Heavy Metal Diffusion through Soft Clay under High Hydraulic Gradients

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ABSTRACT

This study was focused on the determination of contaminant transport parameters of heavy metal Zinc moving through saturated soft Bangkok undisturbed clay under high hydraulic gradients. These parameters were compared with contaminant transport determined under concentration gradient alone (pure diffusion). In total fifteen column tests were conducted and a mathematical model was applied to determine the coefficients. Two different source concentrations conditions, constant and decreasing, were applied. Testing periods were ranged from 15-60 days while hydraulic gradients were ranged from 0-500. The curves between relative concentration and time and pore volume were developed for the constant source condition whereas curves between source reservoirs concentrations and time were developed for decreasing source condition. The effective diffusion and distribution coefficients, D_e and K_d, were determined by curve fitting using the computer code POLLUTE v 6.3. The results showed that diffusion coefficient increases and distribution coefficient decreases as hydraulic gradient increases from 0 to high value of 500 due to contribution of dispersion and additional molecular diffusion at high advective velocity. Thus, testing at high gradients ensures the safe performance of earthen barriers under worse conditions.

Key Words: **Diffusion, High Hydraulic Gradient, Column Test, Retardation, Zinc Cation, Soft Undis-Turbed Clay Liner.**

1. INTRODUCTION

Fine-grained geological materials (clays) are currently used as barrier materials to prevent the migration of contaminants from waste disposal landfills into groundwater. The potential impact of waste disposal on water quality is a major concern to humans. The toxic organic and inorganic chemicals (heavy metals) get their entry into aquifers used to extract water for human consumption. The problem of ground and surface water contamination is of prime concern because even a small quantity of toxic heavy metals and organic compounds in the water may pose a potential health risk. Therefore, regulations for the design and time evaluation require the study of these facilities, particularly their liner systems. When clay liners are used as barriers between contaminants and groundwater aquifers to prevent breakthrough of these contaminants into groundwater,

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knowledge of the rate at which contaminants will migrate through the barrier (liner) is essential. This requires study and quantification of the mechanisms of contaminant transport and retardation through the fine-grained materials and prediction of contaminant fluxes through the barrier mineral liners, made from only clay or/and clay with geo-membrane. The well-known mechanisms which affect the transport of contaminants through saturated clayey barriers are conventional phenomenon of advection caused by bulk motion of the fluid phase of soil driven by hydraulic gradient; dispersive transport caused by velocity variations about the mean velocity in soil pores; by molecular diffusion driven by chemical concentration gradient and geo-chemical retardation reactions. As these barriers are made of clay soil) having very low hydraulic conductivity and subjected to low hydraulic gradients, advection and dispersion are taken negligible but the dominant mechanism of solute transport is molecular diffusion [1]. Clay particles being negatively charged can trap positively charged heavy metal cations. Also the presence of organic matter, carbonates, oxides in solid phase of soil can react with organic/inorganic contaminants present in leachate causing their retardation.

In this research work, contaminant transport parameters for diffusion, dispersion, advection and retardation through porous media of soft Bangkok clay in relation to heavy metal cation zinc under high hydraulic gradients were experimentally studied. In previous studies diffusion tests were conducted for pure diffusion condition or at low hydraulic gradient to simulate field situation due to the fact that under working conditions hydraulic gradients in most cases are not high. But the tests under pure diffusion condition or at low hydraulic gradients take longer testing times which may be inconvenient for designers for whom test is only a part of overall design work. Applying high hydraulic gradients reduce the testing time to significant level. Further, in order to ensure safety of these facilities to environment, ultimate or limiting retaining capacity under worst conditions of high hydraulic gradients due to mounding of leachate in the case failure of leachate collection system or withdrawal of groundwater from underlying aquifer or other unforeseen reasons should be carried out. In this case hydraulic gradient may substantially high during their service life span. Therefore, column tests should be performed under high hydraulic gradients. The parameters determined from above tests are not identical to conventional tests with low or no gradients. Therefore, correction factors should be multiplied to the parameters determined from advective-diffusion test at higher hydraulic gradients to get real parameters relevant to the design. Thus testing at higher gradient is a good check of the ultimate fate of these barriers under worst situation.

2. BACKGROUND

The primary mechanisms in the case of contaminant transport through saturated clay barriers are advection and diffusion. Advection involves the movement of contamination with flowing water due to hydraulic gradient whereas molecular diffusion is the movement of contaminant from points of high chemical concentration to low chemical concentration. Diffusion is significant in the fine-grained clayey soils where hydraulic conductivity is low and advection is the dominant process in coarse-grained soils [2]. Delay transit time or retardation in clay liners may be due to various chemical reactions, sorption (adsorption), biological degradations and radioactive decay. Sorption reactions, which includes adsorption as well as chemisorptions is one of the important geochemical reaction, which is considered in modeling the transport of reactive specie. Convection is a fluid motion caused by pressure gradient whereas advection is movement of chemicals with flowing fluid through pores of soil mass at the seepage velocity or groundwater velocity analogous to movement of standing people on walkway in airport. This flow is driven by a difference in energy levels between the two points called hydraulic gradient.

2.1 Molecular Diffusion

Diffusion is an irreversible process due to chemicals being transported spontaneously from one part of a system to another as a result of random molecular motion. This random molecular motion results in net transport of the chemical species from a region of higher concentration to a region of lower concentration. As a result, diffusion may be thought of as the transport of a chemical species because of a gradient in its concentration [3]. Diffusion is a slow process of contaminant migration. As a practical matter, under most condition of ground water flow mostly in sands (aquifers) advection is dominant but diffusion is insignificant and is neglected but in low permeable materials such as clays the effect of diffusion on solute transit time can be significant. The type of diffusion, in which geotechnical engineer is interested, is the transient state diffusion in a soil media.

2.2 Effect of Reduction in Cross-Sectional Area of Flow

Due to the reduced cross sectional area of flow in soil, the concentration of the diffusing species, c, is the concentration in the liquid phase of the pore space. Since contaminant fluxes (denoted by f) are defined with respect to the total cross-sectional area of flow, the flux equation is modified by introducing volumetric water content to incorporate that reduction [4].

$$f = -D_O \theta \left(\partial c / \partial z \right) \tag{1}$$

where z is direction of transport [L], D_o is free solution diffusion coefficient, θ is volume of moisture per total volume of soil and known as volumetric water content, and f is contaminant mass flux [M L-2T-1]

$$D_e = \tau D_o \tag{2}$$

Where D_e is Effective diffusion coefficient, D_o is Diffusion coefficient (free solution), and τ is tortuosity factor

2.3 Transient or Non-Steady State Diffusion

The transient form of the transport equation for diffusion in soil depends on whether the chemical species or tracer is non-reactive or reactive. A reactive chemical species is subject to chemical and biochemical reactions or radioactive decay, or both. Of the numerous types of chemical and biochemical reactions, which can affect contaminant transport of reactive species in soil, only adsorption-desorption (sorption) reactions and radioactive decay are routinely modelled [5]. Sorption refers to a mass transfer process between the contaminants dissolved in ground water (aqueous phase) and the contaminants sorbed on the porous medium (solid phase).

2.4 Mechanical Dispersion

Mechanical dispersion is a mixing process like the molecular diffusion but it depends on the seepage velocity. It occurs due to the fluctuation of seepage velocity induced by the local heterogeneity of the media. Mechanical dispersion results in dilution of the solute at the advancing stage. Though the transport mechanisms of molecular diffusion and mechanical dispersion are inherently very different, these can be mathematically modelled for most practical purposes in the same way. Thus, both processes can be described with a single coefficient called the coefficient of hydrodynamic dispersion, D, which can be expressed as :

$$D = D_e + D_m \tag{3}$$

Where D is hydrodynamic dispersion, D_e is effective diffusion coefficient, and D_m is mechanical dispersion.

As mechanical dispersion is a function of the seepage velocity, where as molecular diffusion is not, therefore the effect of mechanical dispersion becomes less as the seepage velocity decreases.

2.5 Adjective-Dispersive Equation for Solute Transport

According to Shackelford [3], the differential equation describing the one-dimensional transient transport of a reactive solute subject to reversible sorption reactions in to a saturated soil mass may be written as:

$$\partial c/\partial t = \left(D/R_d \right)\left(\partial^2 c/\partial z^2 \right) - \left(v_s/R_d \right)\left(\partial c/\partial z \right) \tag{4}$$

Where R_d is retardation factor [dimensionless], D_e is effective diffusion coefficient [L^2T^{-1}], D is coefficient of hydrodynamic dispersion [L^2T^{-1}], v_s is seepage velocity [LT^{-1}], c is mass concentration of the solute in the liquid phase at point and time of interest [ML^{-3}], z is direction of transport [L], and t is time of interest [T].

When the seepage velocity is sufficiently low such that mechanical dispersion is negligible, the advection-dispersion equation effectively reduced to an advection-diffusion equation, which may be written as:

$$\partial c/\partial t = \left(D_e/R_d \right)\left(\partial^2 c/\partial z^2 \right) - \left(v_s/R_d \right)\left(\partial c/\partial z \right) \tag{5}$$

2.6 Determination of Diffusion Coefficient by Column Method

There are two types of methods to measure effective diffusion coefficients of chemical species steady state and transient [6]. The column method is less time consuming and is also useful when there is an advective transport in field situation. Further, in column test, the condition of test may vary depending on whether or not the source concentration of contaminant varies with time or remains constant [6].

2.7 Constant Source Concentration

The constant source concentration is the conventional column test in the study of mass transport through soil media [7]. After steady-state fluid flow has been established, the fluid in the influent reservoir (usually DDW) is changed to a solution concentration, c_o of relevant chemical species. The concentration c in the effluent reservoir is measured with time. The results are plotted as relative concentration c/c_o vs. time or Pore volumes of flow (PV). The ratio of the pore volumes of flow of the reactive solute to the pore volumes of non-reactive solute at a relative concentration of 0.5 is the retardation factor, R_d [7].

Breakthrough curves are modeled using the following analytical solution [7-8]:

$$\frac{c}{c_0} = \frac{1}{2}\left[erfc\left(\frac{L - v_s t}{2\sqrt{D\ t / R_d}} \right) + \exp\left(\frac{v_s L}{D} \right) erfc\left(\frac{L + v_s t}{2\sqrt{D\ t / R_d}} \right) \right] \tag{6}$$

Where c/c_o is relative concentration [dimensionless], L is length of the soil column, v_s is seepage velocity, and erfc is complementary error function, the values are tabulated in the texts [7].

As the seepage velocities is very low so the effect of mechanical dispersion is negligible and the effective diffusion coefficient is equal to the hydrodynamic dispersion coefficient, i.e. D_e=D.

2.8 Decreasing Source Concentration

Rowe, et. al. [3] described decreasing source concentration test .In which an initial concentration of a chemical species in the source reservoir which decreases with time. The column consists of a source reservoir, a column of soil, and a porous plate to collect the effluent from the soil. The concentrations of the specified chemical species decrease with time in the source reservoir and eventually increase with time in the effluent collection system. The results are plotted as concentration vs. time. A semi-analytical solution of the advective-dispersive transport equation as computer program, POLLUTE is used to fit theoretical curves to the measured data to determine D values. The end of the test soil is sectioned and the concentration of chemical species is measured as a function of the depth of the soil in the column. Once again, the POLLUTE is used to fit a theoretical curve to the measured concentration profile. The advantages of this technique are that both D_e and R_d for retarded solutes can be determined from the results of single test.

3. MATERIALS AND METHOD

3.1 Geological Formation

Bangkok is situated at the southern part of the flat and low-lying Chao Phraya plain where the ground is also covered with soft marine clay. The subsoil stratigraphy is relatively uniform throughout the Bangkok Metropolitan area. It consists of thick soft, dark to greenish gray silty clay layer extending to depth of around 12-15m. The soil properties are shown in Fig. 1.

3.2 Sampling

Undisturbed large soil samples of 10 inch diameter of Soft Bangkok clay were taken at a depth of 4.0-5.0m with the help of thin wall cylindrical tubes having an internal diameter of 10 inch. The samples were carefully extruded from the tubes and 5cm sections were cut horizontally with fish wire. Then a Plexiglas tube was pushed vertically to put the sample inside the tube without disturbance.

3.3 Saturation of Soil

The soil samples were saturated by the soaking method followed by permeation method. In this method, the saturation of soil sample was done using DDW as a soaking solution. The soil was exposed to a moisture controlled room only from the base to the soaking solution thereby allowing the soaking solution to infiltrate into the

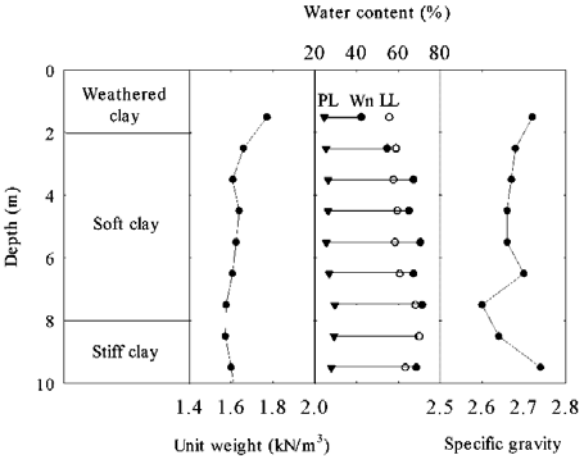

FIG. 1. SOIL PROPERTIES PROFILE

soil by capillarity prior to the start of the diffusion test. This process took two weeks. The soil was then exposed to the permeation method for 10 days under a hydraulic gradient of 250.

3.4 Metal Solution

For this study heavy metal solution was obtained by dissolving chloride salt $ZnCl_2$ in DDW. For zinc salt the concentration of metal solution was kept 0.001m. The reason for taking low ionic concentration is the consideration of infinite dilution in our study. At higher concentration retardation potential of soil reduces and retardation shows non linear behaviour.

3.5 Column Test

Total 15 column tests were conducted as summarized in Table 1.

Each sample was permeated with a specified concentration of salt solution of $ZnCl_2$ under a controlled small head of 6 cm for a certain test period of 15-60 days. Each column cell consists of a 5cm inside diameter hollow acrylic cylinder, and a hanger weight system to provide good seating of the sample in the column. There is one inlet in this test setup which was used as an influent inlet as well as a pressure inlet. At the bottom of the equipment there is one outlet to collect the effluent. A plastic fitting was attached to the base plate through which the effluent is drained as shown in Fig. 2. Tests were carried out with three hydraulic gradients (0,250 and 500) and two different source conditions (constant and decreasing).

TABLE 1. DETAILS OF COLUMN TESTS

Metal Solution ($ZnCl_2$)	Diffusion Tests		
Hydraulic Gradients (i)	0	250	500
Constant Source Concentration	3	2	2
Decreasing Source Concentration	4	2	2
Total Number of Tests	15		

Eight tests were performed for the advection-diffusion condition, out of which four tests were performed with a decreasing concentration and four were performed with a constant concentration of a source solution. In decreasing source concentration condition, the volume of leachate was maintained by adding de-ionized water at the influent. In constant source concentration condition the source concentration was kept constant for the entire test period by changing the solution every two days. Two types of hydraulic gradients (i=250 and 500) were applied in these tests. In case of constant source concentration the effluent volume was collected at a regular interval of one day for each column for chemical analysis while for decreasing source test the influent solution was analyzed every sixth day. For gradient of 500 the effluent concentration was

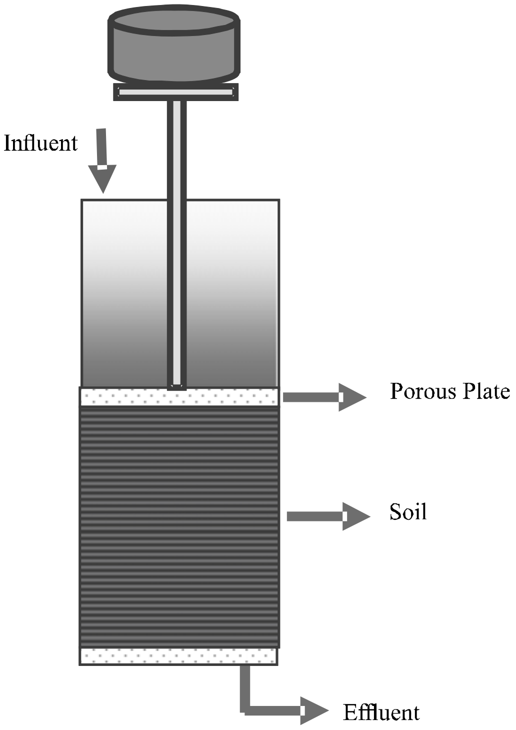

FIG. 2. COLUMN TEST SETUP

taken every three days because of high gradient and less testing time (15 days). These diffusion tests are shown in Fig. 3.

Seven tests were performed with a pure diffusion condition, (i= 0) for three different time periods 30, 48 and 60 days. In three tests constant source concentration was maintained. The four remaining tests were set for decreasing source concentration.

3.6 Chemical Analysis

The concentrations, in the source (influent) reservoir in the case of decreasing source test and the effluent reservoir in the case of constant source, were determined against time with a spectrophotometer. The results were plotted as relative concentration, c/c_o vs. time or Pore volumes of flow (PV) for constant source concentration tests and source concentration vs. time for decreasing source concentration tests.

In order to determine the diffusion coefficient and distribution coefficient, the pore water concentration within the soil depth are measured at the end of the test. Hence at the end of the test, the samples were cut in thickness of one centimeter, and extraction of contaminant was carried out by taking 5 grams of wet soil from each section separately and washing it with 30 ml of DDW and put on shaker for 24 hours. Later, the suspension was centrifuged for 45 minutes at 4000 rpm. Water content was determined for each section of soil by oven drying method at temperature of 105°C for 24 hours. Zinc from soil transported though soil during diffusion was determined from the clear supernatant obtained from centrifuge tube by Zincon method of Hatch spectrophotometer DR 4000. Inverse of dilution factor was multiplied to convert concentration in DDW to actual concentration of Zinc in pore water [9].

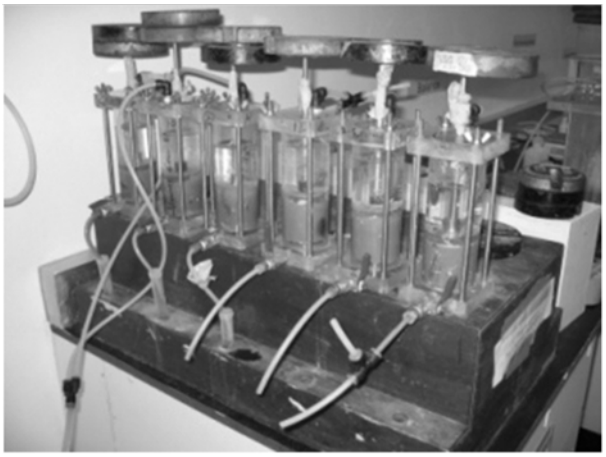

FIG. 3. CONSTANT SOURCE CONCENTRATION WITH DEPTH FOR ZN^{2+}

3.7 Semi-Analytical Simulation of Chemical Transportation

The computer program POLLUTE v 6.3, which directly models column test was used to fit the theoretical curves to the experimental data for measuring the contaminant transport parameters D_e and K_d. Thus by adjusting the diffusion, D_e and distribution, K_d coefficients and matching the resulting theoretical curve to the observed drop of concentration with depth and observed drop of concentration in source reservoir with time these parameters are estimated.

4. RESULTS

The results of the column diffusion tests are shown in Table 2.

Pure diffusion tests under zero hydraulic gradient (under concentration gradient).

4.1 Constant Source Concentration Condition

At concentration gradient (pure diffusion) condition, zinc transporting through the porous media of soil sample the effective diffusion coefficient, D_e, in the range of 2.55-3.01×10^{-6} cm^2/sec with an average of 2.82×10^{-6} cm^2/sec .

The distribution coefficient, K_d, is in the range of 21.8-24.7 cm^3/g with an average value of 23.13 cm^3/g. The diffusion and distribution coefficients show slightly increasing trends with increasing testing time. The coefficients determined with constant source concentration conditions show slightly higher values as compared to decreasing source concentration test conditions.

4.2 Decreasing Source Concentration Condition

In case of decreasing source concentration, the parameters are back calculated not only from depth profile but also from profile between variations in the source concentration with time (source profile) by using curve fitting to experimental points by using POLLUTE v 6.3.

From the depth profile for zinc as shown in Fig. 4, the effective diffusion coefficient D_e is in the range of 2.31-2.89x$10^{-6}cm^2/sec$ with an average value of 2.58x$10^{-6} cm^2/s$. The distribution coefficient, K_d, is in the range of 20.6-24.5 cm^3/g with an average value of 22.15 cm^3/g. Whereas from the source reservoir concentration profile the range for effective diffusion coefficient is within 2.20-2.55x$10^{-6}cm^2/sec$ with an average value of 2.37x10^{-6} cm^2/sec. The distribution coefficient, K_d, is in the range of 20-24 cm^3/g with an average value of 21.63 cm^3/g. The parameters, diffusion coefficient and distribution coefficient show slightly increasing trend with increasing testing time.

Advection-diffusion Tests under high hydraulic gradients of 250.

TABLE 2. DETAILS OF De AND Kd VALUES FOR Zn^{2+}

Parameter	Source Condition	Hydraulic Gradient (i) and Testing Time, t, (Days)				
		i=250 t=0	i=500 t=5	i=0		
				t=0	t=48	t=60
$D_e(10^{-6}cm^2/sec)$	Constant	3.47 [01V]	3.94 [03V]	2.55 [05V]	3.01 [06V]	2.89 [07V]
		3.70 [02V]	4.17 [04V]	-	-	-
$K_d(cm^3/g)$	Constant	15.90 [01V]	13.8 [03V]	21.80 [05V]	22.90 [06V]	24.7 [07V]
		15.70 [02V]	14.2 [04V]	-	-	-
$D_e(10^{-6}cm^2/sec)$	Decreasing	3.36 [08V]	3.70 [10V]	2.31 [12V]	2.66 [13V]	2.89 [14V]
		3.36 [09V]	3.94 [11V]	-	-	-
$K_d(cm^3/g)$	Decreasing	15.8 [08V]	13.8 [10V]	21.10 [12V]	22.40 [13V]	24.50 [14V]
		16.1 [09V]	13.90 [11V]	-	-	-
$D_e(10^{-6}cm^2/sec)$	Decreasing	3.13 [08V]	3.47 [10V]	2.20 [12V]	2.43 [13V]	2.55 [14V]
		3.24 [09V]	3.82 [11V]	-	-	-
$K_d(cm^3/g)$	Decreasing	15.6 [08V]	13.50 [10V]	20.50 [12V]	22.00 [13V]	24.00 [14V]
		16.0 [09V]	13.70 [11V]	-	-	-

4.3 Constant Source Concentration Test

Under the hydraulic gradient of 250 in constant source condition, diffusion coefficient is in the range of 3.47-3.70x10^{-6}cm^2/sec with an average of 3.59x10^{-6}cm^2/sec determined from the depth profile and relative concentration variation with time as shown in Fig. 5 . The distribution coefficient, K_d, is in the range of 15.7-15.9 cm^3/g with an average of 15.8 cm^3/g. The parameters determined with constant source concentration condition show slightly higher values as compared to decreasing source concentration test conditions at this gradient. Moreover, it can be observed that diffusion coefficient has higher value while distribution coefficient has lower value as compared to test parameters with pure diffusion under the same conditions.

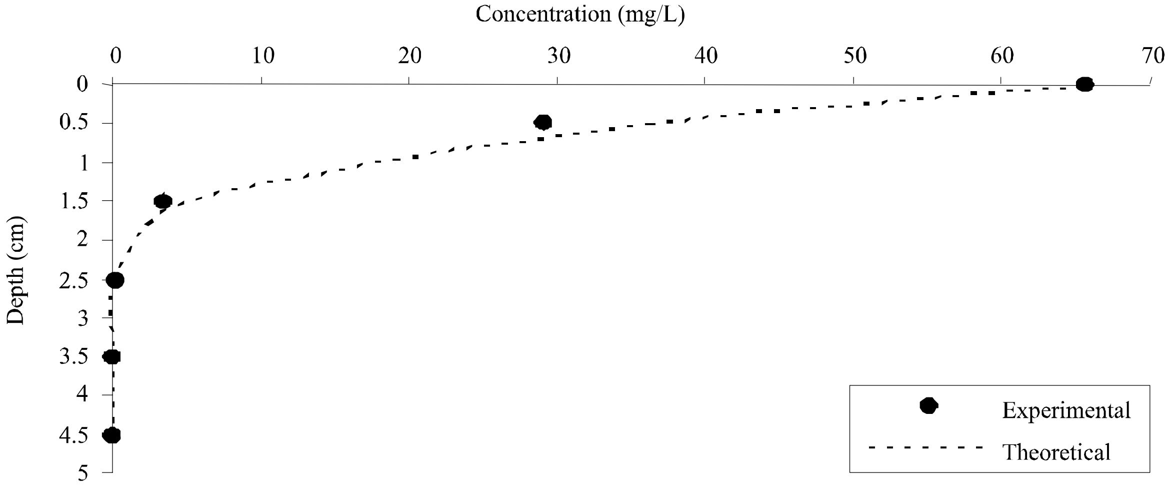

FIG. 4. RELATIVE CONCENTRATION VERSUS TIME FOR ZN^{2+}

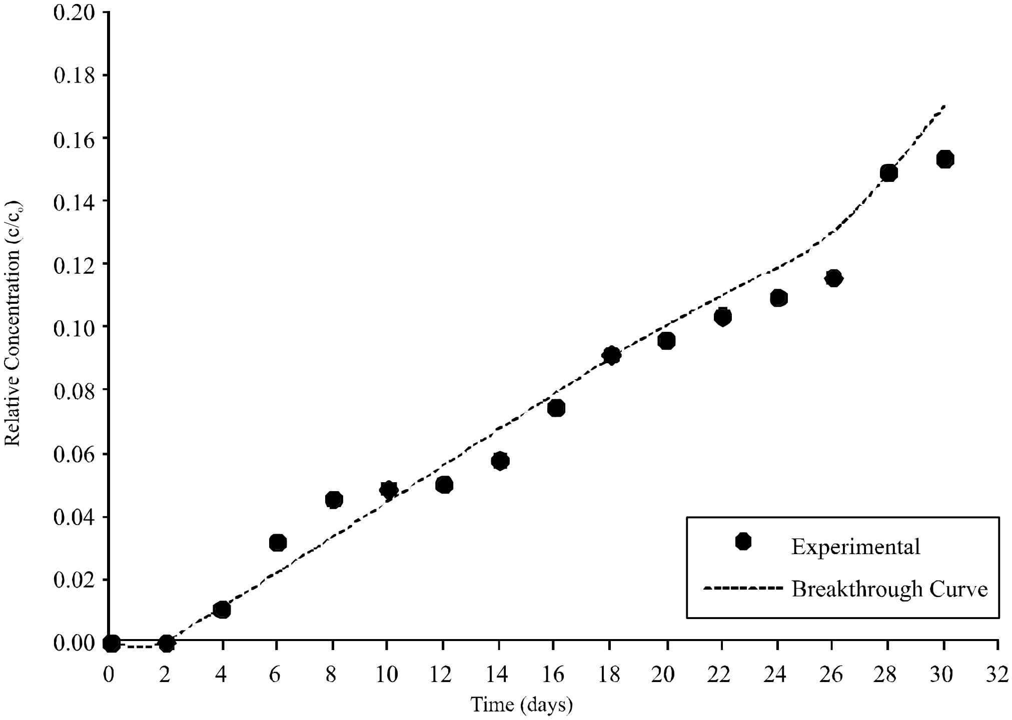

FIG. 5. SOURCE CONCENTRATION VERSUS TIME FOR ZN^{2+}

4.4 Decreasing Source Concentration Condition

In case of decreasing source concentration, the parameters were back calculated not only from depth profile but also from the variations of the source concentration with time (source profile) as shown in Fig. 5. From the depth profile for zinc, the effective diffusion coefficient De is within 3.35-3.37x10^{-6}cm^2/sec with an average of 3.36x10^{-6}cm^2/s. The distribution coefficient, K_d, is in the range of 15.8-16.1 cm^3/g with an average of 15.95 cm^3/g. From the source reservoir concentration profile the range for effective diffusion coefficient is within 3.13-3.24x10^{-6}cm^2/sec with an average of 3.19x10^{-6}cm^2/sec. The distribution coefficient, K_d, is in the range of 15.6-16 cm^3/g with an average of 15.8 cm^3/g. The parameters determined from the source concentration are slightly lower than determined from the depth profile. Moreover, it can be observed that the diffusion coefficient has a higher value while the distribution coefficient has lower a value compared to the test parameters under pure diffusion (zero hydraulic gradient) under the same conditions.

Advection-diffusion Tests under high hydraulic gradients of 500.

4.5 Constant Source Concentration Condition

Under the hydraulic gradient of 500 in constant source condition the diffusion coefficient is in the range of 3.94-4.17x10^{-6}cm^2/sec with an average of 4.06x10^{-6}cm^2/sec, determined from the depth profile. The distribution coefficient, K_d, is in the range of 13.8-14.2 cm^3/g with an average of 14.0 cm^3/g. The parameters determined with constant source concentration conditions show slightly higher values as compared to decreasing source concentration test conditions at this gradient too. Moreover, it can be observed that the diffusion coefficient is higher and the distribution coefficient is lower than the values determined from the test performed at 0 or 250 hydraulic gradients at the same conditions.

4.6 Decreasing Source Concentration Condition

In case of decreasing source concentration, the parameters are back calculated not only from depth profile but also from variations in the source concentration with time (source profile). From the depth profile for zinc as shown in Fig. 6, the effective diffusion coefficient D_e is in the range of 3.7-3.94x10^{-6}cm^2/sec with an average of 3.82x10^{-6}cm^2/s. The distribution coefficient, K_d, is in the range of 13.8-13.9 cm^3/g with an average of 13.85 cm^3/g. From the source reser-voir concentration profile the range for effective diffusion coefficient is within 3.47-3.82x10^{-6}cm^2/sec with an average of 3.65x10^{-6}cm^2/sec. The distribution coefficient, K_d, is in the range of 13.5-13.7 cm^3/g with an average of 13.6 cm^3/g. It can be observed that the diffusion coefficient is higher and distribution coefficient is lower than de-termined from the test performed at 0 or 250 hydraulic gradients under the same conditions.

The effective diffusion coefficients, D_e, and distribution factor obtained for the Soft Bangkok clay fall into the range given by other references for similar types of soils with zinc.

5. DISCUSSIONS

It is evident from the results above that the average diffusion coefficient increases and the distribution coefficient decreases as the hydraulic gradient increases from 0-500. This trend in increase of the diffusion coefficient may be attributed to the effect of mechanical dispersion at high advective (pore) velocity under high hydraulic gradient. The dispersion (mixing) effect is negligible up to the maximum advective velocity of 0.035 m/a. At hydraulic gradients of 250 and 500, the advective velocities reach 4.3 m/a and 9 m/a respectively. These values are high to cause dispersion which is negligible at low or zero hydraulic gradients. Thus this coefficient can be more appropriately referred to as "Coefficient of hydrodynamic dispersion", as literature suggests, which includes the contribution of both effects molecular diffusion and mechanical dispersions. For pure diffusion test or tests conducted at low hydraulic gradients this effect can be ignored but is substantially present at high gradients. All previous diffusion tests in literature [2,10] were performed either in pure diffusion condition or at low hydraulic gradients where contribution of dispersion was negligible. This study was conducted at high hydraulic gradients so an effect of dispersion was observed. Therefore, due to the contribution of dispersion, the coefficient of hydrodynamic dispersion (diffusion coefficient) increases as the hydraulic gradient increases from 0 to higher. It may be possible that there is some additional molecular diffusion at high hydraulic gradient because of increase of pore spaces due to high pore pressure. The combined coefficient of diffusion-dispersion increases as the hydraulic gradient increases in these tests.

Also it can be observed that the distribution coefficient K_d is showing lower values as the hydraulic gradient increases from zero to high value of 500. The reason for this decrease may be related to less probability of interaction of the zinc cations with the soil components due to high pore (advective) velocity, resultantly its faster movement. In pure diffusion condition contaminants stay for relatively longer time in interaction with soil and may have more probability for absorption with the soil components. This phenomenon well explains this decreasing trend in distribution coefficient with higher hydraulic gradient.

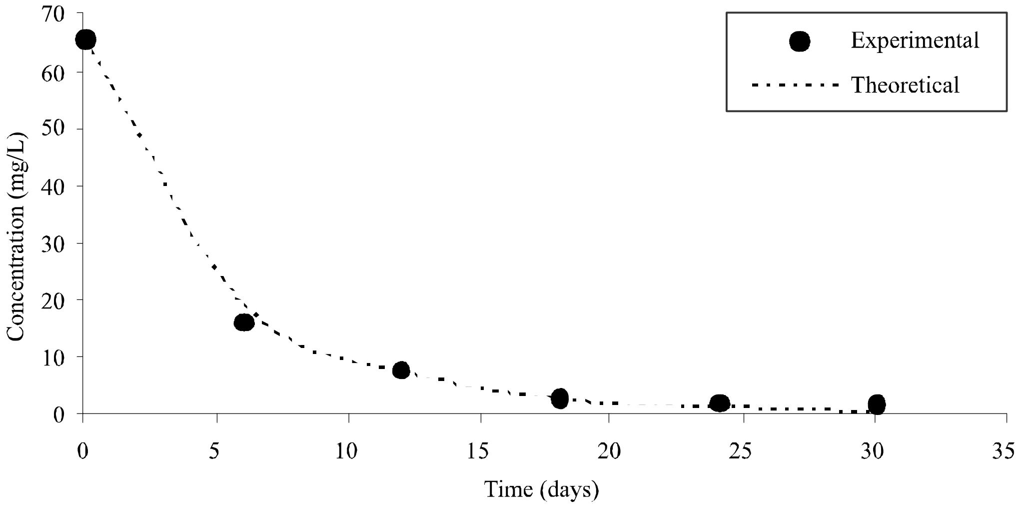

FIGURE 6: SOURCE CONCENTRATION VERSUS TIME FOR ZN^{2+}

6. CONCLUSIONS

The contaminant transport parameters of heavy metal zinc through saturated Soft Bangkok clay were studied under pure diffusion and high hydraulic gradients for different source conditions with various testing times. Based on this study, the following conclusions were drawn:

(i) Soft Bangkok Clay has adsorption capacity for Zn^{+2}cation, which was observed by the distribution coefficient.

(ii) The diffusion coefficient increases and distribution coefficient decreases as hydraulic gradient in-creases from 0 to high value of 500 due to the contribution of dispersion or additional molecular diffusion at high advective velocity. Thus, testing at high gradients ensures the safe performance of earthen barriers under worse conditions.

(iii) High hydraulic gradients reduce testing time considerably which is a major advantage to conducting columns tests for designers, provided appropriate correction is adopted or will result with conservative transit times.

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