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An Experiment to Measure Transport Parameters in a Saturated Heterogeneous Scaled Medium

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An Experiment to Measure Transport Parameters in a Saturated Heterogeneous Scaled Medium

Submitted in Partial Fulfillment of the Requirements for Graduation with Honors to the Department of Mathematics, Physics, Engineering, and Computer Science at Carroll College, Helena, Montana

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April 7, 1995
An Experiment to Measure Transport Parameters in a Saturated Heterogeneous Scaled Medium

by

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A thesis for honors recognition approved for the Department of Mathematics, Engineering, Physics, and Computer Science

Carroll College
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Abstract

One of the major difficulties in groundwater research is determining an appropriate scale at which to conduct an experiment. Because of a phenomenon called the scale effect, measured values of parameters in heterogeneous media can vary with the scale of measurement. The objective of this experiment was to measure the parameters of dispersivity and velocity at different length scales, to see if the measured values would converge to a limit at some scale of measurement. A good deal of research has been conducted on the scale effect in heterogeneous media, but this phenomenon is still not totally understood. The heterogeneous medium for this experiment consisted of two sands of differing hydraulic conductivity. A special structured pattern was constructed of the two sands in a flow cell in which dispersivity and velocity could be measured at several length scales. The dependence of the measurements on the scale of measurement could then be studied. An interesting result of the experiment was that values of dispersivity converged at the longest length scale while values of velocity never reached a limit. Finally, it appeared that dispersivity values measured throughout the flow cell varied depending on which type of sand the measurement was taken in.
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Introduction

One of the major difficulties in groundwater research is determining an appropriate scale at which to conduct an experiment. Should one consider a sample that is 2 kilometers, 2 meters, or 2 centimeters in length? In a heterogeneous medium, the measured values of parameters can vary with the scale of the experiment. These variations are due to a phenomenon known as the scale effect. Our objective is to measure two such parameters, the velocity of transport and dispersivity, over several different length scales, and see if it is possible to find a length scale at which the values converge on some limit. Theory suggests that these limits occur, but laboratory experiments on heterogeneous media to back up the theory are lacking. A laboratory experiment involving groundwater transport of solutes through a saturated heterogeneous porous medium was designed by Dr. Stephen Silliman, Associate Professor in the Department of Civil Engineering and Geological Sciences at the University of Notre Dame. We performed the experiment from June through August, 1994 in the Groundwater Research Laboratory at Notre Dame. This was part of an ongoing project sponsored by the United States Department of Energy. The purpose of this project is to improve capabilities for measuring parameters in the field that will allow us to model and predict more accurately groundwater transport of solutes such as spilled chemicals.
Definition of terms

Before describing the experiment, I will define some of the terminology that will be used in this paper. The following definitions are adapted from Freeze and Cherry, 1979. Darcy's Law is an empirical relationship used to predict groundwater motion. It states that the volume of flow per unit area per time through a medium is proportional to the hydraulic gradient. This hydraulic gradient is the gradient of a potential function known as hydraulic head. Hydraulic head, \( h \), is found by dividing the total potential energy density, \( \rho gz + p \), at a point in a fluid by the weight density of the fluid, \( \rho g \). It has dimensions of length. The hydraulic head is dependent both on elevation and on the pressure at a given measurement point.

Hydraulic gradient is given the symbol \( i \) and, in one dimension, is equal to \( \frac{\Delta h}{\Delta x} \), or in differential form, \( \frac{\partial h}{\partial x} \),

where \( \Delta h \) is the change in hydraulic head between two different measurement points and \( \Delta x \) is the distance between them. Darcy's law is formally written as:

\[
Q = -KiA
\]  

(1)

where

\( Q = \) outflow rate (\( L^3/T \), i.e. meters\(^3\)/sec)
\( K = \) hydraulic conductivity (\( L/T \), i.e. meters/sec)
\( i = \) hydraulic gradient (\( L/L \), i.e. dimensionless)
\( A = \) cross sectional area of the medium (\( L^2 \), i.e. meters\(^2\))
The hydraulic conductivity, $K$, is a property of the material, as well as of the fluid flowing through it. Materials with large pores between particles typically have high values of hydraulic conductivity because water (or any other fluid) can pass through these large pores with little resistance. Gravel is an example of a material with a high conductivity. On the other hand, materials with small pores between the individual particles have low values for hydraulic conductivity. Limestone or clay are a couple of examples of this type of medium.

The experiment discussed below deals with transport through a saturated heterogeneous medium. A heterogeneous medium is a medium whose hydraulic conductivity varies with position. A soil which has different layers of sand and gravel is an example of a heterogeneous medium. If a soil consists entirely of fine-grained sand, the medium is instead homogeneous. The transport considered in this experiment is that of a dissolved solute in water. The term saturated refers to the fact that all pores within the medium are filled with water.

Two additional terms that need to be defined are advection and dispersion. They are the two mechanisms that combine to cause the transport of solutes. Advection refers to the movement of the center of mass of the solute cloud with the average velocity of the fluid transporting it. All of the solute and the fluid move with the same velocity. The solute is moved by the bulk motion of the fluid.
Advection is characterized by the velocity of the center of mass of the solute. A graphical representation for advection is shown in Figure 1. Part a) shows a cloud of solute traveling laterally. The center of mass (represented by the black dot) is traveling with the fluid's average velocity. Because all of the particles in the cloud have the same velocity the shape of the cloud does not change as it moves. Part b) shows solute concentration at a sensor location versus time. Before the cloud arrives at the sensor, the concentration is zero. As the cloud passes over the sensor the concentration of solute in the cloud is recorded. Graphs of this type are called breakthrough curves because they show the way that concentration goes from the initial to final value at a given location. The vertical line shows that concentration at this location jumps from zero to full concentration of solute instantaneously.

![Figure 1-Advection](image-url)
Dispersion is responsible for the spread of solute around its center of mass and causes the solution to become diluted. Because of dispersion, the solute in our experiment does not travel with the average fluid velocity. Dispersion has been shown to result from heterogeneities in the hydraulic conductivity of the medium (Silliman and Simpson, 1987). Dispersion is a macroscopic occurrence in that it can be seen with the naked eye. A graphical representation for dispersion is shown in Figure 2. Part a) shows the spread of the solute front about its center of mass, as it travels laterally with the fluid. Part b) is again a breakthrough curve which shows how the concentration rises to full concentration when the effects of dispersion are included. This time, the solute concentration gradually rises from zero up to full concentration. Eventually, the concentration would fall to zero with the trailing portion of the cloud.

Figure 2-Dispersion
Literature Review

A great deal of laboratory, field, and theoretical research on the scale effect is the basis of our research. In the field, Sudicky et al. [1983] have shown that the classical advection-dispersion equation inadequately describes solute transport because dispersion is a time- or scale-dependent phenomenon that cannot be assumed to be constant. Pickens and Grisak [1981b] conducted a set of laboratory and field tests on a layered heterogeneous medium. They developed a linear relationship between a dispersion parameter, dispersivity, and distance of solute travel. They have proposed that this nonconstant dispersivity would reach an asymptotic limit in time.

In another laboratory experiment, Sudicky et al. [1985] showed that the classical advection-dispersion equation could not properly model flow in a layered medium. For their experiment, the effects of local longitudinal dispersion (dispersion in the direction of flow) were much lower than were the dispersive effects of molecular diffusion between a layer of sand and silt. Therefore, an equation including the effects of this diffusion and neglecting the effects of longitudinal dispersion could be a better model for solute transport.

Two theoretical experiments on the scale effect also deserve mention. Schwartz [1977] performed a statistical analysis of a heterogeneous medium and focused on macroscopic (i.e., from well to well) dispersive effects.
instead of microscopic (pore scale) effects. In some of the experimental media he produced, Schwartz found that dispersivity was a function of space. He also found that in media where hydraulic conductivity differences between regions were minimal, dispersivity also was lower. Gelhar et al. [1979] performed a statistical analysis of a stratified heterogeneous medium. They found that values of dispersivity depend upon variations in hydraulic conductivity. They also were able to show that values of dispersivity reach an asymptotic value that was dependent upon the structure of the medium, over a large time period.

The present study that we have conducted builds on this previous work on heterogeneous media. It is a study on the scale effect in measuring dispersivity. A good deal of research has been done on the scale effect, but this effect is still not totally understood. A medium was constructed for this study that contained a heterogeneous pattern which was repeated at several different scales of length. This allowed us to determine if the scale of measurement had an effect on the measured values of dispersivity, and whether these values would reach an asymptotic limit at one of these length scales.

**Experimental Design**

The purpose of the experiment is to model the transport of a solute in groundwater. The solute we used was salt dissolved in water, so we were actually studying transport
of the chloride ion. We chose this solute because it is non-reactive with the sandy medium through which it traveled. Thus we could focus on the actual hydraulics of the system without having to worry about the chemical interactions of the solute and the sandy medium.

We conducted the experiment in a Plexiglas flow cell (See Figure 3). The dimensions of the cell were 91 cm X 46 cm X 10 cm. The inflow end contained a reservoir where the solute was mixed with the water. A pump was used to force the solution laterally across the cell.

![Figure 3-Flow cell](image)
On the outflow end was an outflow reservoir divided into three equal sections. One constant hydraulic head outflow tube drained each of the three outflow reservoirs. The outflow reservoirs were mixed reservoirs, meaning that instead of draining one small area, each outflow tube received fluid from approximately one third of the cell. Therefore, instead of being a point measurement, the outflow tubes should provide measurements averaged out over the length of the cell.

Inside the cell we packed a special heterogeneous porous medium. The medium consisted of two different conductivity sands, one high and one low. The pattern was based on a fractal pattern called the Menger sponge, which is shown in Figure 4. The various rectangles were regions of high conductivity sand and the surrounding material was low conductivity sand. If one looks at a small area of the cell (like the very upper left corner) one notices a pattern in which one rectangle is surrounded by eight smaller rectangles (the smallest rectangles in the picture). Then, taking a wider view, this center rectangle becomes one of the eight rectangles surrounding an even larger center rectangle. Finally, looking at the center of the figure, one sees the largest rectangle surrounded again by eight smaller rectangles. At each scale of the pattern, the proportion of the area of a small rectangle to the area of the large rectangle is the same.
This Menger sponge is called a scaled pattern because the same pattern is seen at a number of different scales. This property, that the patterns of heterogeneities are repeated at different scales, is a concept in fractal geometry known as self-similarity (Wheatcraft and Tyler, 1988). This and other types of self-similar fractal patterns are believed to exist in soils found in the field.

Our experiment was a two-dimensional experiment. If one picks a point in Figure 4 and moves either horizontally or vertically, one eventually runs into a different conductivity sand. However, going from that point into the cell, perpendicular to the paper, one remains in the same conductivity sand.

Sampling tubes were located on the back wall of the cell. The points where these tubes were located can be seen
as the circles in Figure 5, which shows the exact pattern that was packed in the flow cell. The smallest scale in the Menger sponge has been eliminated due to difficulty in packing. We used these sampling tubes to collect outflow samples of fluid throughout the experiment. These outflow samples were used to calculate solute concentrations at various times and locations. We called these internal measurement locations our piezometer points, because they also served as piezometers for measuring hydraulic data on a related project.

Figure 5-Piezometer locations

Originally, we planned to use electrical readings to measure concentrations of the solute. Chloride ions are charge carriers which allow electrical current to flow through aqueous salt solutions. The resistance of a given
sample of solution is directly proportional to the concentration of chloride in the solution. Thus the concentration of chloride can be determined by measuring the electrical resistance of the salt solution. However, because there were problems with the electrodes, we opted to take most of the concentration measurements from the outflow tubes instead. In further experiments at Notre Dame, Dr. Silliman replaced the stainless wires with platinum and obtained better results.

After packing the cell with sand (which we did under water to keep air bubbles out), we put the lid in place and sealed the flow cell. Initially, the solution that saturated the medium was distilled water. The first test we performed was to photograph a visible tracer as it moved through the sample. We introduced a pulse of water containing red food coloring, which allowed us to see how the solute was transported through the medium and to verify that the solutes could not take any shortcuts near the walls of the cell. We documented the results with snapshots at different times during the test. A representative photo is shown in Figure 6. The dye was flushed from the cell using pure distilled water.

During the quantitative part of the experiment, we raised the concentration of solute from zero (distilled water) to the final concentration in several jumps. At each jump, we collected outflow samples at several points within the cell and at various time intervals until the full
concentration was reached throughout the entire cell. Some of the points we measured were the internal measurement tubes and some were the outflow tubes at the end of the flow cell. We continued to inject the fluid at the inflow end until the fluid leaving the outflow tubes had the same concentration as the injected fluid.

Figure 6-Photograph of visual test

The chloride ion concentration of each of these samples was later calculated. This was done using a specific ion electrode and by comparing with a calibration curve to give the actual concentration of the samples. The calibration curves were constructed by finding the mV reading on the meter for solutions whose concentrations were
known. All of the data were recorded and graphed in a series of breakthrough curves, some of which appear later in this paper.

Theory

The one-dimensional form of the advection-dispersion equation is (Ogata and Banks, 1961)

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x}$$  \hspace{1cm} (2)

where

- $D =$ the dispersion coefficient ($L^2/T$)
- $C =$ the solute concentration ($M/L^3$)
- $x =$ distance ($L$)
- $v =$ average linear groundwater velocity ($L/T$)
- $t =$ time ($T$)

The dispersion coefficient $D$ can be written as $D = \alpha v + D^*$ (Freeze and Cherry, 1979). $D^*$ is the coefficient of molecular diffusion which is negligible for this experiment because we pumped at a large enough velocity (Freeze and Cherry, 1979). Therefore $D = \alpha V$, where $\alpha$ is a quantity called the dispersivity and $V =$ velocity. The solution of this equation for a continuous source at the end of a semiinfinite domain is: (Ogata and Banks, 1961)

$$\frac{C}{C_0} = \frac{1}{2} \left[ \text{erfc} \left( \frac{x-Vt}{2\sqrt{\alpha Vt}} \right) + \exp \left( \frac{V x}{\alpha Vt} \right) \text{erfc} \left( \frac{x+Vt}{2\sqrt{\alpha Vt}} \right) \right]$$  \hspace{1cm} (3)
The term \( erfc \) is short for the complementary error function, which is related to the cumulative normal distribution (Ross, 1970). The quantity, \( C/C_0 \), is the ratio of the solute concentration at a given location in the medium to the full concentration in the inflow reservoir. The other terms in the solution all refer to the same quantities as their counterparts in the advection-dispersion equation.

The second term of the solution is negligible for all but small \( x \) and \( t \). The equation can therefore be written as (Silliman and Simpson, 1987)

\[
\frac{C}{C_0} = \frac{1}{2} \text{erfc} \left( \frac{x - Vt}{2\sqrt{aVt}} \right)
\]  

This solution is used to fit a curve to the actual concentration data that we obtained at the measurement points at various times. We plotted the actual data points and then superimposed the curve onto the points. The curve could be adjusted by giving different values for the velocity and dispersivity. The curves that we produced were breakthrough curves similar to the ones shown in Figures 1b) and 2b) with the exception that those curves dealt with finite length input of solute while our experiment involved continuous input of solute. These curves show at different points inside the cell how the chloride concentration in the solution increased as it flowed laterally across the cell.
By adjusting the input values of velocity and dispersivity in the Fortran program, we found the curve that best fit the actual data. Changing the value of dispersivity adjusted the slope of the curve, while changing the velocity moved the curve to the left or right. As expected, a higher value of dispersivity made the curve more skewed to the right. A dispersivity of zero would correspond to Figure 1 b) where the curve is a vertical line. Because our experiment involved continuous input of solute, our curves do not drop back to zero as in Figure 1b). A higher value of velocity shifted the curve to the left along the time axis. Obviously a greater velocity of transport would cause the concentration to peak in a shorter time period.

Results

The purpose of this experiment was to find a length scale in the laboratory where we would see convergence of velocity and dispersivity on some limiting values. We were also looking to determine whether these values are dependent upon the scale of measurement. In addition, we were trying to collect some data from the scaled medium for comparison with a later experiment with a random field.

Figure 7 shows the relationship between velocity of solute transport and distance from the inflow. There are three types of measurements shown in this figure. Those points labeled 'X' are points from the electrodes which were
located at approximately 10 and 30 cm from the inflow. Some of the data from the electrodes appeared to be reliable, so those have been included. The points labeled '*' are measurements from the piezometer points. Recall, these are the internal points throughout the cell from which we extracted samples in order to measure solute concentrations. Finally, the points labeled 'o' are measurements from the outflow tubes.

![Graph](image)

**Figure 7-Variation in velocity with distance from inflow**

As expected, we noticed a rather high variance in velocity at internal points throughout the cell. Look, for example, at the two points located at a distance of 20 cm from the inflow. Actually, a third point lies on top of the lower point located at 20 cm. The discrepancy in these
values can be accounted for by realizing that these points are located at different heights within the cell. Therefore, the paths that the solutes follow to reach the measurement points can differ significantly. High values of velocity occur at points that are located in (or behind) the rectangular regions of high conductivity sand. It stands to reason that solutes will travel more quickly to those points than to points located in the middle of the low conductivity areas.

Inspection of the three outflow points located at 91 cm reveals three features. First, the highest velocity at that distance comes from the middle outflow (this is not indicated on this graph.) This is a result that we did expect to see because that outflow sits directly behind many of the high conductivity rectangles, including the large one in the center. Our earlier visual experiment showed quite clearly that the solutes traveled quickly across these large high conductivity zones.

Another observation to be made about these velocity values is that, as we expected to see, the top outflow had a lower velocity than the other two. The reason that we expected to see this was that the overall outflow volume at the top was significantly less than the volumes flowing through the bottom and middle outflows.

A final conclusion from the data at the outflows is that there is a significant variance among the three velocity values. For the internal measurement points, we
had anticipated a large variance. However, for these outflows points, we expected to see a low variance of velocity because the solution flowing into these outflow tubes was mixed in the outflow reservoir. Therefore, the solution draining into each tube flowed through all of the heterogeneities represented in the cell. Such was the case for all three outflows, so we expected the velocities roughly to average out to the same value for each one. It seems quite likely that when we conduct the random field experiment these values will be a lot closer.

Figure 8 relates the dispersivity, $\alpha$, with distance from the inflow. Again, the points labeled 'X' came from the electrodes, the points labeled '*' came from the piezometer tubes, and the points labeled 'o' came from the outflow tubes.

The first thing to notice is the large variation in values for dispersivity at 20 cm. A third point is located on top of the lower value at this distance. This variation can be explained by the fact that the points were located in different conductivity sands; i.e., the high value was measured in low conductivity sand and the lower values were measured in high conductivity sand. Measurements taken from the two different materials will have a different sample support, which (by one definition) is the area over which fluid is drawn (Silliman, 1995). When fluid is drawn from a low conductivity zone, it must be drawn from a larger capture zone than in a high conductivity zone to obtain the
same volume of fluid. This is because the low conductivity sand has smaller pores and thus a smaller volume of fluid can be contained within a zone of low conductivity sand than in a zone of equal size containing high conductivity sand. Therefore, a higher dispersivity is expected because previous research (such as that of Pickens and Grisak, 1981b) has shown that dispersivity increases with distance of travel.

![Diagram of dispersivity variation with distance from inflow]

Figure 8-Variation in dispersivity with distance from inflow

A second important observation to be made from Figure 8 is that the values for dispersivity taken at the three outflows converged. As with the velocities at the outflows, we did expect the dispersivity values at the outflows to converge for these measurements because the fluid is mixed
in the outflow reservoirs. One of the overriding goals of our experiment was to see if the values of dispersivity would converge at some length scale. Indeed, dispersivity does converge over the longest length scale (91 cm) in our flow cell.

Again, as we expected, the outflow dispersivities converged to a fairly high value. We expected to see a lot of dispersion simply because we are averaging outflows from a lot of different high and low conductivity zones. By the time the solute has traveled over the whole cell, it should be quite widely dispersed.

Figures 7 and 8 can also be compared to each other at the points located at 20 cm from the inflow to further reinforce that the measurements taken in high conductivity sand give high values for solute transport velocity and low values for the dispersivity.

Figures 9 and 10 are breakthrough curves with normalized concentration on the dependent axis and time on the independent axis. The normalized concentration at a given time is a percentage of the full concentration of the injected water. Therefore, when the curve reaches a concentration of 0.5 the concentration at the measured location is half of the concentration of the injected water. If not for the effects of dispersion, these graphs would appear as vertical lines instead of sloped lines. The degree to which the curve is sloped from the vertical is determined by the value of dispersivity. The horizontal
translation of the curve is determined by the solute velocity.

Figure 9-Piezometer sample concentration curves

Figure 9 comes from data gathered from three different internal points, one at 21 cm, one at 47 cm, and one at 77 cm from the inflow. As expected, the curve at 77 cm is skewed more to the right, indicating an increased degree of dispersion with increasing distance of travel. The fact that the curves have different horizontal locations does not indicate anything about their relative solute velocities because the points are at different distances from the inflows. Obviously the curve located at 77 cm will be shifted to the right along the time axis from the other two
because it would take much longer for the solute to reach that spot. If the measurement points were located at the same distance from the inflow, then the graph of the one with the greatest solute velocity would be shifted farthest to the left.

Figure 10 shows breakthrough curves for two of the outflow tubes. These points are located at the same distance from the inflow, so a comparison can be made between their velocities. The shift to the left of the graph of the middle outflow indicates a greater velocity of solute transport to the middle outflow. This makes sense because the middle outflow sits directly behind a lot of high conductivity sand, including the large rectangle in the center. Again it should be noted that the outflow volume in the middle was significantly greater than outflow volume at the top. This serves as an indicator of the greater velocity across the middle of the cell. Although the data for the bottom outflow are not shown, their behavior was quite similar to the top outflow. The significant differences between the two curves, especially in the velocity parameter, came as somewhat of a surprise to us. While we expected to see some differences in these velocity values, the actual differences were greater than anticipated for these mixed outflows. We still expect that there will be less variation in velocity measurements on the random field experiment.
Conclusions

This research and experiment deals with a subject about which a lot of theory and general field data exist, but not a lot of controlled laboratory experiments. Consequently, some of the results are consistent with our expectations, while some results came as a surprise to us. The non-convergence of velocities at the cell outflows was not a result we expected to see. As I have discussed previously, we expected the transport of fluid across the range of heterogeneities to cause the values of velocity and dispersivity to be averaged out prior to the outflow from the cell. The implications of the non-converging velocities
may be quite significant to groundwater research. In the field one needs to be able to sample data at various test wells and use those data to make predictions about the surrounding locations. It is desirable to make generalizations about a given parameter because it would be impossible to drill enough wells to completely describe groundwater transport characteristics across a region. However, it is also important to make observations such as the non-converging velocities of our cell, in order that researchers in the field do not draw faulty conclusions based on assumptions that a parameter's behavior is well-defined.

An encouraging result of our research was the convergence of dispersivities over a (relatively) large length scale. Perhaps it is possible to find a length scale for a given medium at which the dispersivity converges to a limit. This could allow accurate modeling of transport in the field. It is intriguing that convergence did indeed occur for dispersivities, while it did not occur for velocities. This phenomenon may be a function of this structured medium that we chose to study, and probably will not be a result we see with the random field experiment.

Finally, the variation of the measured values of dispersivity for the internal points of the cell was a result that has not been seen before. This result could lead to a change in research techniques because, until this time, field sampling has not taken into account the
conductivity of the material being measured. Perhaps further research will have to come up with a more precise and efficient method for measuring dispersivities in the field.
References


