An experimental study on the determination of dispersion coefficient in layered soils

Hamed Mahdipanah, Askari Tashakori, Samad Emamgholizadeh, and Eisa Maroufpoor

ABSTRACT

Dispersivity is a measurable parameter in soil porous media that is used for studying the transport of contaminants to groundwater. The value of this parameter depends on various factors, including the kind of porous media (homogeneous or heterogeneous), flow velocity, initial contaminant concentration, travel distance, and sampling method. A physical model with dimensions of 0.10 m in width, 0.80 m in height, and 1.10 m in length was constructed to investigate the effects of these parameters on the dispersivity value. The stratified soil consisted of three 20-cm-thick layers containing fine-grained, medium-grained, and coarse-grained soil. Sodium chloride solutions with electrical conductivity values of 10, 14, and 19 dS/m were used as the contaminants. Flow was forced through the layered heterogeneous soils at three discharge velocities of 17.58, 22.02, and 26.18 m/s. The point and mixed sampling methods were used. The results indicated that the soil dispersivity values in the layered heterogeneous soils and homogeneous soil were influenced by contaminant concentration, flow velocity, and travel distance. Moreover, the dispersivity values obtained by point sampling were lower than those obtained using the mixed sampling method, and the mean dispersivity value in the layered heterogeneous soils was lower than that of the homogeneous soil.

Key words: contaminant transport, groundwater quality and contamination, heterogeneous soil, leaching, porous media, soil-water quality

INTRODUCTION

Irreparable damage to groundwater resources has occurred in recent years due to factors such as the over-extraction of groundwater due to rapid population growth (Zektser et al. 2005; Emamgholizadeh et al. 2014). Moreover, the infiltration of contaminants resulting from agricultural and industrial activities, and leaching of agrochemicals to groundwater has reduced the quality of the existing water resources (Zhang et al. 2006; Bear & Cheng 2010).

Consequently, the protection of groundwater resources must be considered when planning the water resources of a country. Achieving this objective requires the identification of contaminant sources and the determination of equations governing contaminant transport. Also, knowing the dispersion of leachate to the surface water or groundwater can help in its proper management (Fandiño et al. 2020). Contaminants in porous media move by bulk transport, molecular diffusion, and hydrodynamic dispersion mechanisms. In the past, dispersivity values for all porous media were usually thought to be constant. However, many studies during the past three decades have shown that it is not always possible to consider a fixed value for dispersivity and that it is also dependent on various factors such as soil texture, travel distance, flow velocity, thickness of the layer and saturated or unsaturated soil (Kumahor et al. 2015; Karadimitriou et al. 2016; Zhuang et al. 2021).

Al-Tabbaa et al. (2000) were done experimental study on the horizontal flume with length, width, and height of 0.45 m, 0.38 m, and 0.25 m, respectively. They used saturated homogeneous sandy fine-grained, medium-grained, and coarse-grained soils under one-dimensional flow conditions. Results showed that that the average contaminant (sodium-chloride) velocity in short travel distances was higher than the average pore water velocity. This difference between the two velocities is one of the
factors influencing dispersivity in the porous media. In addition, considering the differences in infiltrability of soils with different gradation, they determined dispersivity of all three types of sand separately for the layer thickness of 0.18 m under one-dimensional flow conditions. The dispersivity values of coarse-grained, medium-grained and fine-grained sand were 0.0767 m, 0.063 m and 0.0427 m, respectively. They also carried out an experiment on homogeneous medium-grained sand with the three thicknesses of 0.08, 0.18 and 0.25 m and concluded that dispersivity behavior was also controlled by soil gradation and thickness. Scale effects are another parameter influencing the differences in dispersivity values obtained in laboratory and field studies. Considering the importance of this point, many researchers, including Thomas & Cleall (2001), Benamar et al. (2007), Estabragh et al. (2014), Emamgholizadeh et al. (2017), Muller & Ramsburg (2018), Bharati et al. (2019), Mahmoodlu et al. (2020), and Yang et al. (2021) have studied dispersivity values in soils.

Shamir & Harleman (1967) were one of the first researchers who studied solute transport in porous media. They performed their experiments using alternating layers of sand that had various particle sizes, and a mean thickness of 0.30 m. The porous media was a horizontal soil column with 3 m length, and the sodium chloride tracer was guided parallel to the soil layers inside the porous media. The dispersivity values obtained in the two experiments were in the 0.0007–0.0044 m range.

Based on experimental study, Van de Pol et al. (1977), and De Smedt & Wierenga (1978) believed that in multilayered soils, the mean volumetric water content of each layer, and the calculated dispersivity value could be used to show the concentration distribution of the contaminant. They obtained an approximate analytical solution for the advection-dispersion equation to be used for nonreactive salts, and the steady flow inside soils with nonuniform moisture distribution.

Sudicky & Cherry (1979) used point samples in their field studies and compared the results with dispersivity coefficients obtained in laboratory and field studies employing mixed samples. The results of their field studies using point samples were the same as those of laboratory studies, but they were substantially lower than the dispersivity values mentioned in reports on field studies using mixed samples.

In addition, Pickens and Grisak (1981) investigated the results of many studies based on laboratory studies, field studies, and numerical modelling. The dispersivity values reported in the studies based on numerical modelling ranged from 12 to 61 m; larger values were obtained with increases in the size of the study area.

However, considering breakthrough curves (BTCs) (curves of concentration versus time) in laboratory experiments on undisturbed samples, the dispersivity values ranged from 0.0001 to 0.01 m, and the values obtained from the analysis of the various types of field experiments using different tracers ranged from 0.012 to 15.2 m. In addition, the researchers reported that in most studies and tracer experiments, mixed methods sampling was employed. Samples were taken from observational wells in experiments on groundwater monitoring.

In the study of dispersion coefficients, the sampling method can be an influential factor. Two methods of sampling, namely point sampling and mixed sampling were used. In the point sampling method, samples were taken from specific points in the body of a well; but in the mixed sampling method, samples were taken from the solution inside the wells.

The reason for this is that in point sampling, the pollutant passes through different paths of soil layers, meaning that this type of sampling reflects the real soil conditions; therefore, using this sampling technique provides more accurate values for the dispersion coefficient (Sudicky & Cherry 1979; Pickens & Grisak 1981a). Pickens and Grisak (1981) believed that larger dispersivity values were obtained in field research compared to laboratory studies because they used different sampling methods.

The longitudinal dispersivity values in the field experiments that Pickens & Grisak (1981b) conducted were in the 0.002–0.035 m range (0.007 m on average) for all the 29 samples. They injected iodine tracer into the natural horizontal layers of a sandy aquifer (with a thickness of 8.2 m), the upper, and lower boundaries of which were silty clay. The estimated hydraulic conductivity of the sandy aquifer (with the mean particle size of 0.12–0.21 mm, and porosity of 0.38) was in the $2 \times 10^{-2} \cdot 2 \times 10^{-3}$ cm/s range. They did not observe any evidence showing dispersivity was dependent on the travel distance inside the aquifer layers (dispersivity was independent of travel distance). The dispersivity values obtained from the analysis of point sample data indicated that all the layers had a relatively identical dispersivity value.

Table 1 lists the dispersivity values in a number of experiments conducted on heterogeneous soils. Parker & Albrecht (1987) obtained reduced field-scale values of dispersivity for multilayered soils. In their studies, three undisturbed soil samples with different sizes were taken from the field, sorted, and washed, placed in separate pressure cells, and wetted from the bottom for 1 to 2 days to minimize the air entrapped in them. Each sample had soil with a composite multilayered texture consisting of alternating loam (0.20 m thick), and clay (0.70 m thick). Experiment was performed using bromide as a tracer on saturated samples to determine dispersivity values for the salts. These values were in the 0.87–0.97 m range.

| Layer Type   | Thickness (m) | Dispersivity (m) |
|--------------|---------------|------------------|
| Loam         | 0.20          | 0.87–0.97        |
| Clay         | 0.70          |                  |
| Total        |               |                  |
They concluded that field-scale dispersivity values gradually decreased with decreasing depth due to macroscopic velocity changes, especially in systems where soil layers were perpendicular to the mean flow direction.

In general, dispersivity followed a log-normal distribution overtime. Using small columns, alternating layers of loam soil, and sandy soil, Selim et al. (1977) concluded that the order of the layers had no effect on the shape or the concentration distribution of the outgoing fluid. They also noticed that the profile of the multilayered soil column could be considered to be homogeneous, and the concentration distribution of the outgoing fluid calculated using the mean residence time for situations where linear adsorption equilibrium occurred. They also found that under unsaturated conditions together with a steady flow the concentration distribution of the reactive and nonreactive salts at a given site in the soil profile could be predicted by using the mean soil moisture.

Ahmadi & Bertin (2020) used a medium with two types of porosity (a heterogeneous model), investigated the various conditions in contaminant transport and compared the process of performing the experiments with the simulated models having the same type of porosity in previous studies. They reported that dispersivity was strongly influenced by the saturation conditions when the porous media was saturated with air and water. Various studies have been done for the movement of salts inside homogeneous, and heterogeneous soils, but relatively few studies have been conducted on the effects of heterogeneous multilayered soils on the transport of salts (Selim et al. 1977; Gillham & Cherry 1982; Porro et al. 1993; Costa et al. 1994).

Younes et al. (2020), also, studied the effect of travel distance on dispersivity values in porous media. They stated that the differences in travel distance were mainly controlled by transverse diffusion, whereas concentration distribution was sensitive to longitudinal diffusion and transverse dispersion length, with the latter being the most important parameter controlling the amount of salt infiltration into the aquifer.

A literature review shows that many studies have been done on contamination in homogeneous soil. The characteristics of soil at the field scale vary depending on the point and depth, and one does not expect to find homogeneous soil in real conditions due to the sedimentation process in the aquifers. Therefore, considering homogeneous soils is ideal for pure studies. In other words, field soils are inherently heterogeneous and show significant variability in hydraulic properties even within a particular soil type (Warrick & Nielsen 1980). Thus, it affects the flow and transport phenomena (Soraganvi et al. 2020).

With respect to this issue, in this study the process of contaminant transfer in heterogeneous and layered soils were considered. With this purpose, in the present study, we attempted to study the effects of velocities and concentrations on breakthrough curves and dispersivity coefficients. Also, the effects of travel distance and sampling method were also investigated and the dispersivity coefficients of a heterogeneous and layered soil were compared with those of homogeneous soil.

### MATERIALS AND METHODS

A laboratory physical model was built consisting of a rectangular shaped tank made of safety glass with a length, width, and height of 1.10, 0.10, and 0.80 m, respectively (Figure 1).
The rectangular tank had three parts: the inlet, the porous media, and the outlet. These parts were separated by perforated sheets to make the flow one-dimensional, ensuring that the contaminant passed through the entire column length horizontally. The perforated sheets were covered with fine cotton fabric to prevent fine particles from passing through and pores from clogging. A constant flow velocity was created throughout the tank by attaching the water and contaminant sources separately to a regulator with a constant hydraulic height (which could be adjusted for each experiment), and the flow entered the tank inlet after passing through the regulator. Moreover, the flow exceeding the constant flow needed for the experiment spilt over from inside the regulator. At a distance of 0.10 m from the bottom of the tank, sampling valves were installed horizontally to take point samples. The horizontal distance from the first valve from the inlet was 0.20 m. The second and third valves were 0.50 and 0.80 m away from the inlet, respectively. In addition, perforated polyethylene pipes protected by stainless steel 100 wire mesh were placed as samplers along the width of the simulated aquifer. In the mixed methods sampling process, samples were taken at the model outlet at different times.

Sodium chloride or bromide was used in most similar research. Therefore, sodium chloride was also selected as the contaminant in the present study as it was safe, and available. Sea salt-free from any sediment was the source of the sodium chloride, and its type did not change during the experiments.

The concentration of landfill leachate in real conditions is about 9 g/l (with an Electricity Conductivity (EC) of 14 dS/m) (Ayotamuno 1999; Kanzari et al. 2018). It has also been observed that salinity in some groundwater has reached 19 dS/m (Narjary et al. 2019). Therefore, in this study, sodium chloride solutions with EC values of 10, 14, and 19 dS/m were used in all experiments.

Moreover, experiments were done using three discharge flow velocities of 17.58, 22.02, and $26.18 \times 10^{-5}$ m/s, respectively. Approximate values of these three velocities have also been used by other researchers such as Pickens & Grisak (1981a), and Al-Tabbaa et al. (2000). We used three sizes of sand (fine, medium, coarse) in the experiments. To obtain these, sands were washed, dried, and then filtered using standard sieves. The remaining sand between two consecutive sieves were used. Table 2 indicates the sand particle size range used in this study.

To simulate an aquifer experiments were carried out using two kinds of soils: (i) stratified or layered heterogeneous soil (with three layers) and (ii) homogeneous soils. For layered heterogeneous soil, three gradings of sand, including coarse
sand (2.36–2.8 mm), medium sand (2–2.36 mm), and fine sand (1–1.18 mm), were used. The coarse, medium, and fine sands were placed from the bottom to the top, respectively, and the thickness of each layer was 0.20 m. Each soil layer was homogeneous (Figure 2). For the second series of experiments, only coarse-grained homogeneous soil was used. In other words, the model was uniformly filled with coarse-grained sand with a thickness of 0.60 m.

In all experiments, sampling was done using two methods: point and mixed sampling. Point sampling was taken using five valves located at horizontal distances of 0.20, 0.50 and 0.80 m (Port 1, Port 2, and Port 3) and vertical distances of 0.10, 0.30, and 0.50 m (Port 3, Port 4, and Port 5). The mixed samples were taken from the solution inside the output part (see Figures 1 and 2). Samples were also taken from these ports and outlet sections at different time intervals from the beginning to the end of the experiment to investigate the changes of concentration of contaminant versus time.

In this study, we used perforated pipes with a diameter of 6 mm (spaghetti pipe). The perforated tube connected to the outlet port valves was very small, meaning it had minimal impact on the flow distribution in the model. Because the size of the perforated tube is so small, the volume of the solution inside it is much smaller than the sample size of the container (about 20 ml). Therefore, it could not have a significant effect on the results. In addition, before taking each sample, 4 ml (slightly more than the volume of the tube), it was removed from the outlet to minimize its effect.

Also, the experiments were performed at three flow velocities and the mentioned three concentrations. Making tangible differences in the hydraulic conductivity (K) and the other geohydrological characteristics of the simulated aquifers were the reasons for selecting sand with various particle sizes. The following assumptions were formulated for contaminant transport in the simulated aquifer: (1) the direction of the fluid flow was horizontal, (2) the sand porosity was constant, and, (3) the porous media in each layer was homogeneous, and saturated. To prepare the tank, water was poured into a height, a little higher than the intended height. At this time, the inlet, and outlet were closed. The dried sand was then gradually added

| Specifications of experiments | Coarse | Medium | Fine | C (dS/m) | V x 10^(-5) (m/s) |
|-------------------------------|--------|--------|------|----------|------------------|
| n %                           | Coarse | Medium | Fine | C1       | C2               | C3               | V1   | V2   | V3   |
| 40                            | 40     | 39     |      | 2.36–2.8 | 2–2.36          | 1–1.18           | 10   | 14   | 19   |
| 10                            | 14     | 19     |      | 10       | 14               | 19               | 17.58| 22.02| 26.18|

Figure 2 | The general schematic of the model, and the simulated aquifer.
from the top of the tank to reach the height considered for the experiment. After pouring a given volume of the sand in, it was gently compacted using a geomembrane piece attached to a wooden handle to obtain the maximum natural density. Before performing each experiment, some pure water was poured into the model (with a height of about 8 cm) and then sand was added to the model with height of 5 cm. The pure water was non-polluting drinking water with a concentration less than 0.50 dS/m. To remove the air bubbles trapped inside the sand, the sand was compacted by a piece of wood with a square cross section (0.06 m $\times$ 0.06 m). This process continued until the thickness of the first layer reached to height of 20 cm. Then the same procedure was done for the next two layers. The flow velocity of interest passing through the column was established by adjusting the outlet height. At the start of the experiment, samples simultaneously were taken from the ports which located at the distance of 0.20, 0.50, and 0.80 m from the beginning of the porous soil media (from right to left) to measure the concentration. Due to the fact that it takes time the contaminant flow reaches to the beginning of the model, some contaminant with the desired concentration was added in the inlet part of the model to reduce the delay time (see Figure 1) and the solution was stirred with a mixer.

The first sampling was performed at $t = 0$ and then at interval time of approximately 2–20 minutes, the concentration of the discharged solution from the ports were measured. The experiments were continued until the concentration of the samples reached the final concentration (10, 14, or 19 dS/m) ($C/C_0 = 1$).

At the end of each experiment, to start the next one, it was necessary to wash the soil out of tank. For this purpose, pure water with low electrical conductivity ran through the tank to flush out the previous higher electrical conductivity water. To do this process, firstly the valve of the pollutant tank (Valve 1) was closed and then the valve of the water tank (Valve 2) was opened, and finally the valve 3 was opened to discharge water of the model through the drain pipe (See Figure 1). The electrical conductivity of the samples was measured by an EC meter device.

**Fried-Cambernous Model**

Many models have been introduced for solute transport processes in aquifers. Since the advection-dispersion equation (ADE) of contaminant transport in soil involves the mechanisms of mass transfer, molecular diffusion, and hydrodynamic dispersion – and considering the effects of these three processes on the movement of contaminants – the one-dimensional advection-dispersion equation for stable solutions in homogeneous saturated porous media with the steady-state flow is given by Equation (1). The ADE is one of the most common equations for describing solute transport in porous media (Bear 1972):

\[
\frac{\partial C}{\partial t} = -v_f \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} \quad (1)
\]

Here, $D$ is the hydrodynamic dispersion coefficient ($M^2 L^{-1}$), $C$ is the contaminant concentration ($ML^{-3}$), $x$ is the travel distance ($L$), and $v_f$ is the pore-water velocity ($LT^{-1}$).

The hydrodynamic dispersion coefficient ($D$) is a criterion for describing the process of solute transport in porous media (Shi et al. 2016) and it is expressed by the two following parameters:

\[
D = \alpha v_f + D^* \quad (2)
\]

Here, $\alpha$ is the dispersivity value of the porous media ($L$), and $D^*$ is the molecular diffusion coefficient of the solution in the porous media ($L^2 T^{-1}$).

This solute transport equation is a nonlinear partial differential equation with temporal ($t$), and spatial ($L$) variables. This type of equation has many solutions, and the initial and boundary conditions of the system must be defined to obtain a single solution. The initial and boundary conditions can mathematically be expressed as follows:

$C(L, t) = 0 \quad$ for $\quad t = 0 \quad$ and $\quad L \geq 0$

$C(L, t) = C_0 \quad$ for $\quad L = 0 \quad$ and $\quad t \geq 0$

$C(L, t) = 0 \quad$ for $\quad L = \infty \quad$ and $\quad t \geq 0$
Taking these conditions into account, Equation (1) for homogeneous saturated porous media will be as follows:

\[
\frac{C}{C_0} = \frac{1}{2} \left[ \text{erfc} \left( \frac{L - vt}{2\sqrt{D}t} \right) + \exp \left( \frac{\nu L}{D} \right) \text{erfc} \left( \frac{L + vt}{2\sqrt{D}t} \right) \right]
\]

Here, \(\text{erfc}\) is the complementary error function, which is defined as:

\[
\text{erfc}(x) = 1 - \text{erf}(x)
\]

Here, \(\text{erf}(x)\) is the error function, \(L\) is the travel distance along the length of the water flow \((L)\), and \(\nu\) is the average linear flow velocity in soil pores \((LT^{-1})\).

If the dispersivity value of the porous media is high or the values of \(L\), and \(t\) variables are large, the value of the second term on the right side of the equation will become negligible. Therefore, we will have:

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{L - vt}{2\sqrt{D}t} \right)
\]

The breakthrough curve (BTC) is obtained by plotting the \(C/C_0\) ratio against time \(t\). Equation (4) is also used to calculate the shape of the breakthrough curves. In the present research, the dispersion parameters were studied by measuring the concentrations of the contaminant passing through the soil column using point, and mixed methods sampling at different transport intervals, and finally by plotting the breakthrough curves. Using the values of the hydrodynamic dispersion coefficient obtained from the Fried-Cambernous model, dispersivity was evaluated.

Hydrodynamic dispersion coefficient is calculated using the Fried and Cambernous model (1971) as follows:

\[
D = \frac{1}{8} \left[ \frac{L - \nu_c t_{0.16}}{\sqrt{t_{0.16}}} - \frac{L - \nu_c t_{0.84}}{\sqrt{t_{0.84}}} \right]^2
\]

Here, \(\nu_c\) is the mean contaminant velocity and it calculated using \(L/t_{0.5}\), in which \(L\) is the length of the soil column, and \(t_{0.5}\), \(t_{0.16}\) and \(t_{0.84}\) are the times of reaching the relative concentrations to 0.5, 0.16, and 0.84.

In this study, like the studies of other researchers, including Ayotamuno (1999), Moazed et al. (2009), Moazed et al. (2012); Pour & Kamanbedast (2011) the Fried-Cambernous model was used to calculate the dispersion coefficient. To use this model, firstly breakthrough curve (BTC) fitted on sample data which taken at different distances or depths, and then the time to reach relative concentrations of 0.16, 0.5 and 0.84 \((t_{0.16}, t_{0.5}, t_{0.84})\) extracted from it and the hydrodynamic dispersion coefficient was calculated using Equation (6). Finally, the diffusion coefficient \((\alpha)\) was obtained from Equation (2).

As in the present study, the Peclet number \((V_f d_{50}/D)\) were found to be greater than 100, and therefore mechanical dispersion was far more dominant than molecular diffusion \((D')\) and it can be ignored of \(D'\) (Bear 1972; Al-Tabbaa et al. 2000). So \(D\) is simplified to:

\[
D = \alpha V_f
\]

In previous research, porous media or aquifers were usually simulated using soils with uniform gradation, contaminants with constant concentration, and flow velocity. Also, point sampling was done along the length or width of the model. Very few studies have investigated the effect of soil heterogeneity on soil dispersivity. Consequently, the present research attempted to determine the effects that each of these parameters had on breakthrough curves, and dispersivity values by considering different flow velocities, and concentrations, and simulating the porous media or aquifers in the layered form, and using mixed methods sampling.
RESULTS AND DISCUSSION

Effects of flow velocity on the breakthrough curve and dispersion coefficient in layered heterogeneous soils

Experiments were conducted at three flow velocities ($V_1 = 17.58 \times 10^{-5}$ m/s, $V_2 = 22.02 \times 10^{-5}$ m/s, and $V_3 = 26.18 \times 10^{-5}$ m/s) to investigate how flow velocity affected the dispersivity value of the layered homogeneous soil. Samples were taken at the horizontal distances of 0.20, 0.50 and 0.80 m (Port 1, Port 2, and Port 3) and vertical distances of 0.10, 0.30, and 0.50 m (Port 3, Port 4, and Port 5) (see Figure 2).

Figure 3 presents the BTCs with the typical ‘S’ shape related to point sampling at three horizontal distances of 0.20, 0.50 and 0.80 m, and concentration of 10 dS/m. Obviously, as the flow velocity increases from $V_1$ to $V_2$ and then to $V_3$, the time required for the contaminant solution to travel from the inlet part to Ports 1, 2, and 3 decreases while the time interval from the start of the experiment to the ascending curve decreases. Also, as can be seen in this figure, the concentration has reached the final value ($C/C_0 = 1$) at different times. For example, in Figure 3(a), when experiment was done with $V_1$, 40 min after the experiment started the concentrations of the samples reached the final value. But for two flow velocities of $V_2$ and $V_3$, the samples reached their final concentration earlier in about 30, and 25 min. For travel distance of 20 cm, when experiments were done with concentration of 10 dS/m ($C_1 = 10$ dS/m), the dispersion coefficient for $V_1$, $V_2$ and $V_3$, were achieved 0.009, 0.013, and 0.05 m, respectively (see Table 3).

The breakthrough curves for Port 2, Port 3, Port 4, and Port 5 are shown in Figure 3(b)–3(e) for the three velocities of $V_1$, $V_2$ and $V_3$. As shown in this figure, the changes in relative concentration over time were as the same as the horizontal travel distance of 0.20 m (Port 1). But at the horizontal travel distance of 0.50 m, it took 6 minutes to observe changes in concentration at this distance, while at the horizontal travel distance of 0.20 m this time was 2 minutes. In addition, the time to reach a concentration of 50% at the horizontal travel distance of 0.50 m was about 10% longer than the travel distance of 0.20 m. In addition, the required time at the horizontal travel distance of 0.50 m was 45 minutes, which indicates that the relative concentration reaches its final value later. Also, the results of Figure 3(b) show that when the velocity increases from $V_1$ to $V_2$ and then $V_3$, the time to reach the final concentration decreases. Furthermore, all five curves followed their trends at shorter time intervals with a steep slope to reach their peak points (the relative concentration of 0.8–1) and then followed their trends with a low positive slope until the end of sampling. In other words, the concentrations of the samples increased for a short time, but then the travel took place at a longer time interval, and with a gently increasing trend in relative concentration to reach the final concentration.

Table 3 also shows the dispersion coefficient ($D$) values calculated using the Fried and Combarnous (1971) model (Equation (6)) for all tested experiments. For example, at concentration of 10 dS/m, the dispersion coefficients for horizontal travel distance of 0.20 m (Port 1) were achieved 0.009, 0.013, 0.03 m for three flow velocities of $V_1$, $V_2$, and $V_3$, respectively. Also, for horizontal travel distance of 0.50 m (Port 2), the dispersion coefficients were achieved 0.03, 0.048, and 0.061 m, respectively. Similarly, the $D$ values for Port 4 was 0.015, 0.009, and 0.02 m, and 0.005, 0.004, 0.003 m for three velocities of ports of $V_1$, $V_2$, and $V_3$, respectively.

In general, it can be concluded that in layered homogeneous soils, velocities can reduce the transfer time of contaminants, and as consequently it increased the dispersion coefficient. This finding is consistent with the studies of other researchers such as Perkins & Johnston (1963); Brigham (1974); Fattah & Hoopes (1985); Brusseau (1993), Ayotamuno (1999).

Effects of concentration on BTC and dispersivity values coefficient in layered heterogeneous soils

Experiments at three concentrations ($C_1 = 10$, $C_2 = 14$, and $C_3 = 19$ dS/m) were carried out to determine the effects of changes in concentration. Figure 4 shows the BTCs of the experiments at these concentrations at a flow velocity of $V_1 = 17.58 \times 10^{-5}$ m/s for five ports. As shown in this figure, there is a similarity in the trends of changes in the BTCs and there is a relatively slight difference between these curves. A comparison of the three curves in Figure 4(a) indicates that with decreases in the contaminant concentrations from 14 and 19 to 10 dS/m, the time to reach the final concentration increased by about 5 and 10 min, respectively. In other words, the results indicate that there was an inverse relationship between contaminant concentration, and the time required for reaching the final concentration. Figure 4(b) and 4(c) show the BTCs for the horizontal distances of 0.50 and 0.80 m. As shown in these figures, the trend of increasing relative concentration over time is similar to the trend depicted by the curves in Figure 4(a). Also, as the results of Figure 4(b) and 4(c) indicated that, as travel distance increases, the time to reach the final concentration ($C/C_0 = 1$) also increases. Also, as the horizontal travel distance increases, the time to reach the concentration of 50% increases, which indicates its effect on the dispersion coefficient.
As shown in Figure 4(a)–4(c), when concentration increased from \( C_1 = 10 \) to \( C_2 = 14 \), and then \( C_3 = 19 \) dS/m, the breakthrough curves (BTCs) moved slowly from left to right. Consequently, this displacement of the BTCs has an effect on the time of concentration to 16, 50, and 80% \((t_{0.16}, t_{0.5}, t_{0.84})\), and finally it has effect on the dispersion coefficients.

Figure 3 | The BTCs at concentration of 10 dS/m. (a) Travel distance of \( x = 20 \) cm, \( y = 10 \) cm (Port 1). (b) Travel distance of \( x = 50 \) cm, \( y = 10 \) cm (Port 2). (c) Travel distance of \( x = 80 \) cm, \( y = 10 \) cm (Port 3). (d) Travel distance of \( x = 80 \) cm, \( y = 30 \) cm (Port 4). (e) Travel distance of \( x = 80 \) cm, \( y = 50 \) cm (Port 5).

As shown in Figure 4(a)–4(c), when concentration increased from \( C_1 = 10 \) to \( C_2 = 14 \), and then \( C_3 = 19 \) dS/m, the breakthrough curves (BTCs) moved slowly from left to right. Consequently, this displacement of the BTCs has an effect on the time of concentration to 16, 50, and 80% \((t_{0.16}, t_{0.5}, t_{0.84})\), and finally it has effect on the dispersion coefficients.
Consequently, mixed methods sampling is one of the effective factors in obtaining large values for dispersivity. Studies by other researchers such as Moazed (2009) showed that point and mixed methods sampling in layered heterogeneous soils compared to point sampling method. This result is consistent with the results of other researchers such as Khan & Jury (1990), Zhang et al. (2014), and Younes et al. (2020) which showed that dispersivity increase with the distance from the source due to its scale dependency.

Effects of point and mixed methods sampling on dispersivity value in the layered heterogeneous soils

Studies by other researchers such as Moazed et al. (2009) showed that point and mixed methods sampling influenced dispersivity values. Therefore, both methods were used for sampling in the present research.

Table 3 lists the dispersivity values calculated by employing the Fried-Cambernous model using point and mixed methods sampling for all the tested velocities. The results obtained from Ports 3, 4 and 5 were compared with the mixed sample collected from solution inside the outlet section; this was done to compare the point and mixed methods sampling techniques. Based on the results of this table, when point and mixed sampling methods were used, the average values obtained for dispersivity were 0.045 cm and 0.162 cm which show that using mixed sampling method give larger dispersivity value (3.6 times) compared to point sampling method. This result is consistent with the results of other researchers such as Moazed et al. (2009). Consequently, mixed methods sampling is one of the effective factors in obtaining large values for dispersivity.

Comparison of the calculated dispersion coefficient for the three ports 3, 4 and 5 show that the value of the dispersion coefficient (α = 2.9 cm) in the first layer (port 3) was greater than ports 4 and 5 with α = 1.5 cm and α = 0.5 cm. The main reason for the larger dispersion coefficient of the first layer (Port 1) compared to the upper layers (Ports 2 and 3) is that they are located in soil with smaller particle size.

Overall, for point sampling method, for three travel distances of 0.20, 0.50, and 0.80 m (Ports 2, 3 and 3) the values of dispersivity for concentration of 10, 14 and 19 dS/m were determined 0.0229, 0.0412, and 0.0538 m, respectively. Also, for Ports 4, and 5 the values of dispersivity for concentration were achieved 0.0238 and 0.0059 m, respectively.

### Table 3 | The calculated values of dispersion coefficient (m) using Fried-Cambernous model in layered heterogeneous soils using point and mixed methods sampling

| Velocity | Concentration |
|----------|---------------|
| **Distance** | **C1** | **C2** | **C3** | **C1** | **C2** | **C3** | **C1** | **C2** | **C3** |
| Port 1 (x = 0.2 m, y = 0.1 m) | 0.0090 | 0.0150 | 0.0400 | 0.0130 | 0.0180 | 0.0110 | 0.0300 | 0.0320 | 0.0380 |
| Port 2 (x = 0.5 m, y = 0.1 m) | 0.0200 | 0.0285 | 0.0680 | 0.0480 | 0.0300 | 0.0255 | 0.0610 | 0.0440 | 0.0455 |
| Port 3 (x = 0.8 m, y = 0.1 m) | 0.0290 | 0.0374 | 0.0743 | 0.0610 | 0.0380 | 0.0453 | 0.0878 | 0.0601 | 0.0540 |
| Port 4 (x = 0.8 m, y = 0.3 m) | 0.0150 | 0.0300 | 0.0400 | 0.0090 | 0.0300 | 0.0100 | 0.0200 | 0.0500 | 0.0100 |
| Port 5 (x = 0.8 m, y = 0.5 m) | 0.0050 | 0.0030 | 0.0130 | 0.0040 | 0.0050 | 0.0090 | 0.0030 | 0.0100 | 0.0010 |
| Mix sample (outlet section) | 0.0602 | 0.0756 | 0.0775 | 0.0461 | 0.0358 | 0.0337 | 0.0457 | 0.0557 | 0.0433 |

### Effects of travel distance on the BTCs, and dispersivity values in the layered heterogeneous soils

The changes in relative concentration with time at the longitudinal travel distances of 0.20, 0.50, and 0.80 m were studied to investigate the effects of travel distance on dispersivity values. Figure 5 displays the breakthrough curves (BTCs) obtained from point sampling at three concentrations of 10, 14 and 19 dS/m, and flow velocity of $V_1 = 17.58 \times 10^{-5}$ m/s. As the three breakthrough curves (BTCs) for three distances of 0.20, 0.50 and 0.80 m shows the trend of BTCs changes were similar to each other, but the time to reach the final relative concentration of $C/C_0 = 1$ were different. Comparison of these curves also shows that the longitudinal travel distance has affected on this curves so that at a travel distance of 0.20 m the breakthrough curves reached earlier to the relative concentration of $C/C_0 = 84\%$ compared to the travel distances of 0.50 and 0.80 m. Based on the BTCs, the dispersion coefficient values have been calculated for each of the experiments which performed with three velocities $V_1 = 17.58 \times 10^{-5}$, $V_2 = 22.02 \times 10^{-5}$, and $V_3 = 26.18 \times 10^{-5}$ m/s as well as three concentrations of $C_1 = 10$, $C_2 = 14$, and $C_3 = 19$ dS/m (Table 3). Comparison of the calculated values of dispersion coefficients in this table for different distances shows that its value increases with increasing distance. On average, for layered heterogonous soil, the amount of dispersion coefficient at the horizontal travel distance of 0.20, 0.50 and 0.80 m was 0.0229, 0.0412, and 0.0538 cm, respectively. In other words, increasing the horizontal travel distance significantly increased the dispersion coefficient (see Figure 6).

These findings are consistent with the results of other researchers such as Khan & Jury (1990), Zhang et al. (1994), and Younes et al. (2020) which showed that dispersivity increase with the distance from the source due to its scale dependency.
Since this experiment was performed in the laboratory, and large values for dispersivity were found in the field studies conducted by Van de Pol et al. (1977), and Butters & Jury (1989), it is predicted that in field studies the values obtained for dispersivity using mixed methods sampling will be much larger than the mean values for point sampling.

**Figure 4** | The BTCs for the flow velocity of $17.58 \times 10^{-3}$ m/s. (a) Travel distance of $x = 20$ cm, $y = 10$ cm (Port 1). (b) Travel distance of $x = 50$ cm, $y = 10$ cm (Port 2). (c) Travel distance of $x = 80$ cm, $y = 10$ cm (Port 3). (d) Travel distance of $x = 80$ cm, $y = 30$ cm (Port 4). (e) Travel distance of $x = 80$ cm, $y = 50$ cm (Port 5).
Figure 5 | The BTCs at flow velocity of $17.58 \times 10^{-5}$ m/s. (a) $C_1 = 10$ dS/m, (b) $C_2 = 14$ dS/m and (c) $C_3 = 19$ dS/m.

Figure 6 | Dispersion coefficient versus horizontal travel distances of 20, 50, and 80 cm (Port 1, Port 2, and Port 3) for layered heterogenous soils.
Comparison of dispersivity values in homogeneous and layered heterogeneous soils

We compared the results of this kind of soil to homogeneous soil (coarse-grained sand with $d_{50} = 7.67$ cm) to study the effect of the stratification of soil on dispersivity. As with the experiments on layered heterogeneous soil, these experiments were carried out using three flow velocities ($V_1 = 17.58 \times 10^{-5}$, $V_2 = 22.02 \times 10^{-5}$, and $V_3 = 26.18 \times 10^{-5}$ m/s), and three concentrations ($C_1 = 10$, $C_2 = 14$ and $C_3 = 19$ dS/m).

Figure 7 shows the BTCs for homogeneous soil for five ports. As this figure shows, the trend of these changes follows the same trend in all experiments. Also, at the horizontal travel distance of 20 cm (Port 1), the time to reach a concentration of 84% was less than at the two distances of 50 and 80 cm (Port 2 and Port 3). Also, the trend of changing BTCs in homogeneous soil was similar to that in layered heterogeneous soils, but the concentration of samples in homogeneous soil reached relative concentrations of 0.16 and 0.84 earlier than layered heterogeneous soils. The dispersion coefficients calculated using the Fried-Camberous model for these two kinds of soils for three ports (3, 4, and 5) were compared.

![Figure 7](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.359/950471/ws2021359.pdf)

**Figure 7** | The BTCs for homogenous soils (a) Travel distance of $x = 20$ cm, $y = 10$ cm (Port 1). (b) Travel distance of $x = 20$ cm, $y = 10$ cm (Port 2). (c) Travel distance of $x = 80$ cm, $y = 10$ cm (Port 3). (d) Travel distance of $x = 80$ cm, $y = 30$ cm (Port 4). (e) Travel distance of $x = 80$ cm, $y = 50$ cm (Port 5). (continued).
As the result of Table 3 for Port 3 indicated for layered heterogeneous soil, the first layer (bottom layer) which contains coarse sand (with grain size of 2.36–2.8 mm) has the highest dispersion coefficient (range 2.90–8.78 with average 5.41 cm for point sampling method). The middle layer which contains medium sand (with grain size of 2–2.36 mm), the results of Port 4 showed that it has the dispersion coefficients of 0.009–0.005 m (average 0.0238 m), and finally the upper layer which contains fine sand with the smallest grain size (1–1.18 mm) the results of Port 5 showed that it has the lowest dispersivity (range 0.10–1.30 with average 0.59 cm).

For homogenous soil for which we used coarse sand, the result showed that the average dispersion coefficient of the samples of Port 3 was about 0.0559 m (Table 4). In comparison to the result of Port 3 related to layered heterogeneous soil (0.0541 m), it was slightly lower it. This change in the dispersion coefficient is due to the presence of adjacent medium sand layer with different dispersion properties which located at the upper of coarse sand layer.

**Table 4** | The calculated values of dispersion coefficient (m) using Fried-Camberous model in homogenous soils using point and mixed methods sampling

| Velocity | Concentration |
|----------|---------------|
| Distance | V1 | C1 | C2 | C3 | V2 | C1 | C2 | C3 | V3 | C1 | C2 | C3 |
| Port 1 (x = 0.2 m, y = 0.1 m) | 0.0120 | 0.0160 | 0.0410 | 0.0170 | 0.0190 | 0.0140 | 0.0360 | 0.0320 | 0.0390 |
| Port 2 (x = 0.5 m, y = 0.1 m) | 0.0210 | 0.0300 | 0.0690 | 0.0510 | 0.0350 | 0.0270 | 0.0670 | 0.0440 | 0.0460 |
| Port 3 (x = 0.8 m, y = 0.1 m) | 0.0310 | 0.0380 | 0.0750 | 0.0650 | 0.0410 | 0.0480 | 0.0880 | 0.0610 | 0.0560 |
| Port 4 (x = 0.8 m, y = 0.3 m) | 0.0290 | 0.0374 | 0.0750 | 0.0630 | 0.0414 | 0.0486 | 0.0860 | 0.0600 | 0.0500 |
| Port 5 (x = 0.8 m, y = 0.5 m) | 0.0280 | 0.0369 | 0.0720 | 0.0643 | 0.0407 | 0.0500 | 0.0810 | 0.0590 | 0.0540 |
| Mix sample (outlet section) | 0.0658 | 0.0791 | 0.0801 | 0.0502 | 0.0386 | 0.0398 | 0.0492 | 0.0587 | 0.0494 |
A t-test was used to determine a significant difference between dispersion coefficient in homogenous and homogenous soils for two methods of point and mixed sampling. Table 5 showed the results of t-test using a 95% confident level. As the results of this table indicated that there were significant differences ($p < 0.05$) between the dispersion coefficient in homogenous and homogenous soils in both point and mixed sampling methods.

Figures 8–10 show the results of these comparisons separately for each of the experiments for Port 3, Port 4, and Port 5. As the results of these figures show, the values of dispersivity were higher in the homogeneous soil than in the layered heterogeneous soil. The values for dispersivity in all the experiments in the homogeneous soil for point and mixed sampling methods were about 49.04% and 7.3% lower than in the layered heterogeneous soil, respectively.

CONCLUSIONS

Considering recent groundwater pollution issues and the importance of studying dispersivity values, the present research studied the relationships between dispersivity, flow velocity, contaminant concentration, and travel distance while also investigating the effects of sampling methods. Experiments were carried out on two kinds of soils, namely homogeneous soil (coarse-grained sand with a particle size of 2.36–2.8 mm) and layered heterogeneous soil with three layers (coarse, medium, and fine sands). The results indicated the following:

1. Comparison of the dispersion coefficient calculated for homogeneous soil and layered heterogeneous soil for point sampling method shows that stratification has affected the dispersion coefficient, and the dispersion coefficients for

| Paired Samples Test | Variables | Mean | Std. deviation | Std. Error Mean | Lower | Upper | t | df | Sig. (2-tailed) |
|---------------------|-----------|------|----------------|-----------------|-------|-------|---|----|----------------|
| Pair 1              | VAR1 – VAR2 | -1.70 | 2.25           | 0.34            | -2.38 | -1.02 | 5.06 | 44 | 0.00001        |
| Pair 2              | VAR3 – VAR4 | 0.41  | 0.14           | 0.05            | -0.52 | -0.31 | 8.76 | 8  | 0.00002        |

VAR1 and VAR2 are the dispersion coefficient in homogenous and homogenous soils, respectively using point method sampling.

VAR3 and VAR4 are dispersion coefficient in homogenous and homogenous soils, respectively using mixed method sampling.

Figure 8 | Percentages of decreasing in dispersivity values in the layered homogenous soil compared to the homogeneous soil at the Port 3 (distance of $x = 80$ cm, $y = 10$ cm).
layered heterogeneous soil was 0.001–0.0878 m (0.0279 on average), and for layered heterogeneous soils it was 0.028–0.088 m (0.0548 on average). In other words, the dispersion coefficient for layered heterogeneous soils was 1.96 times less than the homogeneous soils. This finding is consistent with studies of Van der Zee (2020), Leij & van Genuchten (1995); Al-Tabbaa et al. (2000); Sternberg (2004), Zhang & Wu (2016).

2. For the two kind of soils, travel distance has affected the dispersion coefficient and the dispersivity changes with distance. The dispersion coefficient values increased with increasing horizontal travel distance in homogeneous and layered heterogeneous soil. For layered heterogeneous soil, the mean value of dispersivity at the horizontal travel distance of 0.80 m was 2.35 and 1.31 times compared to the horizontal travel distances of 0.20, and 50 cm, respectively. Also, in the homogeneous soils, its magnitude was about 2.23 and 1.29 times compared to the travel distances of 0.20, and 0.50 m, respectively. These findings are consistent with findings of other researchers such as Fried (1972), Peaudecerf & Sauty (1979), Sudicky & Cherry (1979), Pickens & Grisak (1981a), Gelhar et al. (1992), and Khan & Jury (1990).

3. The amount of dispersion coefficient in homogeneous soil and layered heterogeneous soil changes as velocity changes, but it does not show a clear trend. For three flow velocities ($V_1 = 17.58 \times 10^{-5}$, $V_2 = 22.02 \times 10^{-5}$, and $V_3 = 26.18 \times 10^{-5}$ m/s),
the average values of dispersivity for layered heterogeneous soil were 0.0258, 0.0236, and 0.0364 m, respectively. For homogeneous soil, these values were 0.0408, 0.0417, and 0.0573 m, respectively.

4. The amount of dispersion coefficient in homogeneous soil and layered heterogeneous soil changes as the contaminant concentration changes. However, as with flow velocity, no clear trend emerged. For three contaminant concentrations ($C_1 = 10$, $C_2 = 14$, and $C_3 = 19$ dS/m), the average dispersivity values for layered heterogeneous soil were 0.00047, 0.00041, and 0.00051 m, respectively. Also, for homogeneous soil, it was 0.0277, 0.0285, and 0.0323 m, respectively. In other words, although the concentration changes were very significant (on average 55%), but its effect on the dispersion coefficient is only 11%.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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First received 9 May 2021; accepted in revised form 10 October 2021. Available online 22 October 2021