

Assessing pollutants' migration through saturated soil column

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(Received July 21, 2022, Revised May 1, 2023, Accepted May 15, 2023)

Abstract. In the developing country like India, groundwater is the main sources for household, irrigation and industrial use. Its contamination poses hydro-geological and environmental concern. The hazardous waste sites such as landfills can lead to contamination of ground water. The contaminants existing at such sites can eventually find ingress down through the soil and into the groundwater in case of leakage. It is necessary to understand the process of migration of pollutants through sub-surface porous medium for avoiding health risks. On this backdrop, the present paper investigates the behavior of pollutants' migration through porous media. The laboratory experiments were carried out on a soil-column model that represents porous media. Two different types of soils (standard sand and red soil) were considered as the media. Further, two different solutes, i.e., non-reactive and reactive, were used. The experimental results are simulated through numerical modeling. The percentage variation in the experimental and numerical results is found to be in the range of 0.75- 11.23 % and 0.84 – 1.26% in case of standard sand and red soil, respectively. While a close agreement is observed in most of the breakthrough curves obtained experimentally and numerically, good agreement is seen in either result in one case.

Keywords: break through curves (BTCs); continuous type boundary condition; finite element method (FEM); non-reactive solutes; pollutants' migration; pulse type boundary condition; reactive solute; soil- column; transport phenomena

1. Introduction

Groundwater pollution happens when man-made items such as gasoline, oil, and chemicals contaminate the water, rendering it unhealthy and unfit for human consumption. Materials from the surface of the land can pass through the soil and into the groundwater. An aquifer, in most cases, is a natural reservoir of high-quality water. The groundwater, however, appears to be prone to pollution, limiting or prohibiting its use for home, agricultural, and industrial purposes, although being better protected than surface water. Toxic chemicals are regularly found in the leachate from landfills and industrial waste disposal facilities. To avoid a considerable amount of dangerous compounds being transported into the groundwater system, some caution is required while determining the location of these landfills. Although the flow of pollutants through relatively impermeable soil is gradual, it is possible that major pollution could occur over the time. Therefore, it is critical that such dumping sites be constructed to avoid probable groundwater contamination in the short and long term.

Contaminant transport pollutes both- soil and ground water. In the disposal of reactive chemicals such as tetrachloroethylene, nitrate, and fluoride, the flow and transport of pollutants in subsurface ground water has been a major concern. A variety of physical, chemical, and microbiological processes as well as medium qualities influence solute transport in soil and groundwater. Natural processes such as leaching of natural chemical deposits which can increase concentrations of chlorides, sulphates, iron, and other organic chemicals as well as non-point agricultural sources such as nutrients, metals, pesticides, and microorganisms, waste disposal practises, and industrial discharges, can all affect the quality of subsurface water.

Several industries which deal with fertilizers, steel, aluminium and glass generate fluoride wastes. The fluorides are useful in minimizing dental cavities, but may prove to be toxic in large doses and cause calcification of tissues. Most of the pollutants contaminating the groundwater are reactive in nature and they infiltrate through the *vadoze* zone and reach ground water table and continues to migrate in direction of the flow of groundwater. Hence, it is necessary to understand the process of contaminant transport through sub surface porous media. The literature survey reveals relatively less experimental work in this context, especially using soil-column model. The paper, therefore, deals with the experimental investigations on understanding the movement of pollutants through a saturated porous media. Further, numerical procedure is also developed to simulate the experimental results. Chloride and fluoride are considered as the non-reactive and reactive types of solutes, respectively.

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2. Review of literature

Many experimental, numerical and analytical studies were undertaken by several researchers so as to understand the process of transport of contaminants through sub surface media. Koltz *et al.* (1980) investigated the link between longitudinal and transversal dispersion coefficients in loose soil and mean flow velocity in a large number of laboratory and field tests. Rowe and Booker (1985 and 1986) described a method for assessing 2-D contaminant movement from a landfill into a homogenous clayey layer, as well as 2-D and 3-D pollutant migration across layered soil media. In well-designed modern landfills with clayey barriers, Rowe (1989) identified diffusion as a key (and frequently critical) mechanism controlling pollutant transfer.

A diffusion test was devised for calculating the diffusion coefficient (D) and adsorption coefficient (K_d) for numerous volatile organic species in respect of clayey soil in a laboratory (Barone *et al.* 1992). Harari and Hughes (1994) used the finite element approach to investigate the difficulties of steady advection-diffusion with production. Rowe and Badv (1996) suggested that the existing solute transport theory can adequately predict chloride migration through landfill liners near saturated conditions based on a series of chloride diffusion tests on clayey silt, silt, and sand, both for single layer and two layer systems. Codina (1998) presented a comparison of various finite element models for addressing the advection diffusion-reaction problem.

Rosqvist and Destouni (2000) carried out the numerical modeling of the transport of lithium through undisturbed samples of solid waste and subsequently, experimental landfill on pilot scale using probabilistic Lagrangian approach. Prakash (2000) proposed a quasi-analytical model for analyzing pollutant movement through unsaturated and saturated soil zones. Sheu and Chen (2002) developed a finite element model based on the advective-dispersive equation to forecast pollutant concentrations.

Srivastava *et al.* (2002) investigated the effect of porous media heterogeneity on a spatial concentration profile of reactive transport using the advection-dispersion-reaction equation, which accounted for both physical and chemical non-equilibrium. Hsu (2004) presented high order stochastic analysis of flow and solute transport in strongly heterogeneous porous media. Craig and Rabideau (2006) used an Eulerian finite difference technique based on analytical element method derived parameters to model two-dimensional pollutant transport. Remesikova (2007) provided a computational model for handling convection-dispersion-adsorption issues with both equilibrium and non-equilibrium adsorption based on an operator splitting technique.

The transport of a reactive solute was investigated by Starr *et al.* (2008) across a sand layer between two silt layers using laboratory tests and mathematical simulations. When compared to non-reactive solute, the results exhibited break through curves that were delayed in appearance, had a lower peak concentration, and were more widely scattered. EFGM was used by Praveen Kumar and Dodagoudar (2008) to simulate the one-dimensional advection-dispersion equation involving first-order deterioration across a saturated porous media. The results acquired using EFGM were found to be in good agreement with those obtained from published

experiments. Eljamal *et al.* (2008) presented a conceptual model of solute transport with bioremediation processes using sawdust as a matrix to improve the efficiency of bioremediation in the porous media. Eljamal *et al.* (2009) developed a mathematical model, using data obtained from soil-sawdust column experiments, for describing the biological sulphate reduction processes in porous media. An experimental and numerical analysis of pollutant transport in porous media was given by Patrick *et al.* (2011). As seen in the simulations, lowering the specimen height resulted in early breakthrough and larger levels of contaminant mass outflow. Eljamal *et al.* (2011) reported numerical simulation for reactive solute transport of arsenic in permeable reactive barrier column including zero-valent iron. Massimo *et al.* (2012) conducted multi-tracer laboratory bench-scale experiments and pore-scale simulations in a variety of homogeneous saturated porous media, finding that non-linear compound-dependent parameterization of transverse hydrodynamic dispersion was required to capture observed lateral displacement over a wide range of seepage velocities. Eljamal *et al.* (2012) studies the removal of phosphorous from water using marble dust as the sorbent material by conducting batch tests, kinetic sorption model and isotherm model. The study revealed that the batch tests and the kinetic sorption models results showed that using the marble dust as sorbent material could be removed more than 94.3% of phosphorous from water. Sharma *et al.* (2013) published the results of their experiments on pollutant transfer in saturated layered soil. They also performed numerical study for advective-dispersive transport, including equilibrium sorption and first order degradation constant for multi-layered soil, using the implicit finite difference approach. Swami *et al.* (2013) investigated the behaviour of solute transport over stratified porous media in the lab. The peak of the non-reactive solute was found to be higher than that of the reactive solute. Eljamal *et al.* (2013) investigated the sorption of arsenate from water using zero valent iron ZVI as sorbent. The study revealed that ZVI could be employed as sorbent materials to improve the sorption processes and increase the removal rate of arsenate from water.

Patil and Chore (2014) offered a comprehensive overview of studies on contaminant transport across porous media, emphasizing the need for more experimental work in order to fully comprehend the phenomenon of contaminant transport. Experimental investigation of chloride through saturated soil column was reported by Patil and Chore (2015). The break through curve pattern was found to be nearly identical in all scenarios of varied flow rate and conservative chemical beginning concentration. Berlin *et al.* (2015) reported a study on the use of a numerical model to simulate various non-uniform source distributions in a petroleum-contaminated site in Chennai, India. For around 290 days, Gamze Varank *et al.* (2011) tested ten identical pilot-scale landfill reactors with different alternative composite liners. Organic (phenolic compounds) pollutant transfer across different liner systems from leachate to groundwater were evaluated using one-dimensional (1-D) advection-dispersion transport modelling as a conceptual method. Laboratory experiments on dilution and reactive mixing of steady-state transport in saturated

homogeneous and heterogeneous porous media were presented by Xu Tiantian (2019). More laboratory experiments with sophisticated settings are needed to better understand dilution and reactive mixing processes in natural aquifers, according to the findings.

Wang *et al.* (2019) investigated the migration process in vadose zone through laboratory and numerical experiments of chloride and ammonia nitrogen for evaluating the physical and chemical heterogeneity. By conducting a column experiment, Zhang *et al.* (2018) investigated the effects of colloid size and the molar ratio of $\text{Ca}^{2+}/\text{Na}^{+}$ on the retention and remobilization of colloids in saturated porous media. All of the tests' transport processes were reproduced using a modified numerical model that took into account the processes of Lanmuirian dynamics blocking and a conservative tracer equation. Maamoun *et al.* (2020) studied nanoscale zero valent iron (Fe^0) coated with different layered hydroxide coatings ($\text{Mg}/\text{Al}/\text{Ca}(\text{OH})_N$) for enhancing its suspension stability in aqueous solution and transportability within the porous media. Maamoun *et al.* (2021) reported optimization modeling of $n\text{Fe}^0/\text{Cu-PRV}$ Design for the removal of hexavalent chromium from the ground water. Maamoun *et al.* (2022) developed nickel hydroxide nanoplates for rapid and efficient removal of chromium from aqueous solutions.

According to the literature, there is relatively less work published in terms of experimental investigations involving the soil column. As a result, in the current study, an experimental evaluation of pollutant movement through a saturated soil column was conducted in conjunction with numerical modeling. Chloride anions, which represent non-reactive forms of solutes, and fluoride, which represents reactive types of solutes, were used in the tests. In the experimental experiments, the goal was to determine the relative concentration of solutes at different time intervals by changing the material in the saturated soil column. The experimental results are compared by numerical modeling.

3. Experimental set up and procedure

The transport of the solute in the soil column during continuous saturated water flow was investigated using laboratory tracer experiments. The experimental set-up comprises of soil-column (Fig. 1) made up of an acrylic pipe with an 8 mm wall thickness, a diameter of 100 mm, and a length of 800 mm. The pipe's cross section area was 78.50 cm^2 . The media comprised two different types of soils (hereinafter, referred to as the standard sand and red soil, hereafter) (Fig. 2). The former was received by the Department of Civil Engineering at Datta Meghe College of Engineering in New Mumbai (India) for testing purposes, whereas the later was obtained from Ratnagiri (Maharashtra, India) for investigation purposes. The geotechnical investigations were carried out on both of these media materials. Figs 2 and 3 illustrate the particle size distribution curves for both the soil media. Table 1 summarizes geotechnical properties of these soils that were obtained through laboratory investigation.

The tank was filled with soil media (standard sand and red soil). Using a funnel, the dry dirt was carefully pushed

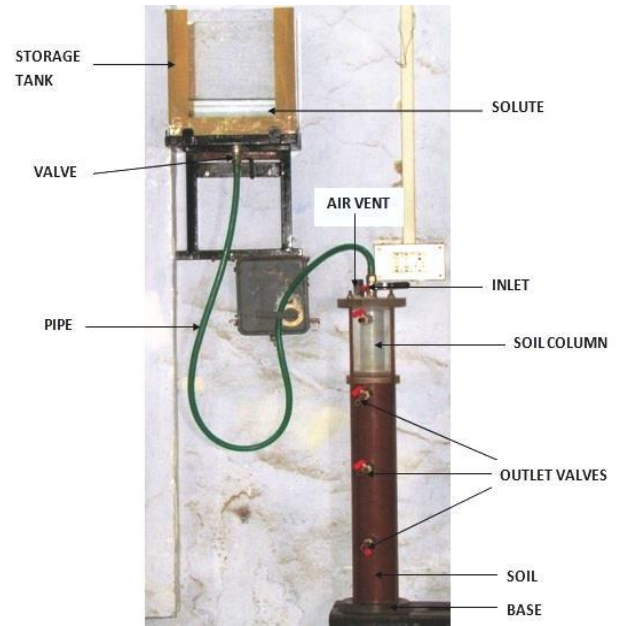


Fig. 1 Set up for soil column experiment

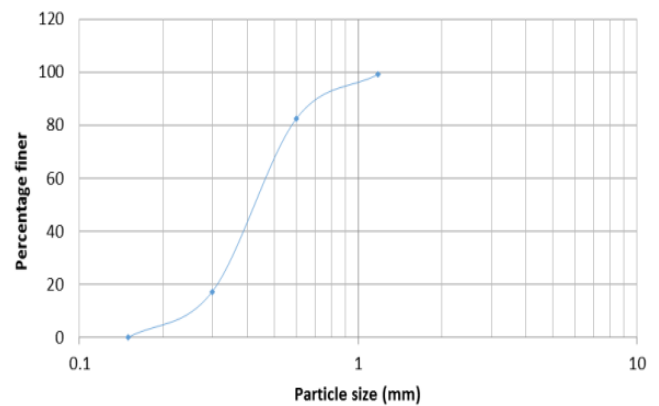


Fig. 2 Particle size distribution (standard sand)

into the column in small increments, avoiding any soil particle-size segregation. As a sturdy support for the soil column, medium porosity fitting glass and plates were given. Organic and inorganic components coexist in the soil media. As a result, the soil column was rinsed out with the desired tap water for around two hours before to the start of the trials. The dirt column was carefully monitored to ensure that it was always flowing. Prior to conducting the studies, the tap water was tested to determine the quantities of free chloride. The properties of the tap water are reported in Table 2. After testing the concentration of tap water, the produced solution of known concentration was stored in a storage tank. The prepared solution was then slowly fed into the soil column, maintaining a constant head of input solution. To begin, the soil column was saturated with tap water, establishing a steady-state water flow situation. To accomplish consistent packing and avoid air bubble entrapment, the water level was always kept above the grains.

Two different types of solutes were used in the investigation, namely- chlorides and fluorides. The known concentrations of sodium chloride solution and fluoride solution were injected as an input into the soil column model

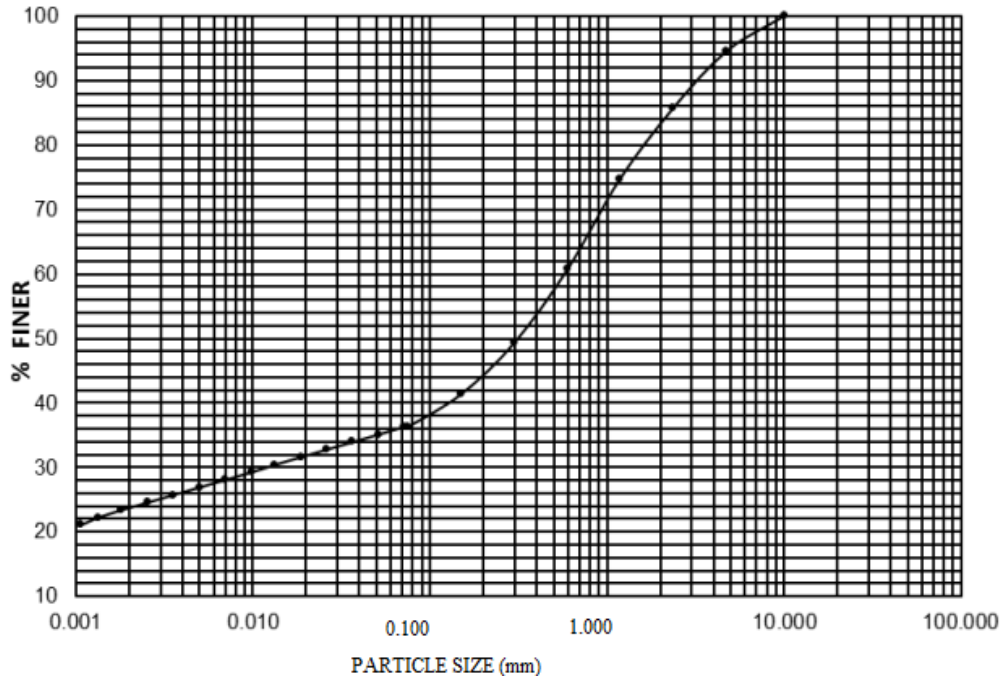


Fig. 3 Particle size distribution (red soil)

Table 1 Summary of geotechnical investigations for different soils used as media

Soil	Specific gravity	Porosity	Moisture contents (%)	Bulk density (g/cm ³)	Liquid limit (%)	Plastic limit (%)	Hydraulic conductivity (mm/sec)
Standard sand	2.67	0.48	8	2.56	--	--	10 ⁺¹
Red soil	2.72	0.30	12	2.71	21.79	19.43	10 ⁻²

Table 2 Properties of the tap water used in the study

Property	Value	Property	Value
Turbidity NTU	0.57	pH	7.92
Dissolved oxygen	8.75 mg/lit	Calcium hardness	30 mg/lit
Chloride	35 mg/lit	Fluorides	1.5 mg/ lit
Residual chlorine	0.2 mg/lit	Alkanity	40 mg/lit
Total hardness	53 mg/lit	Total dissolved solids	272 mg/lit

for half an hour. The concentration of solute in the soil column was measured with constant time increment. Samples of solutes were collected at the outlet of soil column. The concentration of sodium chloride was obtained through titration and for that of fluoride, the spectrophotometer was used. The effluent solutions were collected into the collector in fifteen-minute increments. The measuring cylinder was used to capture a fraction of a water sample for accurate measurement and to double-check the volume collected during a specific time period in order to calculate velocity. By dividing the volume gathered in one minute by the effective cross-sectional area, the velocity was estimated.

To keep the samples safe from direct sunlight, they were kept in airtight vials. Each sample was labelled and analysed after sampling. Potassium chromate was used as an indicator and silver nitrate was used as a titrant for the NaCl solute in

all of the samples. The solute concentration in the effluent fraction was expressed as relative concentrations (C/C_0), where C and C_0 are the effluent fraction and input pulse solute concentrations, respectively.

4. Finite element analysis

A one dimensional numerical model was developed using finite element method. A numerical procedure was programmed in FOTRAN 90 using the 1-D advective - dispersive type differential equation. The break through curves (BTCs) for chloride and fluoride solutes were obtained for soil column, as reported in the preceding section. The parameters given as inputs to the program include the bulk density, porosity, length, dispersion coefficient, distribution coefficient. For performing finite

element analysis, entire soil column was divided into number of elements and nodes.

The governing equation (1-D) for the migration of the contaminant through a saturated porous media is expressed as:

$$\left(1 + \frac{\rho_d}{n} k_d\right) \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - \bar{v}_x \frac{\partial C}{\partial x} - \lambda C \quad (1)$$

where

ρ_d = bulk density of porous medium (ML⁻³)

n = Porosity (L³/L³)

k_d = distribution constant (ML⁻³)

C = Concentration of contaminant (ML⁻³)

D = Dispersion coefficient (L²/T)

λ = is the decay constant (1/T)

$\bar{v}_x$ = Seepage velocity (L/T)

R = Retardation factor = $\left(1 + \frac{\rho_d}{n} K_d\right)$

Initial condition: at $t = 0$, $C = C_i$ in Ω

Boundary conditions: $C(0, t) = C_0$ in Γ_s (Dirichlet boundary condition)

$\frac{\partial C}{\partial x} n_s = g$, in Γ_E (Neumann Boundary condition) which is zero in this case

$C(0, t) = C_0$ at $x = 0$

$$\int_0^L \left(D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x} - R \frac{\partial C}{\partial t} \right) dx = 0 \quad (2)$$

$$\int_0^L D \frac{\partial^2 C}{\partial x^2} dx - \int_0^L v \frac{\partial C}{\partial x} dx - \int_0^L R \frac{\partial C}{\partial t} dx = 0 \quad (3)$$

$C = \sum N_i C_i = NC_e$

$C^T = C_e^T N^T$

where N is the shape function in linear form for a two-node element

$N_1 = 1 - \frac{x}{L}$, $N_2 = \frac{x}{L}$

$$D \frac{\partial C}{\partial x} - D \int_0^L C_e^T N_x^T N_x dx C_e - v \int_0^L C_e^T N^T N_x dx C_e \quad (4)$$

$$- R \int_0^L C_e^T N^T N dx C_e^0 = 0$$

$$D \int_0^L N_x^T N_x dx C_e + v \int_0^L N^T N_x dx C_e \quad (5)$$

$$+ R \int_0^L N^T N_x dx C_e^0 = D \frac{\partial C}{\partial x}$$

$$R \int_0^L N^T N dx C_e^0 + \left[D \int_0^L N_x^T N_x dx + v \int_0^L N^T N_x dx \right] C_e \quad (6)$$

$$= D \frac{\partial C}{\partial x}$$

$$R \int_0^L N^T N dx C_e^{t+\Delta t} + \Delta t K C_e^{t+\Delta t} \quad (7)$$

$$= R \int_0^L N^T N dx C_e^t + D \frac{\partial C}{\partial x}$$

where

$K = K_1 + K_2$

$K_1 = D \int_0^L N_x^T N_x dx$

$K_2 = v \int_0^L N^T N_x dx$

The numerical model so developed was employed for simulating the observed results of non-reactive and reactive solutes through the soil medium observed during experimental studies. The results of either study-experimental and numerical - are discussed in the

subsequent section.

Akaike Information Criterion (AIC) has been considered for comparing the accuracy of numerical prediction (Maamoun *et al.* 2022).

$$AIC = 2K + N \ln \left(\frac{SSE}{N} \right) + \frac{2K(K+1)}{N-K-1} \quad (8)$$

$$\text{where } SSE = \sum_{i=1}^N 2$$

K is the number of parameters of the model. N is number of data points

5. Discussion of results

The results obtained in the context of two different boundary conditions (continuous and pulse type) are reported below through break through curves (BTCs). They show the relationship between the time and relative concentration of the solute measured at the outlet of soil column. Chloride and fluoride were used as a conservative and non-conservative solute respectively. The known concentrations of the sodium chloride solution and fluoride solution were injected into the standard sand as well as red soil, respectively, for half an hour as an input.

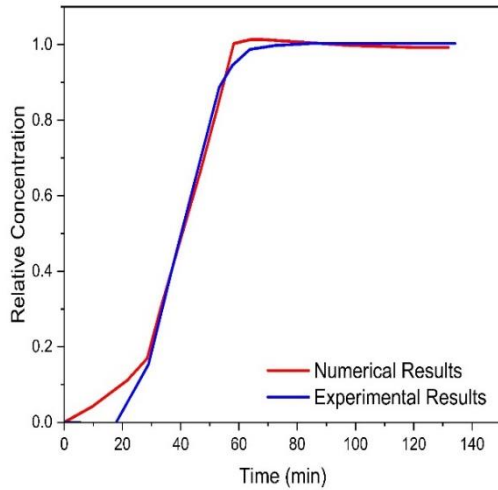
5.1 Studies using standard sand as media

5.1.1 Concentration of chloride (continuous type boundary condition)

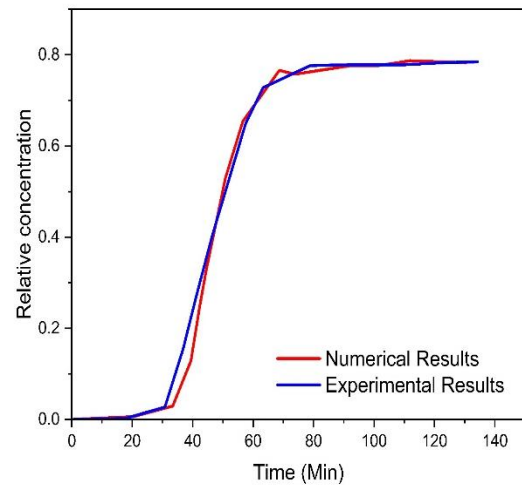
The continuous solute source is the one in which the provided solute source at the intake has a constant concentration and it remains constant during the experiment. The experiments were performed using chloride for continuous type boundary condition. The concentrations of the effluent solute were measured.

Fig. 4 shows the variation of the relative concentration of chloride obtained for an initial concentration of 150 mg/lit for the velocity of 2.4 and 2.6 cm/min observed during the experimental study and that used in the numerical model developed in the present investigation. In experimental study, the relative concentration is seen to increase with time up to 60 min corresponding to the velocity of 2.4 cm/min (Fig. 4a). The corresponding value of the concentration is found to be 0.9964. Thereafter, the relative concentration is seen to remain constant with the average concentration of 1. The trend of variation in relative concentration is found to remain same in the numerical study as that observed in the in experimental study. The relative concentration corresponding to peak value of 60 minutes is observed to be 0.9656. A good agreement is observed in experimental and numerical results ($AIC = 25.7$) with the dispersion coefficient $D = 1.04$ cm²/min and $V = 2.6$ cm/min (Fig. 4a). The relative concentration obtained numerically is found to be on lesser side by 4.65% as compared to that obtained experimentally.

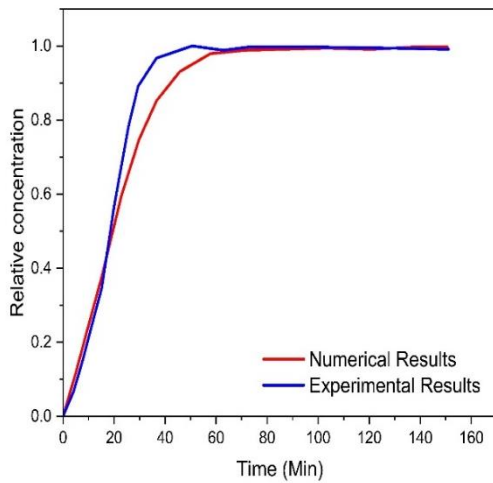
For a velocity of 2.6 cm/min, trend of variation in relative concentrations with time is seen to remain same in both- the experimental and numerical studies. The peak values of the relative concentration are found to occur at 45 minutes and 60 minutes, respectively in the experimental



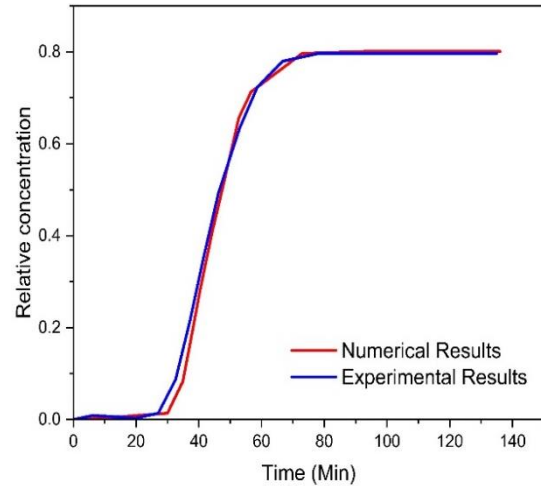
(a) Velocity of 2.4 cm/ min



(a) Velocity of 2.4 cm/ min



(b) Velocity of 2.6 cm/ min



(b) Velocity of 2.9 cm/ min

Fig. 4 Simulated chloride concentration profile through standard sand for initial concentration 150 mg/lit

Fig. 5 Simulated fluoride concentration profile through standard sand for initial concentration of 1.4 mg/lit

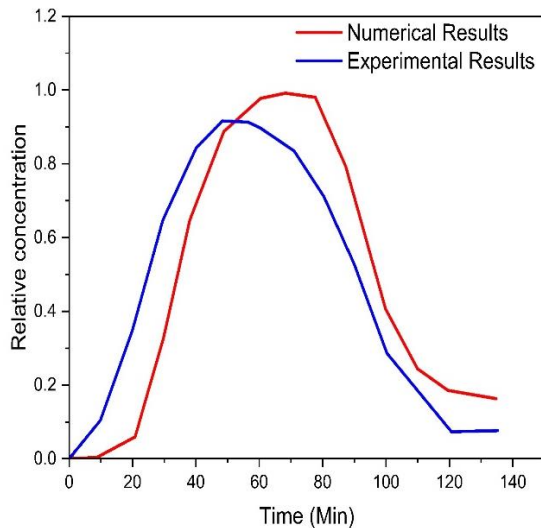
and numerical studies. The values of the relative concentration are observed as the 0.9964 and 0.984, respectively. An excellent agreement is seen in either result ($AIC = 17.7$) with the dispersion coefficient $D = 1.05 \text{ cm}^2/\text{min}$, $1.02 \text{ cm}^2/\text{min}$ and $V = 2.7 \text{ cm/min}$, 2.9 cm/min , respectively. The relative concentration obtained numerically is found to be slightly less, i.e., by 1.24%, as compared to that obtained experimentally with respect to peak point (Fig. 4b).

5.1.2 Concentration of fluoride (continuous type boundary condition)

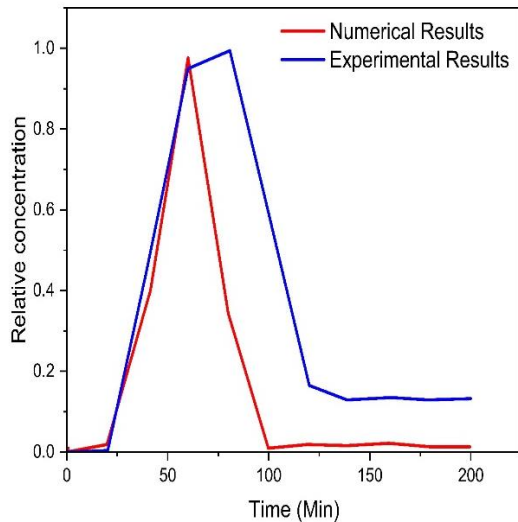
The variation of the relative concentrations of fluoride tracer for an initial concentration of 1.4 mg/ lit corresponding to the velocity of 2.4 and 2.9 cm/min obtained experimentally and numerically is shown in Fig. 5. The experimental studies carried out for an initial concentration at the velocity of 2.4 cm/ min reveal that the relative concentration increases with time up to 75 minutes. The corresponding relative concentration is noted as 0.76 and thereafter, again the concentration remains constant as

as seen in Fig 5(a). However, the concentration, as predicted using the numerical analysis, increases with time up to 60 minutes. The corresponding concentration is noted to be 0.78 and thereafter, it is seen constant with an average concentration to be 1.0. The results observed experimentally and those obtained numerically show an excellent agreement ($AIC = 17$) corresponding to dispersion coefficient $D = 1.0 \text{ cm}^2/\text{min}$ and $V = 2.4 \text{ cm/min}$ (Fig. 5a). The concentration at the peak point of 60 minutes observed experimentally is found to be slightly on higher side (0.75%) as compared to that obtained numerically.

The concentration is found to increase with time up to 60 minutes for the concentration with the velocity of 2.9 cm/ min when the results of experimental and numerical study are compared (Fig. 5(b)). The values of concentrations are noted to be 0.80 and 0.784 in experimental and numerical studies, respectively. The concentration is observed to be constant again and the average values are found to be 0.796 and 1 in case of experimental and numerical studies, respectively. Both the results are found to be in excellent agreement ($AIC = 14.8$) with the



(a) Velocity of 2.4 cm/ min



(b) Velocity of 2.6 cm/ min

Fig. 6 Simulated chloride concentration through standard sand for initial concentration 150 mg/lit

dispersion coefficient $D = 1.2 \text{ cm}^2/\text{min}$ and $V = 2.7 \text{ cm/min}$. The numerical value of the peak concentration is seen to be on the lesser when compared with the experimental value. The percentage difference in either result works out to be 1.5.

5.1.3 Concentration of chloride (pulse type boundary condition)

It has a finite pulse source if the provided solute source is for a predetermined time. Using chloride as the solute and a pulse type boundary condition, the tests were carried out. Figure 6 shows the variation of relative concentration obtained for an initial concentration of 150 mg/ lit of chloride with 2.4 m/sec and 2.6 m/sec velocity through BTCs obtained experimentally and numerically.

As seen from Fig. 6(a), relative concentration increases with time up to 60 minutes in case of an experimental study; the value is observed to be 0.89, and then the concentration is seen to fall. Beyond a time interval of 120

minutes, the concentration remains steady, with an average concentration of 0.075. However, in a numerical study, the concentration is found to increase with time up to 75 minutes while in an experimental study, it is found to increase up to 60 minutes. In numerical study, the corresponding relative concentration is 0.99, and then the concentration drops again. The numerical results show a fairly good agreement with those obtained experimentally ($AIC = 20.3$) for the dispersion coefficient $D = 1.4 \text{ cm}^2/\text{min}$ and $V = 2.4 \text{ cm/min}$. The concentration, at the peak point of 60 minutes is found to be 11.23% more in the numerical study when compared with the one obtained experimentally.

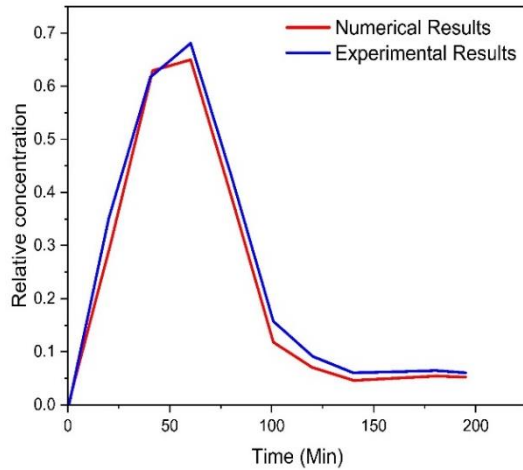
From Fig 6(b), it is seen that the concentration increases with time up to 60 minutes in the experimental study. The relative concentration is 0.9549, and the concentration thereafter begins to drop. Beyond a time period of 100 minutes, the concentration remains constant, with an average value of 0.02. The similar trend of variation in the concentration is also seen in case of numerical results. Notwithstanding, the concentration is found to attain its peak value (0.99) after 75 minutes. The concentration remains constant beyond the time interval of 120 minutes; the average concentration being 0.14. The experimental and numerical results show a very good agreement ($AIC = 37.5$) with respect to the dispersion coefficient $D = 1.4 \text{ cm}^2/\text{min}$, $1.06 \text{ cm}^2/\text{min}$ and $V = 2.7, 2.8 \text{ cm/min}$ (Fig. 6(a) and (b)). The numerical value of the relative concentration corresponding to peak point of 60 minutes is found to be 3.47% less when compared with the experimental one (Fig. 6(a). Further, as seen in Fig. 6(b), concentration at the peak point of 60 minutes obtained numerically is seen to be 3.35 % more when compared with the one obtained experimentally.

5.1.4 Concentration of fluoride (pulse type boundary condition)

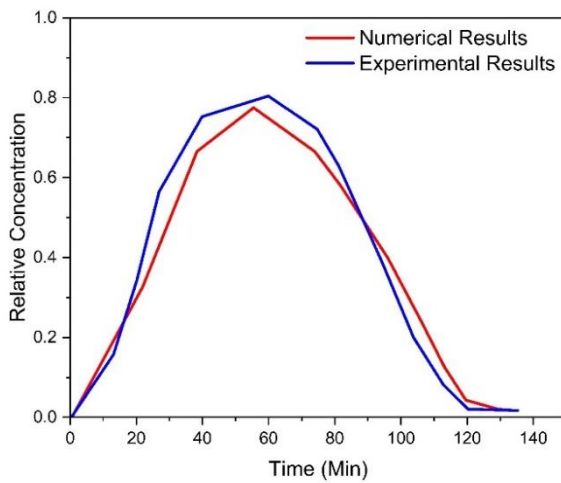
The relative concentration obtained for an initial concentration of 1.4 mg/ lit corresponding to the velocity of 2.4 cm/min and 2.9 cm/min observed during the experimental studies and the one obtained numerically is shown in Fig. 7(a) and (b).

The BTCs for an initial concentration with a velocity of 2.4 cm/min shows that the relative concentration increases with time up to 60 minutes. It is seen that the concentrations are 0.68 and 0.65, respectively. Beyond this, the concentration decreases. The concentration remains constant after the time interval of 135 minutes; the average concentration is observed to be 0.06 in respect of the experimental study while that in numerical study, concentration is found to be constant beyond the interval of 180 minutes and the value of the average concentration is noted to be 0.05. A very good agreement is seen in either result (experimental and numerical with $AIC = 25.8$) at the dispersion coefficient $D = 1.06 \text{ cm}^2/\text{min}$ and $V = 2.8 \text{ cm/min}$ (Fig. 7(a)). The relative concentration obtained by the numerical model is found to be less when compared with the one obtained in the experimental study with percentage variation to be 4.41%.

When compared with time through BTCs with respect to the concentration of 1.4 mg/ lit for the velocity equal to 2.9 cm/min, the relative concentration is found to increase with



(a) Velocity of 2.4 cm/ min



(b) Velocity of 2.9 cm/ min

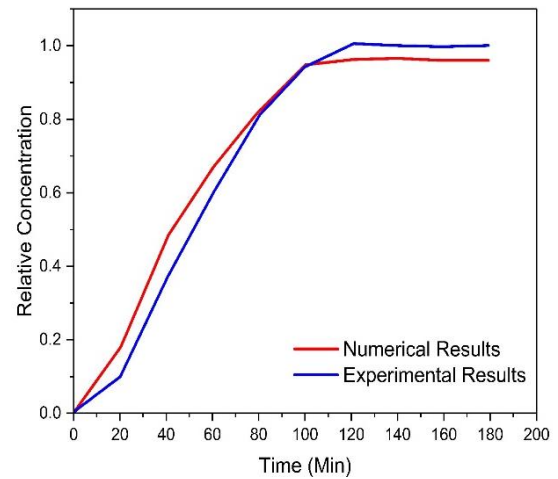
Fig. 7 Simulated fluoride concentration profile through standard sand for initial concentration 1.4 mg/lit

time up to 60 minutes in respect of both the studies, i.e., experimental and numerical. The relative concentrations are seen to be 0.80 and 0.7720, respectively. Again, the concentration decreases. Beyond the interval of 135 minutes, the concentration remains constant and average value of concentration is 0.01 in experimental study whereas in the numerical study, relative concentration remains constant beyond 180 minutes of time interval; average value of concentration being 0.03. Either result show a very good agreement ($AIC = 26.9$) with the dispersion coefficient $D = 1.5 \text{ cm}^2/\text{min}$ and $V = 2.8 \text{ cm/min}$ (Fig. 7(b)). The numerical value of the relative concentration corresponding to peak of 60 minutes is found to be on the lesser side (3.5%) when compared with the experimental value.

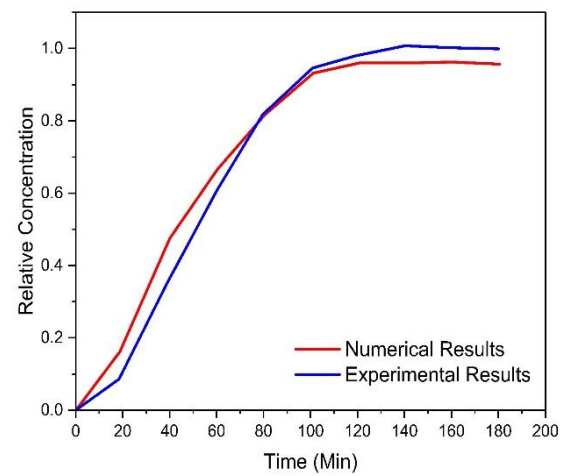
5.2 Studies using red soil as media

5.2.1 Concentration of chloride (continuous type boundary condition)

The experiments were performed using chloride by resorting to the continuous type boundary condition. The



(a) Velocity of 1.0 cm/ min

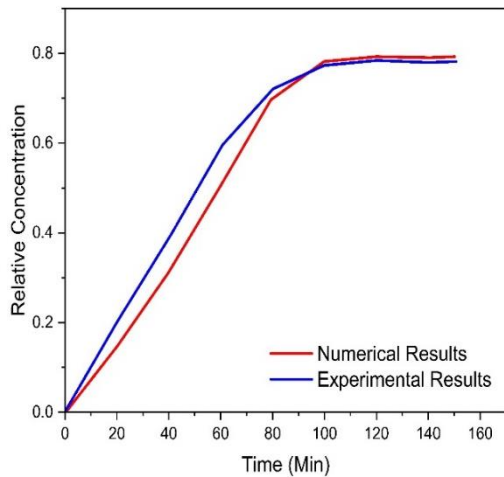


(b) Velocity of 1.4 cm/ min

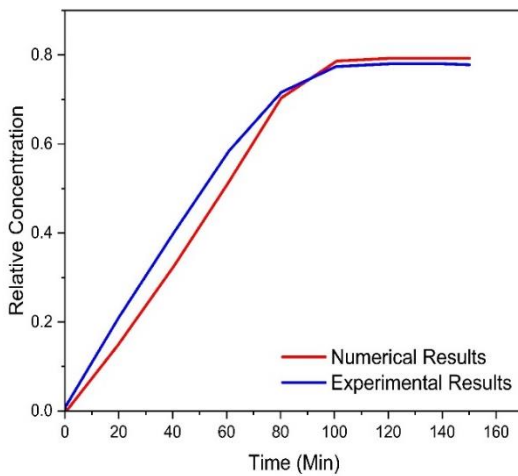
Fig 8 Simulated chloride concentration profile through red soil for initial concentration 150 mg/lit

concentrations of the effluent solute were measured. The variation of the relative concentration obtained in the context of an initial concentration of 150 mg/ lit for velocity of 1.0 and 1.4 cm/min is shown in Fig. 8(a) and (b).

The relative concentration is found to increase with time up to 105 minutes in either study- experimental and numerical. The concentration corresponding to peak point is observed to be 0.97 and 0.9628, respectively in case of experimental and numerical studies (Fig. 8(a)). After the concentration attains the peak point, the same is observed to be constant. A very close agreement is seen in the results obtained experimentally and numerically ($AIC = 22.8$) with the dispersion coefficient $D = 1.7 \text{ cm}^2/\text{min}$. The relative concentration at the peak point of 75 minutes as obtained using the numerical model is found to be 0.84 % less than that obtained experimentally. From Fig. 8(b), it is seen that the concentration increases with time interval up to 135 and 105 minutes, respectively when measured experimentally and obtained numerically for an initial concentration of 150 mg/lit with the velocity of 1.4 cm/min. The corresponding values of the relative concentrations are noted to be 0.97 and 0.96, respectively, beyond which the concentration is



(a) Velocity of 1.0 cm/ min



(b) Velocity of 1.4 cm/ min

Fig. 9 Simulated concentration profile of fluoride through red soil for initial concentration of 1.4 mg/lit

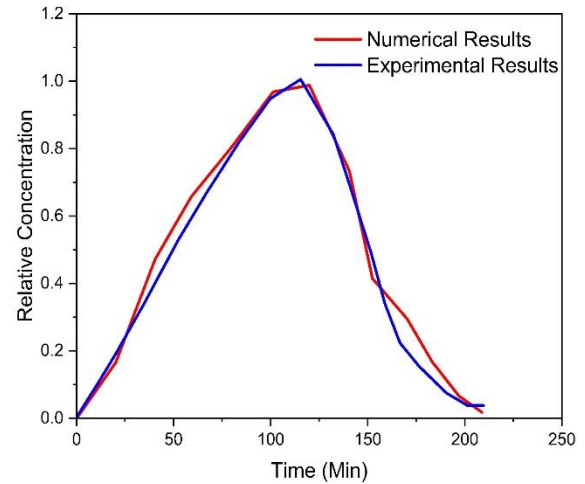
observed to remain constant.

The experimental and numerical studies show a very close agreement ($AIC=34$) therein with the dispersion coefficient $D = 1.8 \text{ cm}^2/\text{min}$. The relative concentration at the peak point of 105 minutes obtained numerically is found to be 1% less than that obtained experimentally.

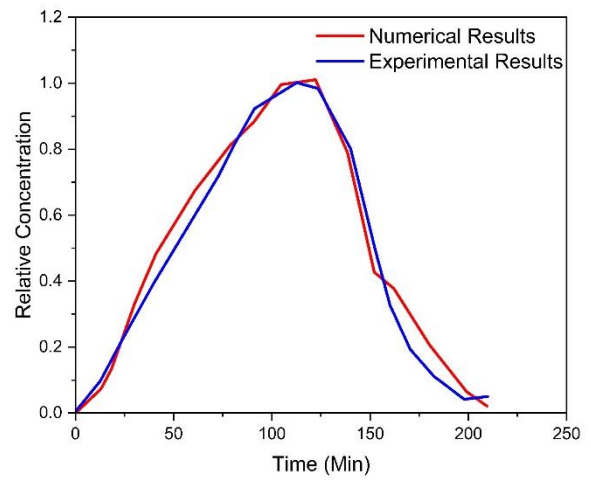
5.2.2 Concentration of fluoride (continuous type boundary condition)

The experiments were performed using fluoride by resorting to the continuous type boundary condition. The concentrations of the effluent solute were measured. The variation of relative concentration obtained with respect to an initial concentration of 1.4 mg/ lit for the velocity of 1.0 cm/min and 1.4 cm/min, respectively is shown in Fig. 9 (a and b).

The relative concentration, obtained experimentally and numerically, increases with time up to 105 minutes (Fig. 9 a and b) in respect of both the flow rate, i.e., 1 and 1.4 cm/min. The corresponding concentrations are noted as 0.784 and 0.79, respectively for the velocity of the tracer to be 1 cm/ min. Further, the concentrations are observed to be



(a) Velocity of 1.0 cm/ min



(b) Velocity of 1.4 cm/ min

Fig. 10 Simulated chloride concentration profile through red soil for initial concentration 150 mg/lit

0.784 and 0.756 for a velocity of 1.4 cm/min. In either study carried out for two different velocities of the tracer, it is seen that the concentration remains constant beyond it attains the peak value after the time interval of 105 minutes. The experimental and numerical results observed with respect to the velocity of the tracer 1 cm/min exhibit a fair agreement ($AIC = 89.8$) therein with a dispersion coefficient $D = 1.6 \text{ cm}^2/\text{min}$. The relative concentration at the peak point of 105 minutes as obtained using the numerical model is found to be 1.26 % more than that observed experimentally. Along similar lines, close agreement is seen in the experimental and numerical results for velocity of 1.4 cm/min of the tracer ($AIC = 47.6$) with the dispersion coefficient (D) of $1.7 \text{ cm}^2/\text{min}$. The relative concentration obtained using the numerical model is found to be 1.26% higher than that observed experimentally.

5.2.3 Concentration of chloride (pulse type boundary condition)

The experiments were performed using chloride by resorting to the pulse type boundary condition. The concentrations of the effluent solute were measured. The

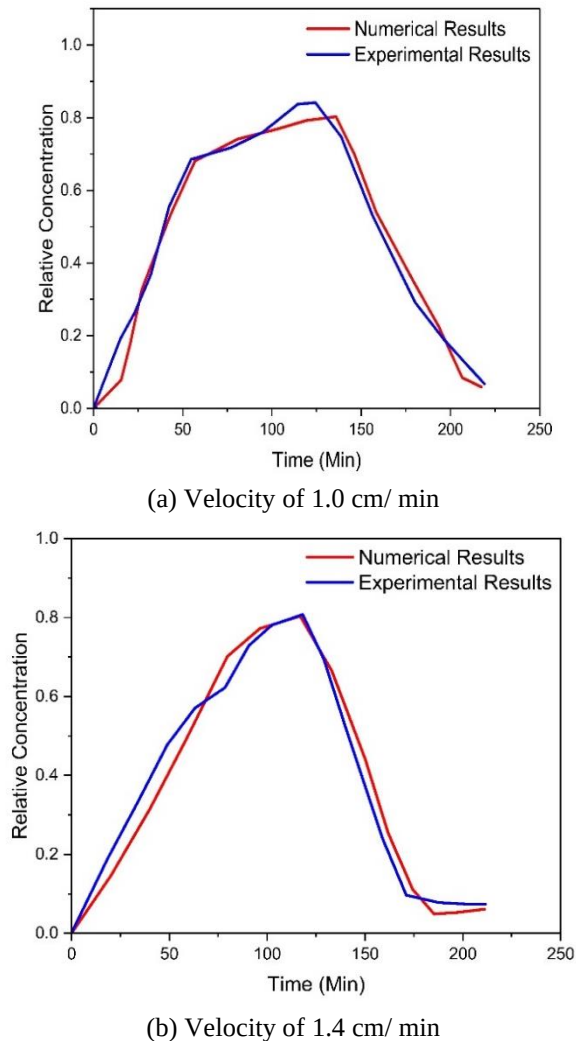


Fig. 11 Simulated fluoride concentration profile through red soil for initial concentration of 1.4 mg/lit

variation of the relative concentration as obtained experimentally and numerically (initial solute concentration = 150 mg/lit; velocity = 1 and 1.4 cm/min) is shown in Fig. 10.

In the experimental investigation, the relative concentration increases with time up to 135 minutes (Fig. 10(a)). The matching relative concentration is found to be 1.0 and the concentration then decreases. Beyond 210-minute time span, the concentration remains constant, with an average value of 0.04. The concentration is found to increase with time up to 135 minutes in the numerical analysis. The equivalent relative concentration is 0.9845 and the concentration, thereafter, begins to drop. The concentration becomes constant beyond the time interval of 180 minutes and the average value of the concentration is observed to be 0.08. The experimental and the numerical results exhibit an excellent agreement therein (AIC = 23.9) with the dispersion coefficient $D = 1.8 \text{ cm}^2/\text{min}$. The relative concentration at the peak point of 75 minutes as obtained using the numerical model is found to be 1.23% higher than that obtained experimentally.

In Fig 10(b), concentration increases with time up for

105 minutes in the numerical studies. The corresponding value of the concentration is noted as 0.9868 and thereafter, again the concentration decreases. It remains constant beyond 180 minutes of time interval; the average value is observed to be 0.05. Along similar lines, the concentration is found to increase with increase in the time interval up to 105 minutes in the case of an experimental study. The value of the concentration is seen to be 1.0 and thereafter, again the concentration decreases. The concentration becomes constant beyond 180 minutes of time interval and the average value of the concentration is noted to be 0.06. The experimental and numerical results show an excellent agreement between them, with the dispersion coefficient $D = 1.7 \text{ cm}^2/\text{min}$. The relative concentration at the peak point of 75 minutes as obtained using the numerical model is found to be 1.25% higher than that obtained experimentally (AIC = 17.3).

5.2.4 Concentration of fluoride (pulse type boundary condition)

The variation of the relative concentration obtained for an initial concentration of 1.4 mg/ lit and the velocity of 1 cm/min and 1.4 cm/min , respectively is shown in Fig. 11(a) and (b).

As seen from Fig. 11(a), the relative concentration obtained experimentally increases with time up to 135 minutes. The corresponding value of the relative concentration is noted 0.8428 and then, the concentration decreases. The concentration remains constant beyond 210 minutes of the time interval; the average value of the concentration is observed to be 0.04. The concentration obtained numerically increases with time up to 135 minutes. The corresponding value of the concentration is noted 0.7845 and then, the concentration decreases. It is observed to remain constant beyond 220 minutes of time interval; the average value is noted to be 0.08. The experimental and numerical results show a close agreement (AIC=17.3) therein corresponding to the dispersion coefficient of $D = 1.8 \text{ cm}^2/\text{min}$. The relative concentration at the peak point of 105 minutes obtained numerically is found to be 1.23% more than that obtained experimentally.

Further, as indicated in Fig. 11(b), the concentration obtained experimentally increases with time interval up to 135 minutes. The corresponding value of the relative concentration is found to be 0.798 and thereafter, it decreases. The concentration remains constant beyond 210 minutes of time interval; average value being 0.04. The concentration obtained numerically increases with increase in time up to 120 minutes. The corresponding concentration is 0.780 and then, the concentration decreases. It remains constant beyond the time interval of 180 minutes with the average value equal to 0.08.

Experimental and numerical results obtained in the current study demonstrate a very close agreement (AIC = 16.9) with dispersion coefficient $D = 1.7 \text{ cm}^2/\text{min}$. The relative concentration at the peak point of 105 minutes as obtained using the numerical model is found to be 1.06% more than that that obtained experimentally. The maximum value of the relative concentration for non-conservative solute (fluoride) is observed to be in the range of 0.7 - 0.8 in

all the cases. It is also well known that fluoride chemical is reactive. Once it comes in contact with the soil media, it is adsorbed on the soil surface.

6. Conclusions

The paper presents the experimental investigation and the numerical modeling carried out for studying the migration of contaminants through two different types of porous media (standard sand and red soil) using soil columns and further with respect to conservative and non-conservative solutes. Two boundary conditions- continuous and pulse type were resorted to. Different initial concentrations of either solute with different velocities in respect of the afore-mentioned boundary conditions were used. Few significant conclusions emerged from the present investigation are reported below.

- The pattern of break through curve remains almost same mostly in all the cases of varying initial concentrations of the pollutants, i.e., solute and its rate of flow.
- The peak value of the relative concentration attains after 60 minutes and 105 minutes for standard sand and red soil, respectively.
- The maximum value of the relative concentration for conservative solute (chloride) is observed to be in the range of 0.9 - 0.96.
- The maximum value of the relative concentration for non- conservative solute (fluoride) is observed to be in the range of 0.68 - 0.79.
- Fluoride, being chemically reactive, gets adsorbed on the soil surface once it comes in contact with the soil media.
- The maximum value of the relative concentration reaches earlier in respect of the standard sand as compared to that in case of red soil.
- The effect of velocity is found to be significant on the transport of the solute. Both the tracers seemed to have provided a similar response. Reduction in advection velocity reduces the migration of the solute.
- As regards the solute concentration collected at different depths in the soil column, the concentration attains its peak earlier if the velocity is higher. The concentrations decrease at any given point of time with increase in distance from the source.
- The results obtained using one dimensional finite element model developed in the present study are found to be in close to good agreement with those obtained experimentally.
- The variation in maximum relative concentration observed experimentally and obtained numerically corresponding to peak point, in case of standard sand through soil column is found to be in the range of 0.75-4.65%. In only a case, the variation is found to be 11.23%.
- The variation in the results of maximum relative concentration observed experimentally and obtained numerically in case of red soil as a media through short is observed to be 0.84-1.23%.
- The results of break through curves (BTCs) are found to be compatible and can be useful in predicting the transport

of contaminants.

- The migration of contaminants is seen to be rapid in case of standard sand as a media owing to its porosity as compared to that in red soil.

Acknowledgment

The research described in this paper was partly funded by University of Mumbai (India) through its 'Minor Research Grant Scheme' under the funds received by the University Grant Commission.

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