Laboratory Investigation of Effects of Density difference on Two-Dimensional Dispersivities

Amir Naserin
PhD. Student, Department of Irrigation and Drainage Engineering
Faculty of Water Sciences Engineering, Shahid Chamran University of Ahvaz, Iran
E-mail: Amir8480@gmail.com

Hadi Moazed
Associate Professor, Department of Irrigation and Drainage Engineering
Faculty of Water Sciences Engineering, Shahid Chamran University of Ahvaz, Iran
E-mail: hmoazed955@yahoo.com

Abdorahim Hooshmand
Associate Professor, Department of Irrigation and Drainage Engineering
Faculty of Water Sciences Engineering, Shahid Chamran University of Ahvaz, Iran
E-mail: hooshmand@scu.ac.ir

Mohammad Mahmoodian Shooshtari
Professor, Department of Civil Engineering, Faculty of Engineering
Shahid Chamran University of Ahvaz, Iran

Abstract

Dispersivity is one of the most important parameters in determination of plumes shapes. The density difference between resident and invading solute is an effective factor which can affect on the dispersivity and consequently shape of plumes. To investigate this, laboratory experiments were conducted on coarse and medium sands. Miscible tests were conducted on a physical model with dimensions of 110 cm length, 23 cm width and 75 cm depth. Sodium chloride solution with concentrations ranging from 2.25 to 18 Kg/m$^3$ was selected as tracer. Data on tracer concentration were collected in two dimensions and concentration distributions in the porous media were obtained at 5 hr and 9 hr after the beginning of experiments. By fitting observed and simulated concentration distribution two-dimensional dispersivities were obtained. Results showed that longitudinal and transverse dispersivities of both aquifers are increased by increasing the density difference. The two-dimensional dispersivities has more ascending rate for the aquifer with medium sand than the coarse sand medium by increasing density difference. Also, for both aquifers, the ratio of transverse dispersivity to longitudinal dispersivity rises by the increase in the density difference.

Keywords: Longitudinal Dispersivity, Transverse Dispersivity, Density Difference
1. Introduction

During the past decades, water pollution has become one of the most important concerns of humankind. Different contaminants such as fertilizers, pesticides, septic tanks etc. have been found in groundwater. In the aquifers which are affected by contaminants, determination and prediction of plume size and distribution of pollutant concentration are keynotes for remediation or withdrawal of groundwater. Contaminant transport from its resources is affected by different mechanisms. One of the most important mechanisms is dispersion.

Hydrodynamic dispersion in the porous media consists of two components: diffusion, resulting from Brownian motion, and mechanical dispersion, resulting from local variations of flow velocities, both in magnitude and direction (Bear, 1972).

The dispersivity is most important and ambiguous parameter in monitoring and determination of contaminant plume shapes. Therefore, accurate determination of longitudinal and transverse dispersivities can lead to better identification of contaminant plume development in the porous media. In the past, many researchers paid to longitudinal dispersivity and large amount of data have been presented in the literature (Shulze-mukh, 2005 and Bromly et al., 2007). Although, some believe that the transverse dispersion has a key role in the dilution and mixing of solutes in the porous medium (Masabo et al., 2007), a small group of researchers have been investigated it due to difficulties in measurement. In the contaminant plumes development, the longitudinal and transverse dispersivities must be considered simultaneously. Therefore, the assessments of factors which affect them and their ratios are important.

However, in many models of groundwater solute transport, the dispersivity considered as a constant, but dependence of longitudinal and transverse dispersivity to the travel distance has been assessed by many studies. This can result in the over or underestimation of dispersivity. Generally, the scale-dependent dispersion is due to heterogeneous nature of porous media at different scales (Gelhar et al., 1992). Many methods are introduced for dealing with scale-related problems such as the numerical solutions (Mishra and Parker, 1989), stochastic analysis (Zhang et al., 1994) and analytical methods (Pang and Hunt, 2001).

In the field studies, the natural gradients and forced gradients tracer experiments have been used widely to determine dispersivities. In spite of field tests accuracy, there are some reasons for conducting tracer tests in laboratory. In the field tracer experiments, achieving high resolution data is very difficult because it is time consuming and costly. Hence, the laboratory experiments are the most suitable option for the assessing of fundamental processes effecting on contaminant transport and validation of numerical models dealing with it. Moreover, dispersivities obtained from field scale tests are usually suggested for predicting site-specific transport problems. So, obtained results are not applicable to other aquifers.

There are many evidences that density difference of fluids even at low values can affect the contaminant transport in porous media (Simmons, 2005). The fluid density can be varied by changing its solute concentration, temperature and pressure (Simmons et al., 2010). In the past decades, many researchers investigated variable densities of fluids from different viewpoints. Welty and Gelhar (1991) studied the effects of viscosity and density contrasts using stochastic approach express that, at velocities typical for groundwater contamination transport, density effects are dominant. By introducing the mobility ratio and the gravity number as two dimensionless parameters, Kempers and Haas (1994) compared results of several experiments. As a result, if a denser fluid is above another fluid, gravitational force will distribute the fluids. However, if the less dense fluid is above another, a stable displacement occurs.

Many researches reported effects of Density gradients on the plumes shape. For example, it has been observed that dispersion at the solute front varies with density contrast (Kempers and Hass, 1994). This makes horizontal density gradients in the displacing front. These density gradients are affected by gravity forces and the width of dispersive front reduces. This results in a dispersion coefficient reduction (Watson et al., 2002 and Gutierrez-Neri, 2009). As it was mentioned before, any variation in dispersivity values will change the shape of plume.
Using the nonlinear dispersion theory, some researchers emphasized that the nonlinear effects depend on the fluid velocity and the magnitude of solute concentration gradients, but not on the absolute concentration levels of the resident and/or displacing fluids (Schotting, 1999, Jiao and HÖtzel, 2004, Menand and Woods, 2005). When the density difference between resident and displacing fluids is low, the dispersion is not influenced by gravitational forces. But by increasing this difference, the gravitational forces are growing and so dispersion will be reduced.

Considering the variable density flow phenomena, methods of analyzing plumes developing must changed. The sand tanks which are simulated 2 or 3 dimensional aquifers have been used for investigation of solute transport extensively for the past three decades.

Jiao and Hotzel (2004) performed stable and unstable miscible displacement experiments in a column with the length of 1550 mm and internal diameter of 190 mm. The column was packed with sand in diameters ranging from 0.4 to 0.6 mm and uniformity coefficient of 1.1. The effect of density differences of 0.8, 11.1 and 22 g/L of NaCl on dispersivity was investigated. They concluded that for stable displacements, dispersivity decreases when density differences increase. The contrary is true for unstable displacement.

Landman (2005) conducted numerical experiments and found decreasing trend in the longitudinal dispersivity as the gravity number increases for a nearly homogenous porous media. Jiao and Hotzel (2004) obtained similar results from the laboratory experiments in approximately homogenous media.

Nick et al. (2009) investigated nonlinear behavior of density gradients on the transverse dispersivity using a two-dimensional numerical model. They also assessed the relationship between scaled transverse macro-dispersivity and gravity number in terms of different density difference, flow rate, local transverse dispersivity and heterogeneity. They concluded that in a porous media, the effects of density driven dispersive flux is reduced by decreasing of permeability variations. Moreover, due to density gradients, the transverse dispersivity reduces much more than longitudinal dispersivity in a given porous media.

Wood et al. (2001) studied breakthrough curve changes due to variations of density differences. They conducted one-dimensional experiments on saturated homogenous sand columns and solution densities varied of 1000.5 to 1211 kg/m$^3$. Parameter estimation using advection-dispersion model suggests that unstable plume migration can be fitted with apparent dispersivity at low-density gradients. The Poorer matches obtained when concentration of invading solutions was greater than approximately 13000 mg/L.

Koch and Starke (2001) carried out a 2D tracer experiments in a laboratory sand tank. The tank which had dimensions of 10 m length, 0.1 m width and 1.2 m height were used to investigate the dependence of flow and transport on density in heterogeneous porous media. In contrast to results of pervious studies, increasing in solute concentration did not lead to decreasing transverse dispersion. They also concluded larger dispersion coefficient of porous media reduces the density effect.

The objective of this study is to investigate the dependence of two-dimensional dispersivities on density difference between resident water and plume solute in coarse and medium sand medium at the laboratory scale.

2. Material and Methods
The two-dimensional physical aquifer tank that used in tracer test consisted of a rectangular Plexiglas tank with dimensions of 110 cm length, 23 cm width and 75 cm height. The tank had 100 cm-long porous media bed on the right and 10 cm water storage reservoir on the left. To maintain flow from aquifer tank to water storage reservoir, a perforated Plexiglas with enough pores was placed between these two sections. A cotton cloth was preventing the pores from clogging with sand particles (Figure 1). A steel support frame was built around the tank to avoid deflection of side walls.

The water and contaminant reservoirs were connected to two regulator reservoirs, separately. Water and contaminant supply were obtained by gravity through two constant level regulating
Laboratory Investigation of Effects of Density difference on Two-dimensional Dispersivities

reservoirs separately which was situated above the inlet part which ensures a constant flow rate. These regulating reservoirs stabilized flow at a specified rate. To make sure that the flow through the tank was stable and uniform, the flow rates through the inlet and outlet were measured regularly.

The Inlet part consists of some injectors which distribute flow equally. To increase flow recharge uniformity and conduct of flow on area which had been considered, a thick cotton cloth with dimensions of 25 cm length and 4 cm width was placed under the injectors and on the sand porous media. Water levels in the three manometers were measured relative to the outlet elevation in order to calculate the hydraulic gradient along the two different segments.

Before packing, Probable Fine particles had been winnowed by washing. Water was imported to tank to a height slightly more than desired height. Then, sand particles were poured into a stagnant water body to reach the desired height. After reaching about 4 cm thickness, the sand layer was compacted to reach a maximum natural compaction level and the first layer of sampling needles was set up. Sand was carefully added until it submerged the needles. This procedure was repeated for every layer of sampling needles. Since the experiments conducted in unconfined condition, last sand level was a little above the water imposed levels in tank. Finally, porous media height reached to 56 cm.

Similar to some laboratory experiments (Harleman and Rumer, 1963, Silliman and Zheng, 2001, Alkindi et al., 2011 and Gao et al., 2012); sodium chloride was used as non-reactive tracer. The concentration of sodium chloride was measured using a conductivity meter. Before the experiments, conductivity meter calibrated with the standard solutions. The main advantages of using sodium chloride as a tracer are high solvability, harmlessness for operator health, simplicity in measuring and availability. All experiments were conducted at an ambient temperature of approximately 15 °C.

Before the start of every experiment, uncontaminated water with a constant flux was applied to aquifer. After reaching the inlet and outlet's' recharges to the desired amount, the Water injector and the tracer injector were displaced in the least possible time. At this moment, the test was started. Tracer was injected to porous media for about 35 minutes through the injector. Thereafter water injector was replaced and water flow again established by same velocity.

Avoiding from changes in streamlines, efforts were made to minimize volume of samples. So, 1 ml syringes were used to collect samples from sampling ports on the front side of the porous media zone. The ports had been distributed on the 4*4 cm network to obtain state of concentration in aquifer's zone. To obtain two-dimensional concentration distribution in the porous media, sampling was done at 5 and 9 hours after beginning of each experiment. Samples with low volume were diluted with distilled water in order to be analyzable by means of conductivity meter.

In order to perform investigation on different size of sand, a large amount of silica sand was separated into two different sizes of sand classifications by sieving. Coarse and medium sands were considered as porous media. Sand particles were sieve-analyzed and the grain size distribution curves were constructed to determine d_{10}, d_{50} and d_{90} corresponding to 10, 50 and 60 percent finer by weight on grain grain-size distribution curve, respectively. The Coefficients of Uniformity were calculated as d_{60} divided by d_{10}. Also, the bulk density and porosity of each medium was measured.

To assessing the effects of density differences on two-dimensional dispersivities, the tracer with different solute concentration was prepared. Density differences between resident and displacing water were about 2.25, 4.5, 6.75, 9 and 18 g/L.
2.1. Flow and Transport Model

Since the porous media was isotropic and homogenous, the saturated hydraulic conductivity in different directions was taken as an equal value. Moreover, because no flow is along the tank width, the flow regime in the tank is two-dimensional. So, flow equation can be presented as:

$$K_s \frac{\partial^2 h}{\partial x^2} + K_s \frac{\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t}$$  \hspace{1cm} (1)

Where $h$ is the hydraulic head and $S_s$ is specific storage. Under these conditions, the advective-dispersive equation for solute transport is as follows:

$$\frac{\partial}{\partial x_j} \left( D_{ij} \frac{\partial C}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \left( v_i C \right) = \frac{\partial C}{\partial t}$$  \hspace{1cm} (2)

Where $C$ is the solute concentration, $x_i$ is the distance along the coordinate axis, $D_{ij}$ is the hydrodynamic dispersion tensor ($L^2 T^{-1}$) and $v_i$ is the linear average seepage velocity ($LT^{-1}$).

According to Bear (1972 and 1979) and by neglecting diffusion, the hydrodynamic dispersion tensors for this two dimensional isotropic media can be expressed as:

$$D_{xx} = \alpha_L \frac{v_x^2}{|v|} + \alpha_T \frac{v_z^2}{|v|}$$  \hspace{1cm} (3)

$$D_{xz} = D_{zx} = (\alpha_L - \alpha_T) \frac{v_x v_z}{|v|}$$  \hspace{1cm} (4)

And

$$D_{zz} = \alpha_L \frac{v_z^2}{|v|} + \alpha_T \frac{v_z^2}{|v|}$$  \hspace{1cm} (5)

Where $D_{xx}$ and $D_{zz}$ are the principal components of the dispersion tensor ($L^2 T^{-1}$), $D_{xz}$ and $D_{zx}$ are the cross terms of the dispersion tensor ($L^2 T^{-1}$), $\alpha_L$ and $\alpha_T$ are the longitudinal and transverse dispersivities ($L$), respectively, $v_x$ and $v_z$ are components of velocity vector and $|v| = \left( v_x^2 + v_z^2 \right)^{1/2}$ is the magnitude of velocity vector ($LT^{-1}$).
2.2. Dispersivities Estimation

To simulate groundwater flow, MODFLOW which is a modular three-dimensional finite difference flow code which developed by McDonald and Harbaugh (1988) was used. Concentrations of samples were measured by conductivity meter and the plumes shapes were drawn. Also, simulated concentrations with the flow and transport model were used to draw similar plumes.

The estimated dispersivity values were modified until an acceptable fitness between the observed tracer plumes and concentrations simulated with two dimensional flow and transport model was reached. The porous media was simulated using a grid of one layer, 16 rows and 25 columns. Therefore, a regular grid size of 4 cm is used for each column and row. The aquifer was specified as unconfined and its bottom and sides were described as no flow boundary condition. Since the water levels were constant at the manometers, the upstream and downstream boundary conditions were considered as specific head boundary conditions.

To calculate hydraulic conductivity, the water levels at two manometers and discharge from outlet were measured. The modular three-dimensional transport model (MT3D) (Zheng, 1992) was used to solve advective-dispersive transport equation. By solving this equation the concentration values in different points can be obtained. Different dispersivity values result different distribution of concentration in porous media. The longitudinal and transverse dispersivities were determined when the best agreement was obtained between simulated and measured distribution of concentrations at two different times of observations.

3. Results and Discussion

The physical characteristics and the particle distribution size curves of each porous media presented in Table 1 and Figure 2, respectively. The coarse sand used in this study consisted of particles passing No.10 standard sieve and maintained on No.20 standard sieve. Medium sand used consisted of particles passing No. 30 sieve and maintained on No. 50 sieve. Hence, uniformity coefficient (UC) of porous media of both aquifers was less than two. This shows that both media consisted of homogenous sand particles (Sharpe, 2002).

Table 1:  Physical characteristics of aquifers

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>D_{10}(mm)</th>
<th>D_{50}(mm)</th>
<th>UC</th>
<th>( \rho ) (g cm(^{-3}))</th>
<th>n</th>
<th>K (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sand</td>
<td>0.973</td>
<td>1.47</td>
<td>1.624</td>
<td>1.70</td>
<td>34.6</td>
<td>0.0015</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.31</td>
<td>0.36</td>
<td>1.21</td>
<td>1.73</td>
<td>35.7</td>
<td>0.00034</td>
</tr>
</tbody>
</table>

Figure 2: Particle size distribution curves for the porous media.
Tracer concentration was measured by a sampling port 5 hours and 9 hours after the tracer injection. All of plumes are in good agreement with the flow paths. The plumes had displaced radially from the injection zone after 5 hours and 9 hours. During the experiments, plumes were developed. Since diffusion even for large density differences is negligible (Alkindi et al., 2011), these spreading were indicated that plumes were affected by dispersion.

After each experiment, observed concentration values used to plot plume shapes. Also, concentration values obtained from theoretical model by applying various dispersivity values used to plot simulated plume shapes. For all of the experiments, peak concentration and shape of plumes were considered as indexes for dispersivities estimations (Table 2). Dispersivities were obtained when the best fit between simulated, observed, maximum simulated concentrations and plume shapes were achieved, simultaneously. The relationship between the maximum relative concentrations and density differences are shown in Figure 3. As presented in this figure, the maximum relative concentration of plume is dependent on density difference and maximum relative concentration is reduced by the passage of time (Table 2).

**Figure 3:** Reduction of maximum relative concentration as a function of density differences

All of experiments had unstable plumes except for experiments TC9 and TC10 which had the stable plume. For this experiment concentration distribution shape were obtained. In a short distance its relative concentration varied from 0 to 1 and vice versa. Its stable plume was characterized by development at bottom of tank and its dispersivities were not measured because it is beyond the scope of this paper. Considering experiments Tm9 and Tm10, it is seen that the dropping is dependent on permeability. The plums had not significant fingering and did not occur in the form of lobe –shaped instability in both aquifers.

**Table 2:** Maximum relative observed and calculated concentration at 5 hr and 9 hr

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sand Type</th>
<th>Density Difference (kg/m²)</th>
<th>Maximum Relative Concentration (5 hr)</th>
<th>Maximum Relative Concentration (9 hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Observed</td>
<td>Calculated</td>
</tr>
<tr>
<td>TC1</td>
<td>Coarse</td>
<td>2.25</td>
<td>0.455</td>
<td>0.461</td>
</tr>
<tr>
<td>TC2</td>
<td>Coarse</td>
<td>2.25</td>
<td>0.529</td>
<td>0.531</td>
</tr>
<tr>
<td>TC3</td>
<td>Coarse</td>
<td>4.5</td>
<td>0.281</td>
<td>0.275</td>
</tr>
<tr>
<td>TC4</td>
<td>Coarse</td>
<td>4.5</td>
<td>0.300</td>
<td>0.305</td>
</tr>
<tr>
<td>TC5</td>
<td>Coarse</td>
<td>6.75</td>
<td>0.319</td>
<td>0.319</td>
</tr>
<tr>
<td>TC6</td>
<td>Coarse</td>
<td>6.75</td>
<td>0.281</td>
<td>0.282</td>
</tr>
<tr>
<td>TC7</td>
<td>Coarse</td>
<td>9.0</td>
<td>0.243</td>
<td>0.245</td>
</tr>
<tr>
<td>TC8</td>
<td>Coarse</td>
<td>9.0</td>
<td>0.260</td>
<td>0.262</td>
</tr>
</tbody>
</table>
Table 2: Maximum relative observed and calculated concentration at 5 hr and 9 hr - continued

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TC9</td>
<td>Coarse</td>
<td>18.0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>TC10</td>
<td>Coarse</td>
<td>18.0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>TM1</td>
<td>Medium</td>
<td>2.25</td>
<td>0.586</td>
<td>0.596</td>
<td>0.411</td>
</tr>
<tr>
<td>TM2</td>
<td>Medium</td>
<td>2.25</td>
<td>0.713</td>
<td>0.705</td>
<td>0.465</td>
</tr>
<tr>
<td>TM3</td>
<td>Medium</td>
<td>4.5</td>
<td>0.597</td>
<td>0.597</td>
<td>0.440</td>
</tr>
<tr>
<td>TM4</td>
<td>Medium</td>
<td>4.5</td>
<td>0.598</td>
<td>0.597</td>
<td>0.439</td>
</tr>
<tr>
<td>TM5</td>
<td>Medium</td>
<td>6.75</td>
<td>0.600</td>
<td>0.596</td>
<td>0.424</td>
</tr>
<tr>
<td>TM6</td>
<td>Medium</td>
<td>6.75</td>
<td>0.602</td>
<td>0.596</td>
<td>0.414</td>
</tr>
<tr>
<td>TM7</td>
<td>Medium</td>
<td>9.0</td>
<td>0.594</td>
<td>0.595</td>
<td>0.395</td>
</tr>
<tr>
<td>TM8</td>
<td>Medium</td>
<td>9.0</td>
<td>0.560</td>
<td>0.564</td>
<td>0.405</td>
</tr>
<tr>
<td>TM9</td>
<td>Medium</td>
<td>18.0</td>
<td>0.543</td>
<td>0.542</td>
<td>0.346</td>
</tr>
<tr>
<td>TM10</td>
<td>Medium</td>
<td>18.0</td>
<td>0.537</td>
<td>0.538</td>
<td>0.300</td>
</tr>
</tbody>
</table>

All Results show that longitudinal and transverse dispersivity values obtained for both aquifers were very small and in agreement with results of the previous laboratory researches (Gillham and Cherry, 1982; Olsson and Grathwohl, 2007). Based on Table 3, the minimum and maximum mean of longitudinal dispersivity value obtained for the aquifer with medium sand are 0.96 mm and 1.54 mm which belong to the experiments with density difference of 2.25 and 18 kg/m³, respectively. Also, the minimum and maximum average of longitudinal dispersivity value obtained for the coarse sand aquifer are 1.14 mm and 9.63 mm which belong to the experiments with density difference of 2.25 and 9 kg/m³, respectively. As a result, the longitudinal dispersivity in both aquifers increases by the increase of density difference between resident and invading fluids (Figures 4-5).

Table 3: Mean Values of Longitudinal dispersivity, Transverse dispersivity and ratio of Transverse dispersivity to longitudinal dispersivity for two aquifers

<table>
<thead>
<tr>
<th>Density Difference (kg/m³)</th>
<th>Longitudinal Dispersivity (mm)</th>
<th>Transverse Dispersivity (mm)</th>
<th>α₁/αₖ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coarse Sand</td>
<td>Medium Sand</td>
<td>Coarse Sand</td>
</tr>
<tr>
<td>2.25</td>
<td>1.14</td>
<td>0.96</td>
<td>0.20</td>
</tr>
<tr>
<td>4.5</td>
<td>5.56</td>
<td>1.08</td>
<td>1.08</td>
</tr>
<tr>
<td>6.75</td>
<td>6.83</td>
<td>1.13</td>
<td>1.41</td>
</tr>
<tr>
<td>9</td>
<td>9.63</td>
<td>1.38</td>
<td>2.11</td>
</tr>
<tr>
<td>18</td>
<td>N/A</td>
<td>1.54</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 4: Transverse dispersivity as a function of density difference for Coarse Sand
The minimum and maximum average of transverse dispersivity values obtained for the medium sand aquifer are 0.18 mm and 0.39 mm which belong to the tests with density difference of 2.25 and 18 kg/m$^3$, respectively. Furthermore, minimum and maximum mean of transverse dispersivity for the medium with coarse sand are 1.20 mm and 2.11 mm which belong to experiments with density difference of 2.25 and 9 kg/m$^3$. Hence, an increase in density difference leads to an increased transverse dispersivity (Table 3 and Figures 5-6). Increasing in longitudinal and transverse dispersivities confirms the earlier research observations (e.g. Watson et al., 2002) in which density differences has a significant effect on dispersivities.

Considering results shown in Table 3 and Figures 4-7, it is clear that both transverse and longitudinal dispersivities for coarse sand aquifer were more than those for medium sand aquifer. This is in agreement with findings of earlier researches (e.g. Cirpka et al., 2006 for transverse dispersivity and Xu and Eckstein, 1997 for longitudinal dispersivity). By the increase in density difference, the longitudinal dispersivity for the coarse sand aquifer had more increment than longitudinal dispersivity for aquifer with medium sand. The same condition exists for the transverse dispersivity of these aquifers.

According to Table 3 and Figures 4-7, longitudinal and transverse dispersivities of coarse and medium sand aquifers have an exponential relationship with density differences. This shows that the coarse sand aquifers have a relationship with an exponent more than 1 and aquifer sand medium with less than 1. Hence, it can be concluded that the rising of dispersion by enhancing the density differences occurs in coarse sand media accelerately.

**Figure 5:** Longitudinal dispersivity as a function of density difference for Coarse Sand

![Figure 5](image)

**Figure 6:** Transverse dispersivity as a function of density difference for Medium Sand

![Figure 6](image)
The ratio of transverse dispersivity to longitudinal dispersivity \( \left( \alpha_T / \alpha_L \right) \) is an important factor for estimation of shape of contaminant plume which was also investigated in the experiments such as longitudinal dispersivity and transverse dispersivity. This ratio rises by increasing the density difference between the both aquifers (Table 3 and Figure 8). The coarse sand aquifer is affected more than medium sand aquifer. Accordingly, for a given media, the increase in the density difference between contaminant and resident water leads to broadening the plume shape. Of course, this is against the results of former researches. It happens because the gravitational forces affect the solute transport perpendicular to the flow direction. Hence, in an instable horizontal transport, contrary to instable vertical transport, an increase in the density difference leads to broadening the plume shape.

4. Conclusion
In this paper, the results of a series of two-dimensional experiments on instable displacements of fresh water by salt water solutions in coarse and medium sand aquifers are presented. The experiments were designed to investigate effect of density difference on longitudinal and transverse dispersivities and
specially to assessing its effect on the ratio of transverse to longitudinal dispersivity which is an important factor for determining the shape of contaminant plumes.

Overall, the major conclusions arising from this two-dimensional study of instable tracer displacements are summarized below:

1. In both coarse and medium sand aquifers, the maximum relative concentration is found to reduce by density differences enhancing as the nonlinear behavior.
2. The longitudinal and transverse dispersivities obtained from tracer experiments presented in this paper are in excellent agreement with those reported in the literature.
3. The increasing of the transverse and longitudinal dispersivity of coarse sand aquifer due to density differences is much more than that of the medium sand aquifer. There is more acceleration in raising the transverse and longitudinal dispersivity of aquifer with coarse sand than those for medium sand aquifer.
4. The transverse dispersivity of both aquifer medium increases more than longitudinal dispersivity by increasing density differences. Accordingly, the ratio of transverse to longitudinal dispersivity is enhanced by the increase in the density difference in both aquifers.
5. For a given porous media, in an instable horizontal displacement, the gravitational forces affects perpendicular to flow direction. Hence, the increase of density differences leads to broadening the plume shape.

Acknowledgement
The authors of this article would like to thank the Shahid Chamran University of Ahvaz, College of Graduate Studies and Research, who made this research work possible through a doctoral thesis.

References
Laboratory Investigation of Effects of Density difference on Two-dimensional Dispersivities


Amir Naserin, Hadi Moazed, Abdorahim Hooshmand and Mohammad Mahmoodian Shooshtari


