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Laboratory Scale Effect of Aquifer Thickness on Dispersivity of Porous Media

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Abstract: In the present study, the dependence of dispersivity on the thickness of aquifer has been investigated. The physical model used in the study consisted of a rectangular Plexiglas tank with inner dimensions of 720 mm length, 100 mm width and 1200 mm height. Sodium chloride with an electrical conductivity (EC) of 14 dS m^{-1} was selected as conservative contaminant. Porous media used in the experiments consisted of homogeneous coarse and medium sand particles. The experiments were performed in two different stages. In the first stage, 10 experiments in the aquifer with coarse sand particles and eight experiments in the aquifer with medium sand particles with constant thickness of 100 mm and flow velocities ranging from 4.5×10^{-5} to 11.25×10^{-5} m sec^{-1} were performed. In the second stage, experiments with thicknesses of 200-1000 and 100 mm layer distance were performed. The flow velocity in the second stage was maintained at 9.0×10^{-5} m sec^{-1} for each simulated aquifer, based on the previous studies. Results of the study indicated that: (1) the dispersivity values obtained for coarse and medium sand particles with 100 mm thickness were in the range of 0.25-0.65 and 0.11-0.33 cm, respectively and the mean values of dispersivity for both aquifers were in the range of 0.01 to 1.0 cm which are in agreement with the findings of other researchers, (2) the dispersivity values obtained for aquifers with coarse and medium sand particles and thicknesses of 200-1000 mm were in the range of 0.31-0.63 and 0.14-0.46 cm, respectively, which are in agreement with the findings of others as well, (3) the dispersivity of sandy porous media is independent of particle size and (4) in homogeneous sandy aquifers with coarse and medium particle size, the dispersivity is independent of aquifer thickness.

Key words: Aquifer, dispersivity, dispersion coefficient, aquifer thickness, scale effects

INTRODUCTION

The most general one-dimensional advection-dispersion equation for a non-reactive solute transport in saturated, homogeneous and isotropic porous media under steady-state conditions is as follows (Fried and Cambernous, 1971):

$$\frac{dC}{dt} = D\frac{d^2C}{dL^2} - V\frac{dC}{dL} \quad (1)$$

Where:
L = Curvilinear flow path
V = Average actual groundwater flow
D = Longitudinal hydrodynamic dispersion coefficient
C = Solute concentration
t = Time

Equation 1 is derived based on the assumptions that: (1) contaminants are soluble in water, (2) fluid characteristics (specific weight, viscosity) are independent from solute concentration, (3) fluid s incompressible, (4) molecular diffusion coefficient and mechanical dispersion coefficients are not additive, (5) V = q/n (q = Darcy velocity and n = porosity) and (6) solute is conservative and non-reactive (Bear and Verruijt, 1994). The first and second terms on the right side of equation (1) indicate hydrodynamic dispersion and advection processes, respectively. The hydrodynamic dispersion coefficient (D) can be determined from the following relationship:

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

Where:
α = Dispersivity of media and
D* = Molecular diffusion coefficient of solute in porous media

At low flow velocities, molecular diffusion is the dominant transport process. As a result, in such cases, the hydrodynamic dispersion coefficient will be equal to

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the molecular diffusion coefficient (D = D*). At high flow velocities, mechanical dispersion process will be the dominant process and D = αV. Molecular diffusion coefficient (D*) is negligible when velocity is greater than 10 cm sec^{-1} (Gillham and Cherry, 1982).

A number of theoretical and practical models regarding solute dispersion in porous media have been developed by researchers. Brusseau (1993) presented a general model for miscible displacement. Fried (1975) presented the following relationship for determination of hydrodynamic dispersion coefficient (D) of porous media:

$$D = \frac{1}{8}\left[(L - vt_{0.16})/(t_{0.16})^{1/2} - (L - vt_{0.84})/(t_{0.84})^{1/2}\right]^2 \quad (3)$$

and

$$v = \frac{L}{t_{0.5}} \quad (4)$$

v is seepage (pore) velocity, L is length of soil tank and $t_{0.16}$, $t_{0.5}$, $t_{0.84}$ are times to reach 0.16, 0.50 and 0.84 relative solute concentrations, respectively which can be derived from the related breakthrough curves.

The dependence of dispersivity on the travel distance or length of porous media have been reported by Wierenga and Van Genuchten (1989), Al-Tabbaa *et al.* (2000), Fetter (1999), Pickens and Grisak, (1981b), Klotz *et al.* (1980), Oakes and Edworthy (1977), Butters and Jury (1989), Gelhar *et al.* (1992), Peaudecerf and Sauty (1978) and Sudicky and Cherry (1979). Wierenga and Van Genuchten (1989) arranged 30 and 60 cm long columns filled with sandy loam soils and found the average dispersivity values for Tritium and Chloride in the shorter column equal to 0.80 and 0.87, respectively. The dispersivity value of both Tritium and Chloride for the longer column was about 5 cm. Al-Tabbaa *et al.* (2000) in an experiment on homogeneous medium sand with three thicknesses of 8, 18 and 25 cm found that the dispersivity was volume-dependent and not only travel distance dependent. Fetter (1999), Pickens and Grisak (1981b) found that dispersivity of porous media (aquifer) is travel-distance dependent. Klotz *et al.* (1980) from field experiments found that dispersivity of tracer linearly increases with increasing travel distance. Oakes and Edworthy (1977) using radial and pulse injection in two wells drilled in a sandy aquifer and found that the dispersivity value for total depth was 2 to 4 times that in the separated layers. Butters and Jury (1989) from experiments under unsaturated conditions found considerable increase in dispersivity value with depth up to 4.5 m. In their studies, the dispersivity values at 1.2 and 1.8 m depths were smaller than that at 0.9 and at 4.5 m depth was smaller than those values at 0.9, 1.8 and 3 m depths. Gelhar *et al.* (1992) investigated 104 dispersivity values obtained from 59 different locations and found dispersivity values in the range of 10^{-2} to 10^{-4} m for scale in the range of 10^{-1} to 10^{5} m. Their investigation also showed dispersivity increase with scale. Case studies by Peaudecerf and Sauty (1978) indicated that dispersivity varied with travel distance. Sudicky and Cherry (1979) from field studies found that dispersivity for chloride increased with mean travel distance in the groundwater flow zone. The dependence of dispersivity on travel distance restricts the use of advection-dispersion equation in which it is assumed that dispersivity is independent of the travel distance. On the other hand, Fired *et al.* (1972) has reported that the dispersivity of porous media is independent of travel distance. Fired *et al.* (1972) obtained equal values for dispersivity under laboratory and field conditions and concluded that travel distance has no effect on dispersivity of porous media. Jury *et al.* (1982) found no considerable increase in dispersivity value with increasing depth up to 1.8 m in tracer experiments with bromide under unsaturated conditions in field Al-Tabbaa *et al.* (2000) from experiments in sandy soils with medium particle size and thicknesses of 8, 18 and 25 cm concluded that the dependence of dispersivity on the soil volume is more sophisticated than its dependence on the travel distance. They also concluded that under the same conditions, with increasing soil thickness, the velocity of the contaminant front decreases and dispersivity increases. They believe that this could be due to the increased heterogeneity of the porous media at microscopic scale. On the other hand, a number of laboratory and field studies (Taylor and Howard, 1987; Khan and Jury, 1990) have shown that dispersivity is not scale-dependent.

The dispersivity values at laboratory scale are one to several times smaller than those at field scale (Bresler and Dagan, 1979; Pickens and Grisak, 1981a) Theis (1963) realizes that the variations in dispersivity values under field conditions could be due to the wide variations in hydraulic conductivity and flow velocity through aquifers. Fried *et al.* (1972) found dispersivity values equal to 0.1-0.6 m at local scale (for each layer of aquifer), 5.0-11.0 m at overall scale (total aquifer thickness) and 12.2 m at regional scale (several kilometers).

The objective of the present study was to investigate the dependence of the dispersivity of porous media to its thickness in coarse and medium sandy aquifers at laboratory scale.

MATERIALS AND METHODS

The physical model used in the study consisted of a rectangular Plexiglas tank with inner dimensions of 720 mm length, 100 mm width and 1200 mm height (Fig. 1). The tank had inlet, porous media bed and outlet sections. To simulate one-dimensional flow in the tank, perforated Plexiglas sheets were placed between sections to insure horizontal flow of the contaminant in the whole thickness of the porous media. Also, to prevent clogging of pores of the sheets with sand particles, the flow channels were protected with cotton cloth. To maintain a constant flow rate in the tank, at first, water and contaminant reservoirs were connected to a regulator with a constant hydraulic head (adjustable for each experiment) separately and then, the contaminant was introduced into the inlet section of the tank after passing through the regulator. The overflow discharged from the weir regulator. To provide point samples, sampling ports were placed at 10 cm intervals at the downstream end of the tank so that, the first and last ports were located at 5 and 95 cm from the bottom of the tank, respectively. The sodium chloride was selected as conservative or non-reactive contaminant in all experiments of the study. The reasons for selecting sodium chloride as conservative contaminant were: (1) its availability, (2) its non-dangerous characteristic and (3) its simplicity of measurement by conductivity meter apparatus. The sodium chloride solution with an electrical conductivity (EC) of 14 dS m^{-1} (9 g L^{-1}) was used in all experiments. Coarse and medium sand particles were used as porous media. Sand particles were washed, oven-dried and sieve-analyzed and then the particle size distribution curve, the effective particle size (D_{10}) and the coefficient of uniformity (D_{10}/D_{60}) for each sand were prepared and/or determined. Also, bulk density, void ratio and porosity of each medium were calculated.

The assumptions made in this study for simulation of contaminant transport in aquifers were: (1) horizontal fluid flow, (2) homogeneous media with constant porosity and (3) saturation condition. Experiments were performed in two different phases. In the first phase, 10 experiments in the aquifer with coarse sand particles and eight experiments in the aquifer with medium sand particles with constant thickness of 100 mm and different flow velocities were performed. The minimum and maximum flow velocities for the first stage experiments were 4.5×10^{-5} and 11.25×10^{-5} m sec^{-1}, respectively. The flow velocities were 25-250% of the minimum flow velocity with increments of 25%. The experiments were triplicated. The objective of performing the experiments in the first phase was to obtain the range of variations in dispersivity of the aquifers with 100 mm thickness. In the second phase, experiments with thicknesses of 200 to 1000 mm with 100 mm layer distance and with constant flow velocities were performed for each simulated aquifer. In all experiments, point samples were taken. The experiments were performed under the same conditions for both aquifers and the only variable parameter was the aquifer thickness with 100 mm increment. The flow velocity in

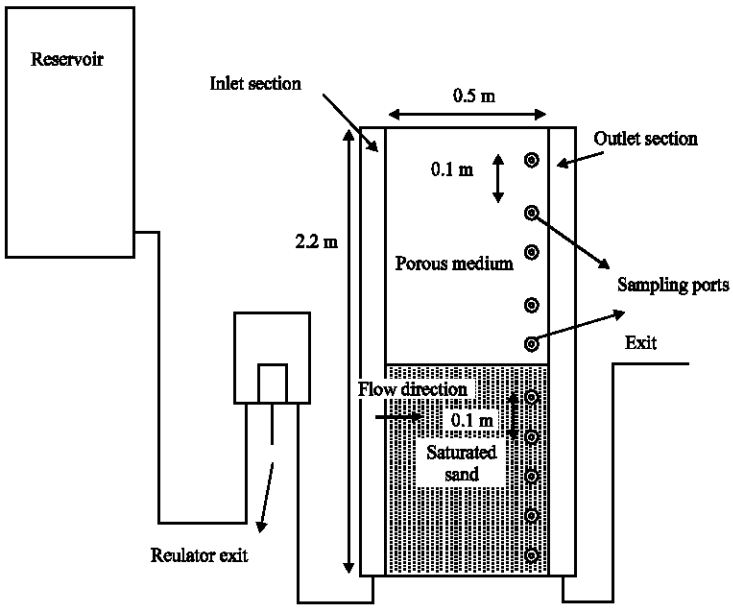

Fig. 1: Schematic diagram of physical model used in the study

the second stage was maintained constant at 9.0×10^{-5} m sec^{-1}, based on the previous studies by Al-Tabbaa *et al.* (2000). To prepare the tank for performing experiments, at first, water was introduced into the tank to a height a small amount above the desired height. At this moment, the inlet and related outlets of the tank were closed. Then, dried sand was added gradually to the tank to reach the desired height. After adding a definite volume of sand to the tank, the sand was compacted slowly to reach a maximum natural compaction level. Samples were collected from the start (t = 0) of the experiments and the Electrical Conductivity (EC) of the samples were measured by EC-meter. The EC of the first sample was the same as that in the aquifer. Then, at 2 to 15 min time intervals, the effluents were collected and their electrical conductivities were measured. The experiments were continued up to the time when the concentration in the final sample reached 14 dS m^{-1}.

RESULTS AND DISCUSSION

The physical and hydraulic characteristics of each aquifer and their particle size distribution curves are presented in Table 1 and Fig. 2, respectively. The coarse sand used in the study consisted of particles passing No. 10 standard sieve and maintained on No. 20 standard sieve and the medium sand used consisted of particles passing No. 30 sieve and maintained on No. 50 sieve. As a result, the porous media of both aquifers had a uniformity coefficient (CU) of less than four, which shows that both media consisted of homogeneous sand particles.

Table 2 shows dispersivity values of both aquifers with 100 mm thickness and various flow velocities. As it is shown in Table 2, the minimum, maximum and average dispersivity values of the aquifer with coarse sand particles were 0.25, 0.65 and 0.36 m, respectively with a standard deviation of 0.12. The minimum, maximum and average dispersivity values for the aquifer with medium sand particles were 0.11, 0.33 and 0.22 m, respectively with a standard deviation of 0.10. This variation in dispersivity values obtained could be due to the inevitable errors occurred during the experiments (all experiments were not performed exactly with the same sand, so that in some instances, the sand of the tank was discarded and then filled with new sand particles; entrapped air in the soil samples) and variability in physical and hydraulic characteristics of aquifers (diameter of the soil pores; soil homogeneity; dead end pores). Accordingly, obtaining a constant dispersivity value even for a constant flow velocity in different replications was not possible. The mean values of dispersivity obtained for both aquifers were in the range of 0.01 to 1.0 cm which are in agreement with the results obtained by Pickens and Grisak (1981a) and Wierenga (2004), who obtained similar values for dispersivity from laboratory studies.

Dispersivity values obtained for the simulated aquifer with coarse sand particles and thicknesses of 200-1000 mm are presented in Table 3. As it is shown in Table 5, the minimum dispersivity value obtained for the aquifer with coarse sand particles is 0.21 cm which belongs to the sample No. four with a thickness of 700 mm and the maximum dispersivity value is 0.93 cm which belongs to sample No. eight with 1000 mm thickness. The minimum and maximum of the average dispersivity values of the aquifer with coarse sand particles are 0.31 and 0.63 cm, respectively which belongs to the aquifer thicknesses of 400 and 1000 mm, respectively.

Dispersivity values obtained for the simulated aquifer with medium sand particles and thicknesses of 200-1000 mm are presented in Table 4. As well, mean values of dispersivity for various thicknesses along with statistical analysis are shown in Table 6. As it is shown in Table 6,

Table 1: Physical and hydraulic characteristics of aquifers

Aquifer	D_{10} (mm)	CU	ρ (g cm^{-3})	n	K ($\times10^{-3}$ m sec^{-1})
Coarse sand	0.90	1.56	1.74	0.34	5.20
Medium sand	0.26	1.12	1.72	0.35	1.04

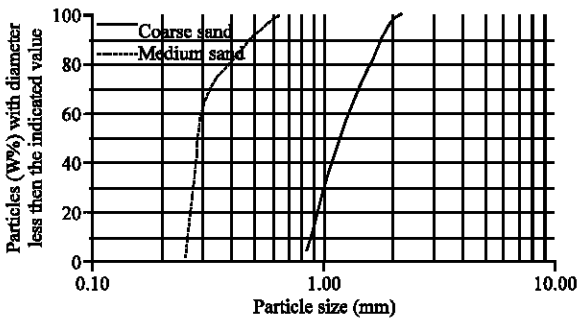

Fig. 2: Particle size distribution curves of sand

Table 2: Dispersivity values of aquifers with 100 mm thickness and various flow velocities

	Coarse sand aquifer			Medium sand aquifer	
Test No.	Darcy velocity (m $sec^{-1}\times10^{-5}$)	(cm)	Test No.	Darcy velocity (m $sec^{-1}\times10^{-5}$)	(cm)
TC1	4.50	0.65	TM1	4.50	0.11
TC2	5.63	0.49	TM2	5.63	0.33
TC3	6.75	0.28	TM3	6.75	0.12
TC4	7.88	0.28	TM4	6.75	0.30
TC5	7.88	0.25	TM5	9.00	0.12
TC6	9.00	0.39	TM6	9.00	0.23
TC7	9.00	0.30	TM7	10.13	0.33
TC8	9.00	0.35	TM8	11.25	0.18
TC9	10.13	0.35			
TC10	11.25	0.26			

Table 3: Dispersivity values of the aquifer with coarse sand various thicknesses

Test No.	Aquifer thickness (cm)	Sampling depth (cm) 0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
TC11	20	0.45	0.56								
TC12	30	0.29	0.57	0.42							
TC13	40	0.25	0.39	0.34	0.24						
TC14	50	0.52	0.53	0.52	0.83	0.30					
TC15	60	0.33	0.53	0.41	0.73	0.33	0.27				
TC16	70	0.34	0.40	0.40	0.58	0.21	0.42	0.26			
TC17	80	0.52	0.45	0.56	0.68	0.43	0.78	0.40	0.29		
TC18	90	0.40	0.52	0.45	0.55	0.46	0.61	0.52	0.82	0.25	
TC19	100	0.44	0.70	0.58	0.70	0.80	0.81	0.61	0.92	0.43	0.35

Table 4: Dispersivity values of the aquifer with medium sand various thicknesses

Test No.	Aquifer thickness (cm)	Sampling depth (cm) 0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
TM 9	20	0.21	0.28								
TM10	30	0.14	0.21	0.14							
TM11	40	0.12	0.17	0.13	0.16						
TM12	50	0.17	0.22	0.18	0.19	0.16					
TM13	60	0.22	0.41	0.24	0.45	0.29	0.40				
TM14	70	0.17	0.40	0.21	0.38	0.35	0.29	0.16			
TM15	80	0.15	0.49	0.47	0.52	0.44	0.43	0.14	0.14		
TM16	90	0.29	0.66	0.65	0.67	0.64	0.45	0.34	0.23/0	0.15	
TM17	100	0.37	0.64	0.69	0.62	0.56	0.52	0.52	0.26	0.23	0.20

Table 5: Analysis of dispersivity values for aquifer with coarse sand and thicknesses of 10-100 cm

Test No.	Aquifer thickness (cm)	Dispersivity values of point samples (cm) Minimum	Mean	Maximum	SD
TC1-TC10	10	0.25	0.36	0.65	0.12
TC11	20	0.45	0.51	0.56	0.08
TC12	30	0.29	0.43	0.57	0.14
TC13	40	0.24	0.31	0.39	0.07
TC14	50	0.30	0.54	0.83	0.19
TC15	60	0.27	0.43	0.73	0.17
TC16	70	0.21	0.37	0.58	0.12
TC17	80	0.29	0.51	0.78	0.16
TC18	90	0.25	0.51	0.82	0.15
TC19	100	0.35	0.63	0.93	0.19
TC11-TC19	20-100	0.21	0.47	0.93	0.10

Table 6: Analysis of dispersivity values for aquifer with medium sand and thicknesses of 10-100 cm

Test No.	Aquifer thickness (cm)	Dispersivity values of point samples (cm) Minimum	Mean	Maximum	SD
TM1-TM8	10	0.11	0.22	0.33	0.10
TM9	20	0.21	0.24	0.28	0.05
TM10	30	0.14	0.16	0.21	0.04
TM11	40	0.12	0.14	0.17	0.02
TM12	50	0.16	0.19	0.22	0.02
TM13	60	0.22	0.33	0.45	0.10
TM14	70	0.16	0.28	0.40	0.10
TM15	80	0.14	0.35	0.52	0.17
TM16	90	0.15	0.45	0.67	0.21
TM17	100	0.20	0.46	0.69	0.18
TM9-TM17	20-100	0.12	0.29	0.69	0.12

the minimum dispersivity value obtained for the aquifer with medium sand particles is 0.12 cm which belongs to the sample No. one with a thickness of 400 mm and the maximum dispersivity value is 0.69 cm which belongs to sample No. three with 1000 mm thickness. The minimum and maximum values of the average dispersivity values of the aquifer with medium sand particles are 0.14 and 0.46 cm, respectively which belongs to the aquifer thickness of 400 and 1000 mm, respectively.

Considering the results shown in Table 5 and 6, it is seen that the dispersivity value of aquifer is not dependent on the thickness of aquifer. This is not in agreement with the findings of Al-Tabbaa *et al.* (2000) who found that the dispersivity increased with increasing the aquifer thickness. The reasons for disagreement between the results obtained in this study and those obtained by Al-Tabbaa *et al.* (2000) could be due to the fact that the experiments of Al-Tabbaa *et al.* (2000) were performed in a sandy aquifer with only medium particle size and only three thicknesses (80, 180 and 250 mm) and only one flow rate (4.5×10^{-5}cm sec^{-1}) whereas in this study, 10 aquifer thicknesses along with two different media (medium sand and coarse sand) and various flow rates were used. Therefore, the results of the present study are more sophisticated and reliable than those obtained by Al-Tabbaa (2000). The dispersivity values obtained by Al-Tabbaa *et al.* (2000) for a sandy aquifer with medium particle size and 80, 180 and 250 mm thicknesses were 5.3, 6.3 and 7.2 cm, respectively which are not in agreement with the dispersivity values (0.01-1.0 cm) reported by Pickens and Grisak (1981a) and Wierenga (2004) for porous media as well. However, the results obtained in the present study are in good agreement with findings of Fired *et al.* (1972) and Jury *et al.* (1982), who found that the dispersivity of porous media is independent of travel distance.

CONCLUSIONS

Conclusions that could be drawn from the results obtained in the present study are as follows:

- The dispersivity values obtained for the aquifers with coarse and medium sand particles with 100 mm thickness were in the range of 0.25-0.65 and 0.11-0.33 cm, respectively and the mean values of dispersivity obtained for both aquifers were in the range of 0.01 to 1.0 cm
- The dispersivity of sandy porous media is independent of particle size of the medium and only a negligible difference exists in this regard for coarse and medium particle sizes
- The dispersivity values obtained for aquifers with coarse and medium sand particles and thicknesses of 200-1000 mm were in the range of 0.31-0.63 and 0.14-0.46 cm, respectively and
- In homogeneous sandy aquifers with coarse and medium particle sizes, the dispersivity value is not dependent on the aquifer thickness

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