depth, c) Water content versus soil depth

Table 2. Results from silt and clay diffusion tests

Parameter	Test DA1	Test DA2	Test DB1	Test DB2	Test DC1	Test DC2	Test DD1	Test DD2
Soil Thickness (cm)	12	12	12	12	12	12	12	12
Leachate Height (cm)	6	6	6	6	6	6	6	6
Volumetric Water Content (cm^3/cm^3)	0.275	0.270	0.306	0.320	0.271	0.271	0.276	0.272
Degree of Saturation (%)	98	96.5	93	95	90	93	98	96
Soil Chloride Background Concentration (mg/l)	113	113	160	160	215	215	138	138
Initial Source Chloride Concentration (mg/l)	1350	1450	1580	1500	1470	1600	1760	1500
Soil Dry Density (g/cm^3)	1.90	1.90	1.83	1.86	1.89	1.91	1.94	1.92
Duration of Test (days)	11.09	13.09	11.08	13.08	10.84	12.84	10.84	13.09
[Cl^-] Effective Diffusion Coefficient $D_e \times 10^{10} (m^2/s)$	9.20	9.37	5.79	6.05	10.0	10.0	9.80	9.66

The average effective diffusion coefficient of 5.9×10^{-10} m^2/s produced the best fit to the experimental results for soil samples in Tests DB1 and DB2. This value and the best fit effective diffusion coefficients obtained for other samples (Table 2) are in the range of the reported values for the silt and clay [1, 2, 8, 22].

b) Advection-diffusion tests

The results obtained from these tests are summarized in Table 3. The chloride concentrations in the pore water, source, and receptor reservoirs were normalized relative to the initial source solution concentrations. The observed and predicted results for Test ADB1 are shown in Fig. 5. The soil characteristics, Darcy velocities, and the duration of the tests in Tests ADB2 and ADB3 (downward flow tests) were similar to Tests ADB4 and ADB5 (upward flow tests), respectively, except for the direction of flow (Table 3). So, the results from similar tests could be plotted together to examine the effect of the direction of flow (the hydraulic trap effect) in these tests. Figures 6 and 7 show the observed data along with the best fit curves predicted by POLLUTE for Tests ADB2 and ADB4, and ADB3 and ADB5, respectively. The predictions are in good agreement with the observed data in all tests. As noted earlier, in each test, samples were packed in the columns with low density (less than field density, Test ADB1), moderate density (at about field density, Tests ADB2 and ADB4) and high density (Tests ADB3 and ADB5). The hydraulic gradient in all tests was 0.5 and the resulting Darcy velocities were 17.6×10^{-6} m/s for Test ADB1, 12.1×10^{-6} m/s for Tests ADB2 and ADB4, and 3.17×10^{-8} m/s for Tests ADB3 and ADB5. The soil water contents were measured at the end of the tests and plotted against soil depth. The water content profiles were almost uniform in soil layers in all tests as shown in the figures. For Tests ADB3 and ADB5, the same diffusion coefficient as obtained in the diffusion tests for this soil with similar density was used in the analysis. The diffusion coefficients for soils in Tests ADB1, ADB2 and ADB4 were predicted using Eq. (4), and the soils observed volumetric water contents.

Table 3. Results from silt downward and upward advection-diffusion tests

Parameter	Test ADB1	Test ADB2	Test ADB3	Test ADB4	Test ADB5
Soil Thickness (cm)	10	10	10	10	10
Height of Source Solution (cm)	5	5	5	5	5
[Cl^-] Source Solution Concentration (mg/l)	1400	1410	2500	1318	2500
[Cl^-] Background Concentration in Soil (mg/l)	90	150	150	150	150
Soil Volumetric Water Content (cm^3/cm^3)	0.5	0.43	0.32	0.43	0.32
Soil Degree of Saturation (%)	98	97	97	98	99
Soil Dry Density (g/cm^3)	1.36	1.56	1.70	1.56	1.7
Test Hydraulic Gradient	0.5	0.5	0.5	0.5	0.5
Darcy Velocity $\times 10^8$ (m/s)	176	121	3.17	121	3.17
[Cl^-] Effective Diffusion Coefficient $\times 10^{10}$ (m^2/s)	9.46	8.06	6.05	8.06	6.05
Test Duration (hours)	26.5	24.9	360	24.9	360

The high downward Darcy velocities in Tests ADB1 and ADB2 caused rapid movement of chloride through the soil and to the receptor reservoirs so that the concentrations in the receptor reservoirs reached 24% and 30% of the initial source concentrations after only 26.5 hours and 25 hours, in Tests ADB1 and ADB2, respectively. Comparing with Test ADB3, which had denser silt with lower Darcy velocity, 21% of the initial source concentration was observed in the receptor after a much longer time (15 days).

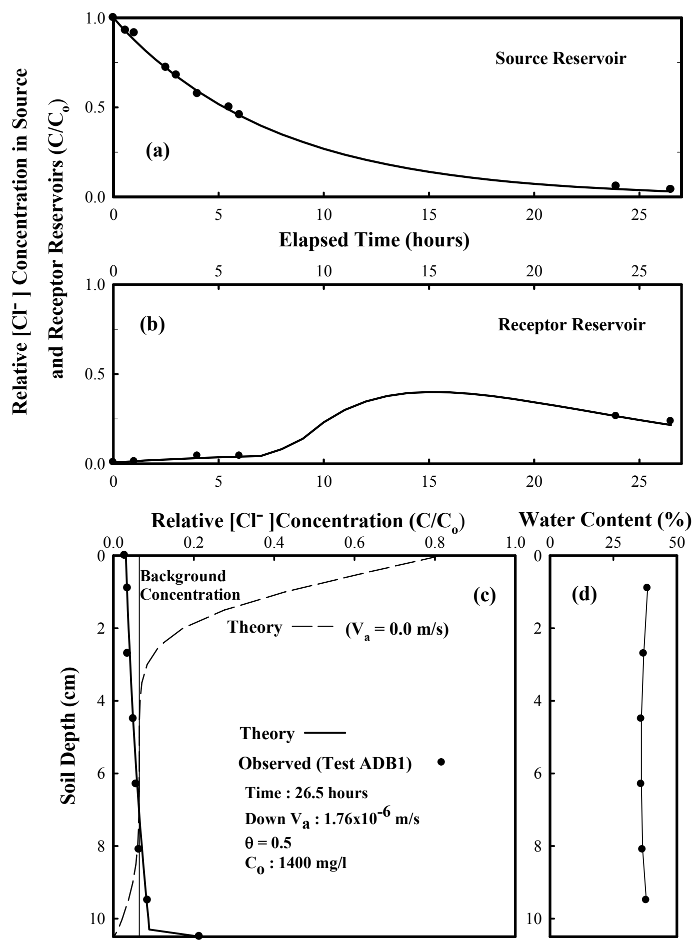

Fig. 5. Observed and modeled profiles of silt advection-diffusion Test ADB1 with downward flow: a) Relative Cl^- concentration in source reservoir versus elapsed time, b) Relative Cl^- concentration in receptor reservoir versus elapsed time, c) Relative Cl^- concentration versus soil depth, d) Water content versus soil depth

Higher upward Darcy velocity in Test ADB4 (1.2×10^{-6} m/s) compared to Test ADB5 (3.17×10^{-8} m/s) caused only 14.8% of the initial source chloride concentration to be detected in the upper source reservoir in 25 hours (end of the test) compared to 88% in Test ADB5, which was detected in the same period. High Darcy flux in Test ADB4 compared to Test ADB5 caused more water to move upward through the soil and into the source reservoir and dilute the chloride concentration.

The normalized concentrations in the receptor reservoirs of Tests ADB2 and ADB3 were compared with those in Tests ADB4 and ADB5, respectively, to examine the effect of upward flow (hydraulic trap). The comparison shows that the hydraulic trap has effectively reduced the contaminant potential in the receptor reservoirs. To quantify this effect, the percentage of the normalized concentration values in the receptor reservoirs were calculated as shown below:

$$\frac{\left(\dfrac{c_{rf}}{c_0}\right)_{ADB4}}{\left(\dfrac{c_{rf}}{c_0}\right)_{ADB2}}\times 100=\frac{0.008}{0.38}\times 100=2.0\% \quad \text{and} \quad \frac{\left(\dfrac{c_{rf}}{c_0}\right)_{ADB5}}{\left(\dfrac{c_{rf}}{c_0}\right)_{ADB3}}\times 100=\frac{0.0004}{0.212}\times 100=0.19\%$$

These values indicate that only 2% and 0.2% of the normalized concentrations have been detected in the receptor reservoirs of Tests ADB4 and ADB5, respectively, and the hydraulic trap system has effectively reduced the contamination potential in the receptor reservoirs.

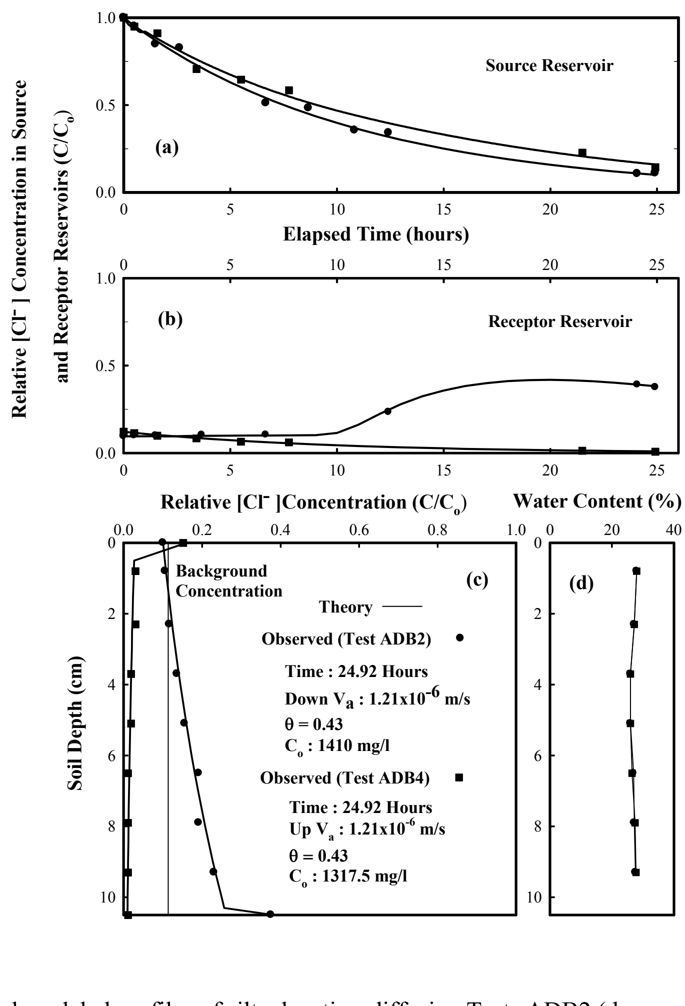

Fig. 6. Observed and modeled profiles of silt advection-diffusion Tests ADB2 (downward flow) and ADB4 (upward flow): a) Relative Cl^- concentration in source reservoir versus elapsed time, b) Relative Cl^- concentration in receptor reservoir versus elapsed time, c) Relative Cl^- concentration versus soil depth, d) Water content versus soil depth

To investigate the effect of diffusion in chloride movement through soil in Test ADB1, the analysis was repeated with zero Darcy velocity (zero advection) and the results plotted as short dashed line in Fig. 5. As shown in the figure, by ignoring Darcy velocity, no theoretical fit could be obtained to the observed data, indicating that diffusion is less responsible for chloride movement through soil and advection, and that some dispersion are the dominant transport mechanisms in this test (Badv and Rowe [23], [24]).

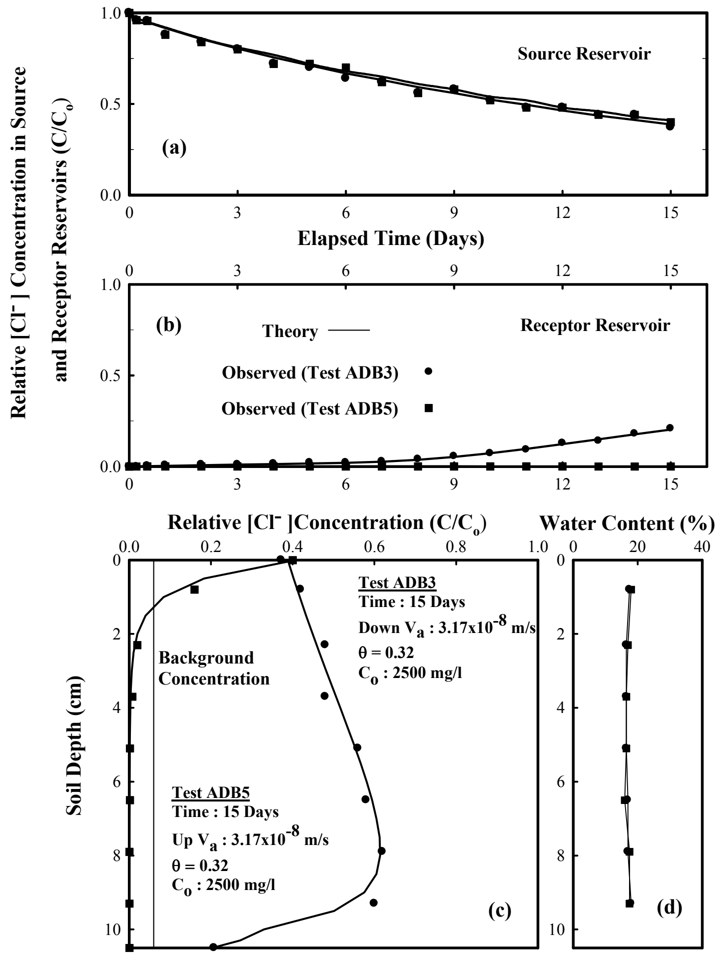

Fig. 7. Observed and modeled profiles of silt advection-diffusion Tests ADB3 (downward flow) and ADB5 (upward flow): a) Relative Cl^- concentration in source reservoir versus elapsed time, b) Relative Cl^- concentration in receptor reservoir versus elapsed time, c) Relative Cl^- concentration versus soil depth, d) Water content versus soil depth

5. SUMMARY AND CONCLUSIONS

The laboratory diffusion and advection-diffusion experiments were performed to examine (1) diffusive movement of chloride through a saturated silt and clay from the Urmia city landfill site; (2) advective-diffusive transport through a silt for different soil densities and Darcy velocities in a downward and upward direction (hydraulic trap). The effect of hydraulic trap configuration in minimizing downward movement of chloride through the silt was examined in the advection-diffusion tests.

The leachate from Urmia city landfill was used as a contaminant source in the diffusion experiments and the diffusion coefficient of chloride was determined for silt and clay. The measured diffusion coefficients for chloride were in the range reported in the literature for similar soils.

Three tests were performed with downward flow through the same silt used in diffusion tests, having different soil density and system Darcy velocity. Advection was most responsible for chloride migration through silt, due to high Darcy velocities observed during the tests. The observed concentrations in source and receptor reservoirs during the tests, as well as soils pore water concentration profiles at the end of the tests, were accurately predicted by the theoretical model. In tests with higher downward Darcy flux (17.6×10^{-6} m/s in Test ADB1 and 12.1×10^{-6} m/s in Test ADB2) chloride movement was accelerated by advection so that 24% and 30% of the initial source concentrations were detected after only 26.5 hours and 25 hours (end of the tests), in Tests ADB1 and ADB2, respectively. But in Test ADB3 with much lower Darcy flux (3.17×10^{-8} m/s), only 21% of the initial source concentration was observed in the receptor after a much longer time (15 days). Diffusion was found to be partly responsible for chloride downward movement in the later test. Two tests were performed with similar soil and test characteristics as downward flow tests, with equal but upward Darcy flux through the soil (the hydraulic trap configuration). Higher upward Darcy flux in the first test (Test ADB4 with 1.2×10^{-6} m/s velocity) compared to the second test (Test ADB5 with 3.17×10^{-8} m/s velocity) caused more water to move upward through the soil and into the source reservoir and dilute the chloride concentration. This resulted in 14.8% of the initial source chloride concentration being detected in the upper source reservoir of high flow test ADB4 in 25 hours, compared to 88% in the low flow test during the same period.

The comparison of the results in tests involving hydraulic trap system with results in similar tests with downward flow showed that the hydraulic trap configuration effectively reduced the contamination potential in the receptor reservoirs which simulated the groundwater aquifer in the laboratory models. In tests involving hydraulic trap, only 2% (high upward flow) and 0.2% (low upward flow) of the normalized concentrations were detected in the receptor reservoirs, compared to similar tests with downward flow.

Results of this study support the use of a natural or engineered hydraulic trap system in landfill design and operation. The interrelationship between hydrogeology and the engineered design (e.g., the selection of the most appropriate landfill base contours with regard to the field long-term potentiometric surfaces) is of great importance.

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