Shahrood University of Technology

Journal of Hydraulic and Water Engineering (JHWE)

Journal homepage: https://jhwe.shahroodut.ac.ir/

Iranian Hydraulic Association (IHA)

Studying Effect of Travel Distance on Dispersion Coefficient in Layered Soil Perpendicular to Flow Direction using Numerical Model

H. Mehdipanah [1,*], N. Ramzanian Azizi [1], A. Golshan [2]

[1] Department of Water Science and Engineering, Qaemshahr Branch, Islamic Azad University, Qaemshahr, Iran.
[2] Expert of Water Engineering, Urban Green Space of Shahrood Municipality, Iran.

Article Info

Article history:
Received: 12 May 2023
Received in revised form: 1 June 2023
Accepted: 5 June 2023
Published online: 7 June 2023

DOI:
10.22044/JHWE.2023.13118.1019

Keywords
Diffusivity
Transfer Distance
Layered Porous Medium
Brigham Model
Hydrous

Abstract

One of the most important measurable properties of the porous medium is dispersivity, which is used in advection-dispersion equations related to pollutant transport in the study of groundwater. In the past, the dispersivity coefficient for the entire porous medium was considered as a constant coefficient but many studies conducted in the last few decades have shown that the dispersivity depends on many parameters including the travel distance. Since most of these studies have been conducted in homogeneous porous media, in this research work, the effect of travel distance of 20, 50, and 80 cm on the dispersivity coefficient in a porous medium corresponding to coarse, medium, and fine granularity is investigated. The results obtained in this research work show that in all travel distances, the volume of pore water reach one before reaching the relative concentration of 0.5, and the pollutant travel rate decrease with increasing travel distance, which is consistent with the results of other studies. Also, the numerical modeling by the Hydrus numerical model show that this model is able to calculate the value of the diffusion coefficient for the travel distances of 20, 50, and 80 cm with the RMSE errors equal to 0.065, 0.068, and 0.061, respectively, which indicates its high accuracy in simulating and moving the contaminant in the porous medium.

1. Introduction

Water is the main source of life, and about three-fourths of the earth is covered by water but in terms of quality, fresh water for drinking, agriculture, and industry is in short supply. The quality of water either has a natural origin that follows a certain system, or the incorrect and excessive human consumption of water sources causes disruption of the current situation. In a qualitative cycle, nature performs natural purification of waters but no matter how great this process is, it is not the answer to removing human biological pollution. The excessive increase in population in the recent years, limited surface water resources and excessive exploitation of underground water tables have caused irreparable damage to the country's water resources in the past years. In addition to the severe fall of the water level in the aquifers, agricultural, industrial, and urban activities have also discharged various pollutants into the underground water tables.

In order to prevent the continued decrease in quantity and quality of the existing resources, management of exploitation and protection of underground water should be placed as a

* Corresponding author. E-mail address: mrpanah@gmail.com, Tel:+ 09122734299

principle and basis in planning. Qualitative management of underground water resources in the first step requires knowing the pollutant sources of the aquifer and the equations governing them, and in the second step, it needs a tool to be able to predict the reaction of different quantitative and qualitative stresses to the underground water table in current and future conditions. One of the measurable and important parameters in the porous medium is dispersivity. The dispersivity used in the displacement-diffusion equation was considered constant for the entire porous medium in the past but studies conducted in the recent years indicate that determining the constant values of dispersivity is not always sufficient, and the effect of different parameters should be taken into account. The effect on soil diffusion should be investigated. Dispersion coefficient is on the most important parameter in the study of pollution of groundwater, river, soil science, and etc. (Emamgholizadeh et al., 2014; Parsaie et al., 2018; Bazoobandi et al., 2022; Mehdipanah et al., 2022; Tao et al., 2022; Liu et al., 2023; Ohadi et al., 2023). According to the report of many researchers such as Emamgholizadeh et al. (2017), Younes et al. (2020), and Mehdipanah et al. (2022), one of the most important parameters affecting the dispersivity coefficient is the travel distance. Using laboratory data, Al-Tabbaa et al. (2000) investigated the movement of a non-reactive pollutant, sodium chloride, using stratified sand over short travel distances under one-dimensional flow conditions. Sand stratifications were used vertically, parallel, and inclined to the main flow direction, and the flow passed through the stratifications with constant average pore water velocity. In this study, they investigated the effect of different soils and imposed flow conditions on solute transport. The results indicated that under one-dimensional flow conditions, the mean contaminant velocity is permanently greater than the mean pore water velocity.

Another factor that can affect the diffusion coefficient is the homogeneity or non-homogeneousness of the soil. Roughly, a little study has been done on the effect of compatible soils on the dispersivity coefficient. Shamir and Harleman (1967) were one of the first researchers who studied the dispersivity coefficient in compatible soils, and reported dispersivity values in the range of 0.07 to 0.44 cm .

Selim et al. (1977) reported that the order of the layers does not affect the distribution of the pollutant in the porous medium. One of the best models for simulating the movement of water, solutes, heat, water absorption by roots, as well as root growth in saturated and unsaturated conditions in soil is the two-dimensional hydrous model. The numerical method used in the model is finite element.

The general equation governing water flow in porous medium is Richard’s equation. This equation has spatial and temporal derivatives and numerical method, and initial and boundary conditions are needed to solve it. Hydrus software provides the possibility to choose the types of boundary conditions that match the reality the most. Solute transport equations take into account incremental diffusion transport in the liquid phase and diffusion in the gas phase.

The transport equations also include concepts for non-linear or non-equilibrium reactions between solid and liquid phases, linear equilibrium reactions between liquid and gas phases, zero-order production, and two first-order degradation reactions: one that is independent of other solutes, and one that it provides inter-solutes involved in successive first-order reactions.

This program may be used to analyze the movement of water and solutes in unsaturated, partially saturated or fully saturated porous media. The porous environment simulated in the software can be composed of homogeneous or non-homogeneous soils. Flow can also occur in a vertical plane, a horizontal plane or in a three-dimensional region that exhibits radial symmetry about the vertical axis. In this model, the numerical solution of the Richards equation is used to investigate the movement of water in the soil, as well as the transport-diffusion equations, to investigate the movement of solutes and heat in the soil. In addition, Hydrus can estimate hydraulic properties and solute transport in an inverse way. So far, many researchers have successfully used the hydrous model. For example, Shiran et al. (2018) and Samani et al. (2019) used Hydrus software to predict the pollutant concentration of drainage water, and reported an explanation coefficient of more than 0.9 in their results. Also Farasati and Seyedian (2013) investigated the dispersivity of salt in the soil using the hydrous model, and stated that the dispersivity of the soil increases with the increase of the transfer distance. They also investigated the effect of soil texture on the dispersivity of sodium chloride by 2D Hydrus software, and stated in his results that the dispersivity of salt depends on the particle size and the amount of mixing of coarse and medium sand. The review of the sources shows that no study has been conducted or reported on the effect of the transfer distance on the diffusion of sandy soils with layers perpendicular to the direction of flow, so in this study, sandy soils with coarse, medium, and fine layers in the vertical position. The direction of the flow was investigated in a laboratory so that this dependence can be presented in an experimental relation and using Brigham's model, it can be used in the general displacement-diffusion equation. Among the reasons for using the layered model in this research, we can mention the following: since the properties of the soil at the farm scale are different at different points and depths, predicting the pollutant transport mechanisms in the soil using homogeneous models is usually it's not precise.

The pollutant transfer process in heterogeneous and layered soils is different from homogeneous soil in many ways, and considering that the soil of agricultural fields and areas where sedimentation occurs is usually layered, therefore, conducting studies on solute transfer processes in these soils are essential. Testing with homogeneous soil assumes ideal conditions.

Therefore, in this research work, for similarity with real conditions, a layered model with coarse, medium and fine arrangement was chosen vertically. Also, to check the accuracy of hydrous numerical model in predicting the process of pollutant distribution in soil, the said porous medium was also simulated in two-dimensional hydrous environment, and the pollutant movement in layered soil perpendicular to the direction of flow was also investigated in this numerical model.

2. Materials and Methods

In order to conduct experiments and collect laboratory data, first the required physical model was designed and built, which is explained in Section 2.1. Then by applying two-dimensional Hydrous model, the pollutant movement in a layered porous medium was simulated.

2.1. Laboratory model

A laboratory model was made in the form of a rectangular tank made of unbreakable glass (tempered glass) with a length of 1.1 m, a width of 0.1 m and a height of 0.8 m. The rectangular tank consisted of three parts: inlet (right side of the tank), porous medium (middle part of the tank), and outlet (left side of the tank).

In order to make the flow one-dimensional, these three parts were separated by porous plates, so that the pollutant passes through the entire soil column horizontally. A cotton net was used to prevent small particles from passing through and clogging the pores of these plates. In order to ensure the intensity of the constant current passing through the tank, the water and pollutant sources were independently connected to a height regulator and the flow after that entered the inlet part of the tank and the excess flow over the intensity of the constant test flow from the head part. The fine regulator was taken out (Fig. 1).

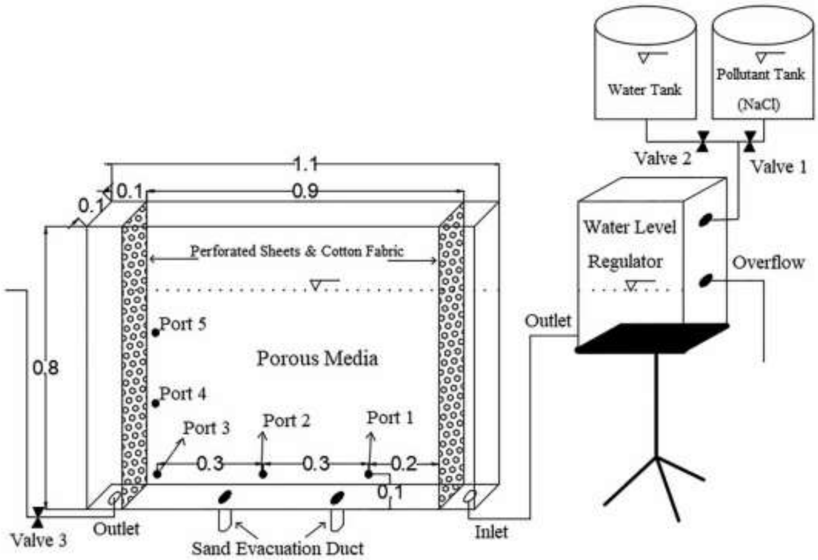


Figure 1. Overview of the laboratory model.

In order to prepare point samples at a distance of 10 cm from the bottom of the tank, sampling valves were installed at a distance of 10 cm from the bottom of the tank in the horizontal direction and 10 cm from the left side of the model. The distance of the first valve in line with the horizon from the entrance part was 20 cm, and the next two valves were 50 and 80 cm, respectively, and the fourth and fifth valves were 30 and 50 cm from the bottom of the model. The number of sampling valves and their intervals can be seen in Table 1. Polyethylene pipes with holes and protected with steel mesh with 100 mesh were installed as samplers across the tank.

Table 1. Distances of sampling ports.

Sampling port number	X (horizontal distance)	Y (vertical distance)
1	20 cm	10 cm
2	50 cm	10 cm
3	80 cm	10 cm
4	80 cm	30 cm
5	80 cm	50 cm

In most of the similar experiments, sodium chloride or bromide was used as a neutral pollutant, and therefore, in this study, sodium chloride was chosen as a pollutant due to its safety and availability. The sodium chloride used in the experiments was sea salt without any sediments. The concentration of 9 grams per liter (14 dS/m) is an example of chlorine ion concentration in landfill leachate or an example of the collected concentration of sodium ion or other similar ions such as potassium (Ayotamuno, 1999).

For this reason, sodium chloride solution with electrical conductivity of 14 dS/m was used for the experiments. Also, the intensity of the passing current in the scope of similar studies was considered as 17.58 × 10-5, 22.02 × 10-5, and 26.18 × 10-5 m/s. Sand in three sizes, fine, medium and coarse, was selected for this research work.

After the sands were washed and dried by standard sieves, they were granulated to obtain the diameter of their particles. Particle size and other soil parameters can be seen in Table **2.**

Table 2. Characteristics of soil sand.

Characteristics of sandy soils	Coarse soil	Medium soil	Fine soil
Sieve passed	7	8	16
Extend on sieve	8	10	18
apparent specific gravity (ρ_b , g/cm^3)	1.59	1.6	1.62
Porosity (n)	0.4	0.39	0.39
Hydraulic conductivity saturation ($\text{K} \times 10^{-4}\ m/s$)	1.601	1.657	1.708

Then the model was filled with coarse, medium, and fine sand respectively from the bottom and each layer was 20 cm thick (Figure 1). For pollutant transport in the simulated aquifer, hypotheses were considered, which were: 1) horizontality of fluid flow direction 2) consistency of sand porosity 3) homogeneity and saturation of the porous medium. To prepare the tank, water was first added to the tank to a height slightly higher than the desired height. At this time, the inlet and outlet channels of the tank were closed. Then the dried sand was gradually added from the top of the tank to reach the desired height. After pouring a certain amount of sand, they were gently pounded by a piece of geomembrane sheet attached to a wooden handle to reach the maximum natural density. Before starting the test, it is necessary to make sure that the air bubbles are removed so that the tank is ready for the test. The intensity of the passing current was also created by adjusting the outlet height. Simultaneously, with the beginning of the experiment, a sample was prepared to measure the concentration. The first readings at time t = 0 was related to the concentration of the solution in the tank and aquifer. Then at intervals of approximately 2 to 20 minutes, the concentration of the output solution from the samplers was measured simultaneously. Sampling continued until the concentration of the samples reached the final concentration (14 dS/m).

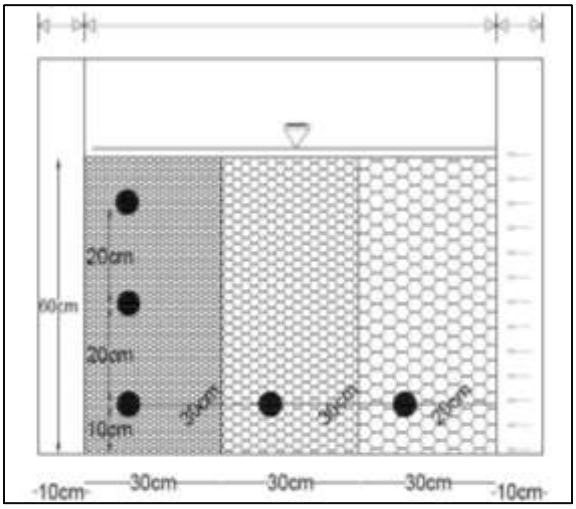


Figure 2. Front view of physical model and simulated aquifer of Brigham model.

So far, many models have been presented for the problem of transporting solutes inside aquifers. Considering that the movement and diffusion of pollutants in the soil is done by three mechanisms: mass transfer, molecular diffusion, and mechanical diffusion, and taking into account the effect of these three processes

on the movement of pollutants, the one-dimensional equation of displacement-diffusion for a stable solution in a homogeneous porous medium and in a saturated state under constant flow conditions is as follows.
The sum of molecular diffusion and mechanical diffusion is called hydrodynamic diffusion:

$$\frac{\delta c}{\delta t} = -v\frac{\delta c}{\delta z}\delta z + D\frac{\delta^2 C}{\delta z^2} \quad (1)$$

D: Hydrodynamic diffusion coefficient M^2L^{-1}
C: Pollutant concentration ML^{-3}
z: Distance L
v: Average real water velocity LT^{-1}

The hydrodynamic diffusion coefficient is expressed by two parameters:

$$D = \alpha V + D^* \quad (2)$$

where α: dispersivity coefficient of porous medium(L), : D^*The molecular diffusion coefficient of the solution in the porous medium (L^2T^{-1}).
This equation is the solute transport equation, which is a non-linear partial derivative equation that has two variables; time (t) and location (L) and a concentration dependent variable (C). These types of equations have many solutions, and in order to obtain a single solution from them, the initial conditions and boundary conditions of the system must be defined. The initial and boundary conditions are expressed mathematically as follows:

C (L, 0)= 0 L ≥ 0
C (0, t)= C0 _
C(∞ , t)= 0 t ≥ 0
With these conditions, the solution of Eq. 1 for saturated homogeneous porous medium is :

$$\frac{C}{C_0} = \frac{1}{2}\left[erfc\left(\frac{L-vt}{2\sqrt{Dt}}\right) + exp\left(\frac{vL}{D}\right)erfc\left(\frac{L+vt}{2\sqrt{Dt}}\right)\right] \quad (3)$$

where erfc is the complementary error function and is defined as follows:

$$erfc = 1 - erf(x) \quad (4)$$

erf (x): Error function.
L: Distance along the flow path.
V(LT^{-1}): Average linear velocity of water in soil pores.

In the conditions that the dispersivity of the porous medium is high, or L and t is large, the value of the second term on the right side of the equation becomes insignificant, so:

$$\frac{C}{C_0} = \frac{1}{2}\left[erfc\left(\frac{L-vt}{2\sqrt{Dt}}\right)\right] \quad (5)$$

The ratio $\frac{C}{C_0}$ versus time (t) in the output of the column represents the breakthrough curve (BTC). Equation (5) is also used to calculate breakthrough shapes breach.

In this research work, by measuring the concentration of the pollutant passing through the soil columns at different travel distances and finally drawing the breakthrough diagrams (BTC)TC, the emission parameters were investigated. To evaluate the dispersion in this research work, the hydrodynamic diffusion values obtained from the Brigham model were used . If a cylinder is filled with soil, the diffusion coefficients, and especially its dispersion coefficient can be determined in the laboratory. In tests conducted on a column of soil, it is common that it expresses the results in terms of the volume of pore water collected.
A volume of pore water is equal to the multiply of the cross-sectional area of the cylinder by the length of the sample and the coefficient of porosity of the soil, that is (A.L.n). On the other hand, one unit of flow intensity from the sample is equal to the flow velocity Vx multiplied by the porosity (n) multiplied by the cross-sectional area of the flow (A) or (V_x n A). Obviously, the total current value is obtained from the product of the unit current intensity during the test (V_x nA_t).
The total number of pore water volume is equal to the total amount of flow divided by the unit volume of pore water, that is:

$$U = \left(\frac{V_x nAt}{ALn}\right) = \left(\frac{V_x t}{L}\right) \quad (6)$$

Pickens and Grisak (1981) used the analytical solution of the Ogata equation obtained by Rifai *et al*. (1956) and used it with the pore water volume number parameter of Brigham (1974) to calculate the diffusion coefficient. The solution of the Ogata equation and the method of obtaining the value of the hydrodynamic diffusion coefficient are as follows:

$$\frac{C}{C_0}=\frac{1}{2}\left[erfc\left(\frac{1-U}{2(UD/VL)^{\frac{1}{2}}}\right)\right] \quad (7)$$

where U is the number of used pore water volume, and L is the length of soil column.

Brigham suggested plotting the fluid concentration versus $\frac{U-1}{U^{0.5}}$ on a probability linear paper. If the data coincides on a straight line under the condition that the average velocity and concentration of the pollutant source are constant, then the values obtained from the experiment follow a normal distribution and the use of the displacement-diffusion model will be valid and the diffusion coefficient is calculated from the slope of the line.
In order to recognize unusual/abnormal data, as a result of closed-end voids or unusual soil columns can be recognized in some cases by using the drawing method.

By assumption $Y=\frac{U-1}{U^{0.5}}$, hydrodynamic diffusion coefficient can be calculated using the following equation:

$$D=(VL/8)(Y_{0.84}-Y_{0.16})^2 \quad (8)$$

In this equation, $Y_{0.16}$ and $Y_{0.84}$ are, respectively, the value of Y corresponding to the relative concentration equal to 0.16 and 0.84 (Pickens and Grisak, 1981).

$\frac{C}{C_0}=0.84$ then $Y_{0.84}=\frac{U-1}{\sqrt{U}}$
$\frac{C}{C_0}=0.16$ then $Y_{0.16}=\frac{U-1}{\sqrt{U}}$
Because $D=\alpha\, v_x + D^*$
So $\alpha=\left[\frac{D-D^*}{V_x}\right]$

2.2. Hydrus model

The movement of water in the porous medium was simulated using the two-dimensional hydrous model (Huang *et al.*, 2006). The governing equations are solved using the linear finite element method applied to a grid of triangular elements. This model was presented at Riverside University of California in 1998 by the American soil salinity laboratory, and until now its modified versions in the form of one-dimensional, two-dimensional and three-dimensional hydrous models have been provided to the researchers. The governing equation of water flow in a porous medium is the two-dimensional Richards equation:

$$\frac{\delta\theta}{\delta t}=\frac{\delta}{\delta x}\left[k(h)\frac{\delta h}{\delta x}\right]+\frac{\delta}{\delta z}\left[k(h)\frac{\delta h}{\delta z}+k(h)\right]-S \quad (10)$$

In this equation, θ is the volumetric moisture percentage ($L^3\,L^{-3}$), h is the water pressure load in the porous media (L), t is time (T), k is the hydraulic conductivity (LT^{-1}), x is the horizontal direction, and z is the vertical direction. S also indicates the amount of water absorbed by the roots from the soil ($L^3\,L^{-3}\,t^{-1}$).
Soil hydraulic characteristics are obtained using the Van Genuchten-Moalem relationship (Simonek *et al.*, 2006).

$$\theta(h)=\begin{cases}\theta r+\frac{\theta s-\theta r}{(1+|\alpha h|^{n})^{m}} & h<0\\ \theta s & h>0\end{cases} \quad (11)$$

$$K(h)=K_sS_e^l\left[1-(1-S_e^{\frac{1}{m}})^m\right]^2 \quad (12)$$

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad m=1-\frac{1}{n} \quad (13)$$

In these equations, s is the percentage of saturated soil water, r is the percentage of remaining soil water, Ks is the saturated hydraulic conductivity, and n, m, and L are parameters dependent on the soil, and α is the image of air intake suction in the saturated state, which they are obtained by fitting the desired equation.
The parameters related to soil hydraulic properties including soil moisture curve parameters, as well as soil saturation hydraulic conductivity parameters (K_s), residual moisture (θ_r) and saturated moisture (θ_s) were predicted by the Rosseta model (Table 2).
This model is one of the add-ons of Hydrus software, which works based on artificial neural network and estimates the hydraulic parameters of the soil by entering data such

as the percentage of granulation, the percentage of moisture in the agricultural capacity and the percentage of different soil textures.

Table 3. Hydraulic parameters of the sands used in the research, estimated by the Rosetta model.

I	Ks (cm/min)	n	Alpha (1/cm)	Qs	Qr	Grading
0.5	1.02498	4.6524	0.0301	0.3687	0.0536	coarse
0.5	0.993875	4.6096	0.0302	0.3625	0.0532	medium
0.5	0.960187	4.5575	0.0302	0.3563	0.0528	fine

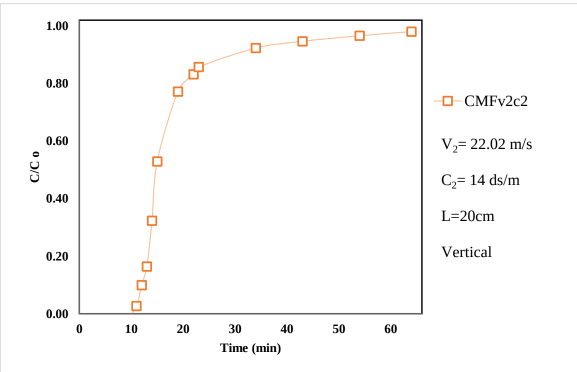
3.Results and Discussion

3.1. Results of laboratory model

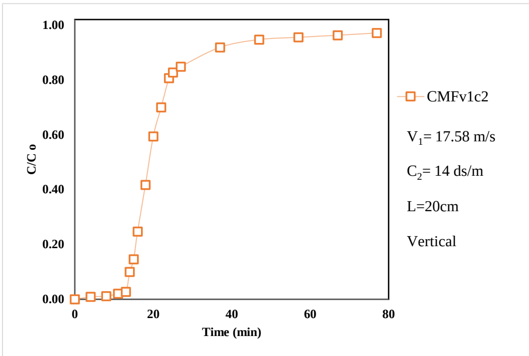
Three experiments were conducted in three layers of sandy soil consisting of coarse, medium, and fine soil in a perpendicular direction. In all the experiments, all the conditions were kept the same and constant, and only the apparent velocity of the flow was changed. The flow velocities were 17.58×10^{-5}, 22.02×10^{-5}, and 26.18×10^{-5} m/s.

The thickness of the soil was equal to 30 cm (each layer) and the soil layers were prepared regularly and uniformly. Figure 3 shows the breakthrough curves of these experiments. In these figures, the test code (CMF), the apparent velocity of the test (V_1, V_2, and V_3 corresponding to the minimum to maximum velocity, respectively), the concentration of the pollutant (C_2 corresponding to the concentration of 14 dS/m) used. The transfer distance and the direction of placement of the layers relative to the flow direction are provided on its right side.

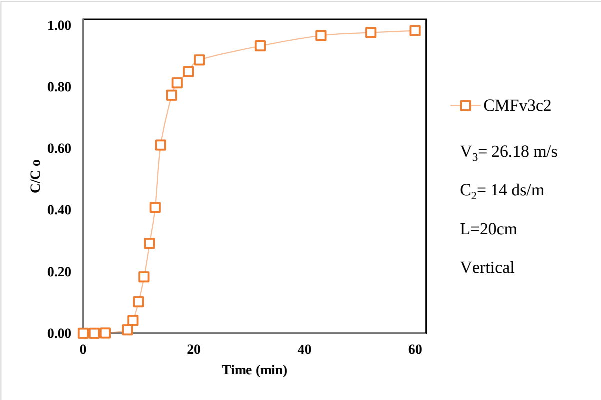
In these graphs, the vertical axis represents the relative concentration and the horizontal axis represents the time elapsed since the start of the experiment. The initial concentration in these experiments was around 0.65-0.68 dS/m and the pollutant concentration or the final concentration was 14 dS/m. Brigham's mathematical model is selected for evaluation. Dispersivity coefficients by Brigham for all tests performed on three layers of coarse, medium, and fine sandy soils with transfer distances of 20, 50 and 80 cm in the horizontal direction and 30 and 50 cm in the vertical direction and three velocity of 17.58×10^{-5}, 22.02×10^{-5}, and 26.18×10^{-5} m/s, and a concentration of 14 dS/m.



b. $CMFv_2c_2$ test (Coarse, medium and fine sand, respectively from the right side of the model).



a. $CMFv_1c_2$ test (Coarse, medium and fine sand respectively, from the right side of the model)



c. $CMFv_3c_2$ test (coarse, medium and fine sand, respectively from the right side of the model).

Figure 3. Breakthrough curves related to tests with three layers of CMF soil, concentration of 14 dS/m, velocity is variable and experiment was conducted at vertical direction.

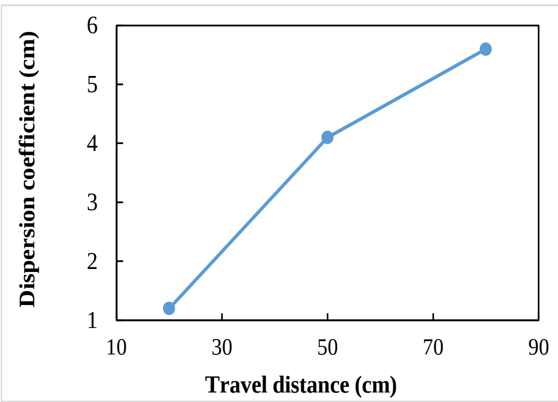
Table 4. Values of the dispersion coefficient of the tests performed with three layers of coarse, medium, and fine soil (respectively from the right side of the model) in the direction perpendicular to the flow direction, using Brigham's analytical model.

Texture	Travel distance (m)		Direction of the ratio layer to flow	Dispersivity	V1C2	V2C2	V3C2
	X	Y					
CMF	0.2	0.1	vertical	α (Br)	0.012	0.015	0.009
CMF	0.5	0.1	vertical	α (Br)	0.041	0.026	0.025
CMF	0.8	0.1	vertical	α (Br)	0.056	0.029	0.037
CMF	0.8	0.3	vertical	α (Br)	0.056	0.029	0.036
CMF	0.8	0.5	vertical	α (Br)	0.055	0.028	0.036

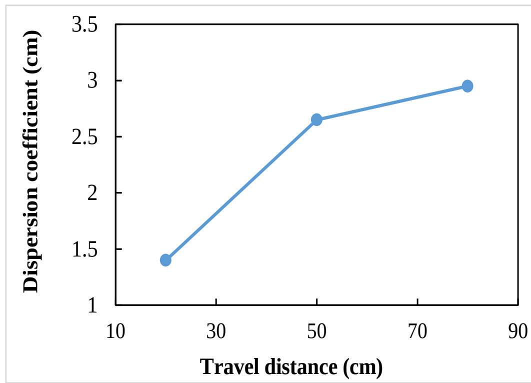
As it can be seen in Figure 3, the breakthrough curves of three-layer coarse, medium, and fine soil tests (CMF) are largely similar, and the time to reach a relative concentration of 50% is almost the same. For example, the dispersivity coefficients from the Brigham model for CMFv1c2, CMFv2c2, and CMFv3c2 tests at a travel distance of 20 cm are calculated as 0.015, 0.012, and 0.009 cm, respectively, and their difference is insignificant and shows that the apparent velocity of the flow does not affect the dispersivity.

As the results of Table (4) show, the dispersivity values in the travel distances from the ports in the horizontal direction, despite the fact that the size of the soil particles decreases, there is an increasing trend, which is due to the increase in the travel distance. In fact, the increase in the travel distance dominates the decrease in the particle size. The comparison of the dispersivity coefficients obtained from the sampling of the last 3 valves, all three of which have a travel distance of 80 cm, does not show a great difference in the dispersivity values.

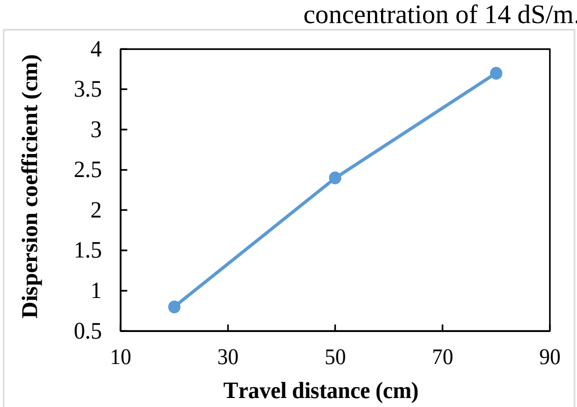
Plotting the dispersivity values against time shows that the dispersivity value increases with time. Among the studies that have mentioned this issue, we can mention the studies of Sudiki *et al*. (1983), Fiberg (1986) and Maroufpour et al. (2014). Figure (5) shows the linear relationships between the average soil dispersivity values and travel distances for CMFv1c2, CMFv2c2 and CMFv3c2 tests. As it can be seen, the coefficient of explanation is more than 0.9 in all three tests. These observations were also reported in Chavoshinejad's research (2009).



a. Experiment with three layers of coarse , medium, and fine soil at a velocity of 17.58 × 10-5 m/s and a concentration of 14 dS/m.



b. Experiment with three layers of coarse , medium and fine soil at a velocity of 22.02 × 10^{-5} and a concentration of 14 dS/m.



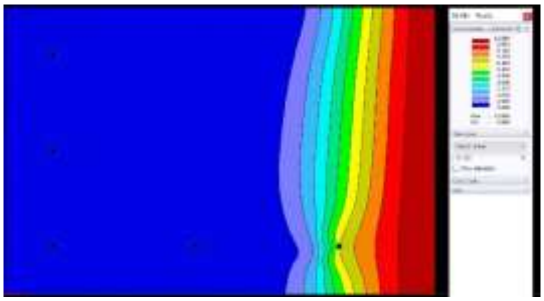
c. Testing with three layers of coarse, medium, and fine soil at velocity 26.18×10-5 m/s and the concentration is dS/m.

Figure 5. Relationship between average diffusion coefficients and travel distance.

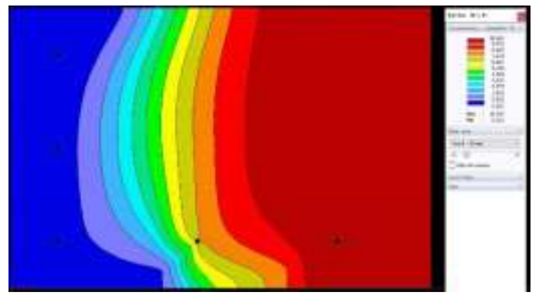
This result is consistent with the results of other researchers such as Ferasti and Sidian (2012) and Younes *et al*., (2020) who have reported an increase in diffusion coefficient values with increasing travel distance in heterogeneous soil.

3.2. Results of hydrous model

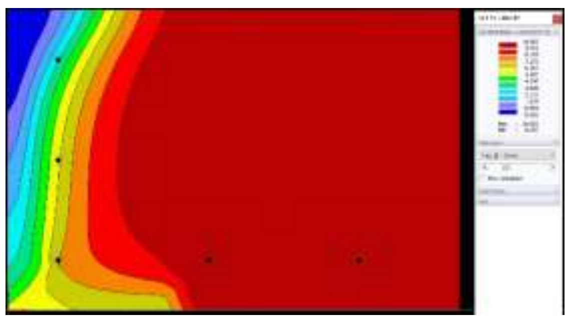
Figure 4 shows the results of sodium chloride simulation using Hydrus model. Also in Figure 5, the changes in the output concentration of sodium chloride against the length of the soil transfer distance in time steps 1, 6, and 15 show that the release rate of sodium chloride is higher in the transfer distance of 20 cm and its value decreases in longer distances. As it can be seen, in the travel distance of 20 cm, sodium chloride spread rapidly in the soil column, and with the increase in the travel distance, the diffusion speed of sodium chloride decreased.



a. Time step 1, the transfer distance of 20 cm to reach the final concentration



b. Time step 6, the transfer distance of 50 cm to reach the final concentration



c. Time step 15, the transfer distance of 80 cm to reach the final concentration

Figure 4. Simulation results of sodium chloride using Hydrus software.

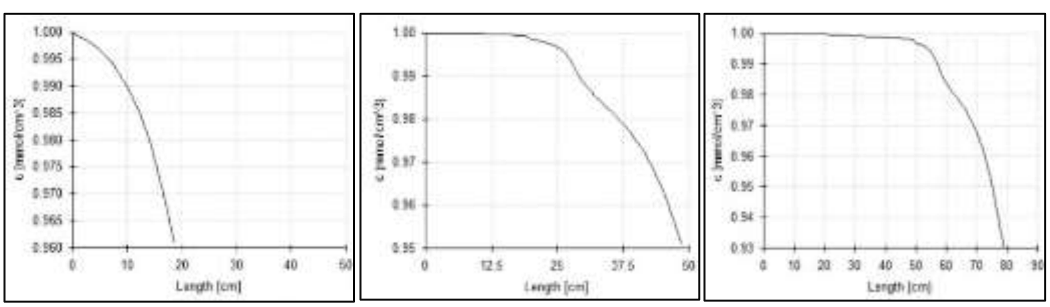
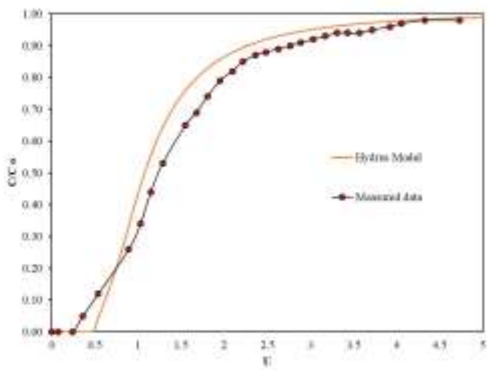
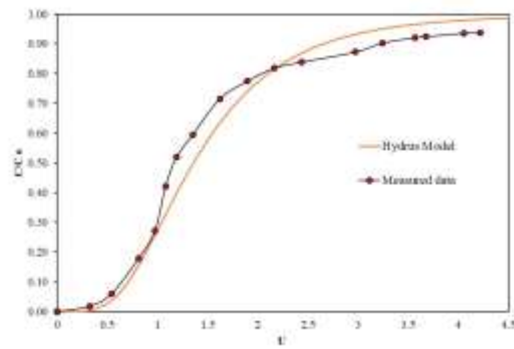


Figure 5. Changes in sodium chloride outlet concentration versus the length of the travel distance (from the right) of 20, 50, and 80 cm, respectively.

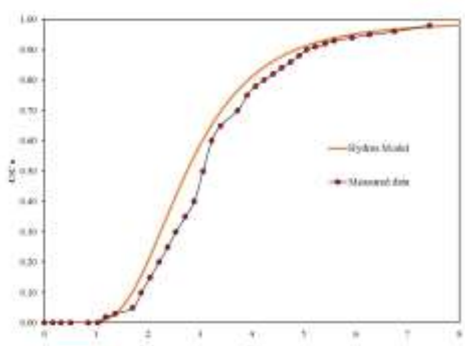
In Figure 6, the breakthrough curve obtained from sampling from the laboratory model is compared with the breakthrough curve obtained from the Hydrus model for travel distances of 20, 50, and 80 cm, and the root mean square error (RMSE) is calculated for each travel distance. The RMSE error rate between the model test and Hydrus simulation is equal to 0.064 for the 20 cm travel distance, 0.067 for the 50 cm travel distance, and 0.061 for the 80 cm travel distance, which shows the accurate prediction of the model. It is from the way of pollutant distribution in the porous medium. In order to compare the experimental results and the numerical model results for the three-layer porous medium, the curves of the volume of pore water used for each transfer distance can be seen in Figure (6). The amount of RMSE error between the physical model and Hydrus simulation for ports 1 to 5 is 0.065, 0.068, 0.061, 0.066, and 0.062, respectively. These results showed that the numerical model can predict the pollutant distribution in the porous medium well.



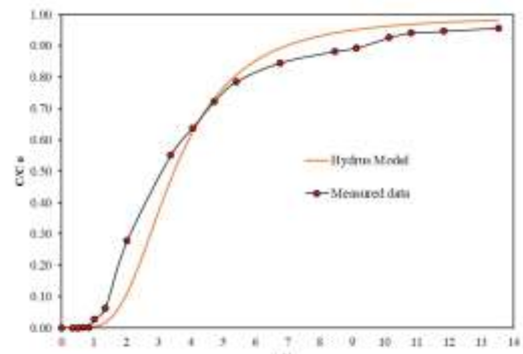
a. 20 cm travel distance (port 1)



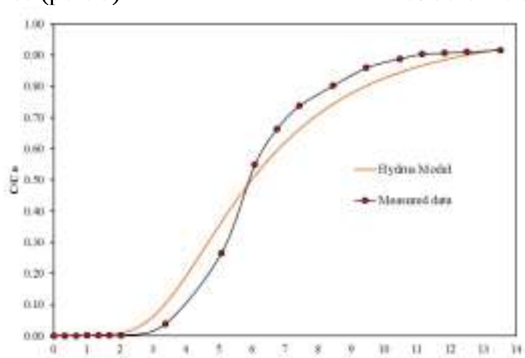
b. 50 cm travel distance (port 2)



c. 80 cm travel distance (port 3)



d. 80 cm travel distance (port 4)



d. 80 cm travel distance (port 5)

Figure 6. Simulation results of sodium chloride using Hydrus software.

4. Conclusion

Considering the importance of investigating the dispersion coefficient in heterogeneous soils and also the importance of the effect of travel distance, in this research work, it was investigated experimentally and numerically. For this purpose, a physical model was built in the form of a rectangular tank made of tempered glass and the experiments were performed in a layered porous medium including sand with three different grain sizes including fine, medium, and coarse grain at three transfer distances of 20, 50, and 80 cm. The emissivity coefficient obtained from the physical model using the Brigham model for the mentioned distances is 0.012, 0.015, and 0.009 cm, respectively. A comparison of the results obtained from the investigation of the effect of travel distance in this study with previous studies such as Maroufpour *et al*. (2014), Frosti and Sidian (2015), and Younes *et al*. (2020) shows that there is agreement between them. In this research, in all travel distances, before reaching the relative concentration of 0.5, the volume of pore water reached the value of one, and the speed of pollutant travel decreased with the increase of travel distance. Also, modeling was done using Hydrus software and comparison was made between the results of physical model and numerical modeling using RMSE error calculation. The RMSE error for travel distances of 20, 50, and 80 cm was obtained as 0.065, 0.068, and 0.061, respectively. These results showed that the numerical model can well predict the pollutant distribution in the porous medium.

Data Availability

The data used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgements

The authors of the manuscript gratefully acknowledge the reviewers for their positive feedbacks and their comments improved the paper.

References

Al-Tabbaa, A., Ayotamuno, J., and Martin, R., 2000. One-dimensional solute transport in stratified sands at short travel distances. *Journal of hazardous materials*, 73(1), pp. 1-15.

Ayotamuno, M.J., 1999. Contaminant transport and immobilisation in stratified sands, University of Birmingham.

Bazoobandi, A., Emamgholizadeh, S., and Ghorbani, H., 2022. Estimating the amount of cadmium and lead in the polluted soil using artificial intelligence models. *European Journal of Environmental and Civil Engineering*, 26(3), pp. 933-951.

Emamgholizadeh, S., Bahman, K., Bateni, S.M., Ghorbani, H., Marofpoor, I., and Nielson, J.R., 2017. Estimation of soil dispersivity using soft computing approaches. *Neural Computing and Applications*, 28, pp. 207-216.

Emamgholizadeh, S., Bahman, K., Ghorbani, H., Maroufpoor, E., and Ajdari, K., 2014. Estimating soil dispersivity coefficient by Artificial Neural Network. *International Journal of Soil Science*, 1(1), pp. 382-390.

Farasati, M., and Seyedian, S., 2013. Effect of Scale on NaCl Dispersivity by HYDRUS 2D. *Journal water and Soil*, 27(4), pp. 823-831.

Liu, Y., Liu, Y., Li, S., Zhang, Q., and Qian, J., 2023. Scale dependence of dispersion coefficient for solute transport in porous media using image analysis. *Journal of Hydrologic Engineering*, 28(6), pp. 04023016.

Maroufpour, A., Kashkuli , H., Moazd, H., and Mohammadouli Samani , H., 2014. Investigating the dependence of soil permeability on its thickness in saturated homogeneous sandy soils . . *Journal of Science of Shahid Chamran University*, 16(1), pp. 16-29.

Mehdipanah, H., Tashakkori, A., Emamgholizadeh, S., and Maroufpoor, E., 2022. Study of the Effect of Transport Distance on Dispersion Coefficient of Sodium Chloride in Horizontal Stratified Sandy Soils and its Simulation with HYDRUS-2D. *Irrigation and Water Engineering*, 13(2), pp. 297-311.

Ohadi, S., Hashemi Monfared, S.A., Azhdary Moghaddam, M., and Givehchi, M., 2023. Feasibility of a novel predictive model based on multilayer perceptron optimized with Harris hawk optimization for estimating of the longitudinal dispersion coefficient in rivers. *Neural Computing and Applications*, 35(9), pp. 7081-7105.

Parsaie, A., Emamgholizadeh, S., Azamathulla, H.M., and Haghiabi, A.H., 2018. ANFIS-based PCA to predict the longitudinal dispersion coefficient in rivers. *International Journal of Hydrology Science and Technology*, 8(4), pp. 410-424.

Samani, F., Tabatabaei, S., Abbasi, F., and Alaei, E., 2019. Hydraulic parameters sensitivity analysis of porous media at inverse solution of bromide transport. *Journal of Water and Soil Science*, 23(3).

Selim, H., Davidson, J., and Rao, P., 1977. Transport of reactive solutes through multilayered soils. *Soil Science Society of America Journal*, 41(1), pp. 3-10.

Shamir, U.Y., and Harleman, D.R., 1967. Dispersion in layered porous media. *Journal of the Hydraulics Division*, 93(5), pp. 237-260.

Shiran , H., Sayad, M., and Taghavi , H., 2018. Modeling of bromide movement in disturbed soil columns using HYDRUS- 1D model. *Watershed Researches (Research and Development)*, 24(3), pp. 21-30.

Tao, H. et al., 2022. Development of new computational machine learning models for longitudinal dispersion coefficient determination: Case study of natural streams, United States. *Environmental Science and Pollution Research*, 29(24), pp. 35841-35861.

Younes, A., Fahs, M., Ataie-Ashtiani, B., and Simmons, C.T., 2020. Effect of distance-dependent dispersivity on density-driven flow in porous media. *Journal of Hydrology*, 589, pp. 125204.