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Flow Channeling in Strongly Heterogeneous Porous Media: A Numerical Study

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ABSTRACT

Flow and solute transport through porous media with strongly variable permeability were studied for parallel and convergent/divergent flows. The variation in hydraulic conductivity K causes the fluid to flow through a porous medium along less resistive pathways. Thus solute dissolved in the fluid is transported with very different velocities. Numerical simulations are performed to study flow and solute transport in a three-dimensional heterogeneous porous medium. It is found that for a strongly heterogeneous medium the particles (or solutes) travel through the medium along preferred flowpaths, which we call channels. These channels possess hydraulic properties that are different from those of the global porous medium. The log hydraulic conductivities along these channels have a greater mean value and a smaller standard deviation. The differences or shifts were calculated as a function of the hydraulic conductivity variance of the global porous medium. It is found that these shifts are maintained regardless of the direction of the hydraulic gradient applied to the porous block. Tracer breakthrough curves for a pulse injection were also calculated. For small standard deviation of the hydraulic conductivity distribution, a peak is found which spreads out around its peak value as the standard deviation is increased. However as the standard deviation is increased further, a new peak at much earlier time emerges. This may be due to increasing channeling effects at large standard deviations. For the case of spherical pressure boundary around point tracer injection, the flow follows the usual divergent pattern only for small variations in hydraulic conductivity. When the standard deviation in log K is large, a significant portion of the flow becomes channelized, i.e. it tends toward a linear flow pattern.

1 INTRODUCTION

The variation of hydraulic conductivity in a porous medium causes the fluids flowing through it to have different velocities. If the variability of the hydraulic conductivity is large, it is expected that fluid velocities cover a wide range of values. Thus a part of contaminants dissolved in the fluid may be transported with velocities larger than the average velocity of the fluid. In practical problems concerning transport of radioactive or toxic wastes, the earlier arrival of contaminants may be of vital importance.

The heterogeneous porous media are very complex. Usually they are characterized by statistical parameters, as for example, the geometric mean of hydraulic conductivity and its standard deviation. Fluid flow and solute transport in heterogeneous porous media have been studied using stochastic methods (Gelhar and Axness, 1983; Gelhar, 1986; Dagan, 1984, 1986; Neuman et al., 1987; Neuman and Zhang, 1990; Graham and McLaughlin, 1989). In most of these theoretical studies small variations in the hydraulic conductivities are assumed and the applicability of results obtained are limited to moderately heterogeneous porous media.

Stochastic modelling by using numerical models are also widely used (Tompson and Gelhar, 1990; Desbarats, 1990; Chin and Wang, 1992). Tompson and Gelhar (1990) using the random walk particle method studied the solute transport through a large heterogeneous medium. Standard deviation of hydraulic conductivity was varied between 1.0 and 2.3 (in natural log base). Desbarats (1990) used values of 1.50 for the standard deviation. In these studies, reasonable agreement is obtained between the numerical simulations and some theoretical relationships when the standard deviation is increased to some large values. Furthermore, results of these three-dimensional models for solute transport have been compared, for example, with the large-scale tracer test conduced at the Borden site (Rajaram and Gelhar, 1991; Graham and McLaughlin, 1991, Zhang and Neuman, 1990).

An important aspect that has been studied is the prediction of solute transport through heterogeneous porous media and its uncertainty (Dagan, 1990; Rubin, 1991b; Rubin and Dagan, 1992). Methods for the prediction of dispersion processes and the spatial moments of a tracer plume are studied by Rubin (1991a, 1990). In these studies Monte Carlo simulations are used for calculating the parameters that characterize the

dispersion. Vomvoris and Gelhar (1990) studied the concentration variability in a three-dimensional aquifer using a spectrally based perturbation approach.

Tsang and Tsang (1989) described flow properties that are found in a fracture with variables apertures and extended their results to transport through a two-dimensional porous medium with strongly variable hydraulic properties. They point out flow channeling occurs in such systems. In this paper we will extended this to the three dimensional case. The similarities and differences between parallel flow and convergent/divergent flow will also be studied. Fluid flow in a porous medium seeks the most conductive paths. For a medium with strongly variable permeability this effect can be very pronounced with the result that some paths will show a very high flow rate. In this paper, we shall discuss the impact of this flow distribution upon the solute transport.

2 THE MODEL

Fluid flowing through a porous medium have variable velocities due to the variability of the medium permeability. The fluid seeks the least resistive pathways. This means that possible solute dissolved in the fluid may be transported longer distances in shorter time, so that a fraction of the solute will have an arrival time that may be many times less than the mean time for the bulk of the fluid.

To study such effects, the porous medium in our model is divided in cubic cells or nodes of dimensions ΔL_x, ΔL_y, and ΔL_z, where the three lengths are equal. A value of hydraulic conductivity is assigned to each node from a conductivity distribution. It is assumed that the hydraulic conductivity is log normally distributed and correlated in the space. An exponential covariance function is used. The generation of the node conductivities is performed by means of a three-dimensional Turning Bands Random Field Generator (Tompson et al., 1989). The hydraulic conductivity distribution is defined by its mean and the standard deviation. In practice the mean value of the distribution works as a scale factor and is set equal to 0.0, implying a value of 1.0 conductivity units for the hydraulic conductivity.

The flow calculations follow the procedure used by Moreno et al. (1988) for flow in a single fracture, with the equations extended to three dimensions. The flow between two adjacent nodes is determined by multiplying the conductance between the centers of these nodes by their respective pressure difference. Let K_1 and K_2 be the hydraulic conductivities of two adjacent nodes, A the area of the interface between the nodes, and Δd the distances from the center of the node to the interface between them. Then the conductance may be calculated as,

$$C = \frac{A}{\frac{\Delta d}{K_1} + \frac{\Delta d}{K_2}} \qquad (1)$$

Once the conductances are known, the mass balance for each node may be established. For given boundary conditions the pressures in the nodes are calculated. Then, from the pressure field the flow between any two adjacent nodes is obtained.

Solute transport through the porous medium is simulated by a particle tracking technique. Particles are introduced at the inlet and are followed through the grid. They are collected at outlet and the travel time for each particle is recorded. From this travel time distribution, we may determine the mean travel time and the variance of the travel times.

An estimate of the dispersion of nonsorbing tracers in an one-dimensional flow system may be done from the travel time distribution. Let us define dispersivity as the ratio of dispersion over water velocity. It is commonly assumed to be dependent only on the properties of the porous medium and has the dimension of length. In our model, the porous block has an arbitrary dimension, and so a dimensionless parameter is more useful. Peclet Number is a dimensionless number which relates the dispersion with the advection and is defined as,

$$Pe = \frac{u\,L}{D} \tag{2}$$

where u is the water velocity, L the travel distance, and D the hydrodynamic dispersion.

Assuming that the one-dimensional advection-dispersion equation is valid, Robinson (1984) deduced several relationships for calculating the water velocity and dispersion as a function of the first and second moment of the particles travel time and/or the inverse travel time. From these relationships, three different expressions are deduced for the Peclet number,

a) as a function of $< t >$ and $< t^{-1} >$

$$Pe = \frac{1}{\sqrt{<t><t^{-1}>} - 1} \tag{3}$$

b) as a function of $< t >$ and $< t^2 >$

$$Pe = - \frac{\sqrt{3 <t^2> - 2 <t>^2} - 4 <t>}{\sqrt{3 <t^2> - 2 <t>^2} - 1 <t>} \tag{4}$$

c) as a function of $< t >$ and $< t^2 >$

$$Pe = - \frac{\sqrt{3 <t^{-2}> - 2 <t^{-1}>^2} - 4 <t^{-1}>}{\sqrt{3 <t^{-2}> - 2 <t^{-1}>^2} - 1 <t^{-1}>} \tag{5}$$

3 CALCULATIONS

Two grid sizes were used, 20x20x20 nodes, the normal grid, and 40x40x40 nodes, the fine grid. The fine grid was used for simulations with a small correlation length. For example for a ratio correlation length to transport length of 0.05, two nodes are used for one correlation length if the fine grid is used. A fine grid was also used for the case where the ratio of correlation length to transport length is 0.10, for the sake of comparison and to check the reliability of results obtained using the normal grid.

Realizations of the three dimensional porous blocks are generated using the Turning Bands Random Field method (Tompson et al., 1989) with mean log conductivity of 0.0 and standard deviation of 1.0. From these realizations, grids with different standard deviations are generated. This means that the structure of the grid in a set of computer runs is the same; only the standard deviation is changed. In this way, the effect of changing the standard deviation on the properties of the porous medium may be studied for the same realization. Standard deviation is varied over a wide interval, from 0.1 to 6.0 (in natural log). A standard deviation of 6.0 implies a porous medium having a very large variation in conductivities (95 % of the values are in an interval that covers about 6 orders of magnitude). The hydraulic conductivities are generated with ratios of correlation length/transport length of 0.05, 0.1 and 0.2.

Pressures are calculated by a matrix solver using a preconditioned conjugate gradient method. Then the flow, and hence the velocity, between adjacent nodes are obtained.

A particle tracking technique is used for calculating solute transport through the porous medium. A great number of particles is introduced with the fluid at the high pressure

medium. A great number of particles is introduced with the fluid at the high pressure side. The number of particles introduced in each inlet node is proportional to the flow through that node, and they are randomly distributed on the inlet surface of the node. Each particle is then followed through the porous medium.

The particle tracking is carried out by calculating the velocity of the particle in its actual location and then moving the particle a small distance $v\Delta t$. The time step is set to be small enough to get reliable results. In most of the cases, the time step was set such that the travel distance is equal to a tenth of ΔL (the node size). The use of an even smaller time step increases the calculation time, but the accuracy of the results is only slightly improved.

The velocity is calculated using an interpolation scheme developed by Goode (1990), which is extended to three-dimensions. The velocity in a given point is calculated by linear interpolation between the velocity in the node where the particle is and the velocities in the adjacent nodes. The velocity, in the section where the particle is located, is calculated by linear interpolation between the velocity at the inlet face and the velocity at the outlet face of the node.

Runs with different numbers of particles were performed to determine the adequate number of particles to be used. A number of about 2000-4000 particles is large enough to get reliable results.

No local dispersion within each path is considered in these calculations, but it may be included in a straightforward way when needed.

a) Regional parallel flow in a isotropic porous medium.

The flow is calculated for the three possible orthogonal directions across the heterogeneous porous block, which we call vertical, north-south and east-west labelled V, H1 and H2 respectively. For these three cases the boundary conditions are similar. No flow conditions are applied on the four faces parallel to the flow direction. For example for the vertical flow, no flow boundaries are set at the north, south, east, and west sides. At the other two sides constant pressures are assumed. The pressure at the inlet is set equal to P_2 and the pressure at outlet is set to be P_1, corresponding to high and low pressures respectively.

For uniform flow and a log normal distribution function of the hydraulic conductivity, linearized approximations of the average hydraulic conductivity may be given (Marsily, 1989, Bakr et al., 1978, Gutjahr et al., 1978)

For two dimensions: $$K = K_G \tag{6}$$

For three dimensions $$K = K_G\left(1 + \frac{\sigma^2}{6}\right) \tag{7}$$

where K is effective hydraulic conductivity, K_G the geometrical mean conductivity (or mean log conductivity) and σ the standard deviation of the hydraulic conductivity. We must keep in mind that these equations are derived by a linearization process and that they are mainly valid for "small" variations in conductivity.

The flow through the grid was calculated for the three possible directions for each realization. First the normal grid was used, and several realizations were carried out using a correlation length of 0.1 L, where L is the travel distance in the direction of the regional flow. The influence of the correlation length on the results is studied by carrying out additional simulations with a correlation length of 0.2 L using the normal grid (20x20x20 nodes) and simulations with a correlation length of 0.05 L using a fine grid (40x40x40 nodes). Finally simulations are performed using also the fine grid to study the influence of the discretization on the results. The normal grid is taken as a grid of 20x20x20 nodes. We find that the calculated flows and flow distributions were similar in both cases.

Results on the flow are shown in Figure 1. The results are expressed as the ratio between the actual flow rate for a given standard deviation and the theoretical flow rate using an effective permeability gives by Equation (7). Each point corresponds to the mean value of at least 12 runs, i.e. 3 directions of 4 or more realizations of the porous block. The statistical spreads of these results are indicated as vertical bars in two example points shown in the figure. These spreads are typical of all other points with the same standard deviation. The results show that the Equation (7) works well for standard deviation of 2.0 or less, but for larger values of the standard deviation the flow rates are significantly larger. The results for standard deviation less than 2.0 also shows that the flow is independent of the correlation length, as predicted by Equation (7). On the other hand, for large standard deviation the spreading of the results is very large and we cannot determine definitely the impact of the correlation length on flow. However, the figure does indicate perhaps that for large standard deviation and small correlation length (0.05 L) the values of the flow rate are smaller than that for the largest correlation length (0.20 L). For a correlation length of 0.10 L the values are intermediate.

The fact that for large standard deviations in hydraulic conductivity (greater than 4.0) the flow rates through the block is significantly larger than that predicted by Equation (7) is due to the fact that for large standard deviation, the fluid seek out paths of very high conductivity. Figures 2a and 2b display the difference between flow at small and large standard deviations. At large values, flow channeling is clearly seen (Figure 2b). Thus fluid flows through large conductivity paths with resulting larger flow rates as expected. This will further be seen in Figure 8.

From these results it may be concluded that the Equation (7) is valid for standard deviation less than 2.0 or 3.0 (in natural log). For strongly heterogeneous media with larger standard deviation, the effective conductivity will be a factor of 2 or more that that predicted by Equation (7). This may be caused by channeling of flow to the least resistive paths in the porous medium as further discussed in the next section.

b) Solute transport in a regional parallel flow. Isotropic porous medium.

A fluid flowing through a porous medium with variable hydraulic conductivity will seek the least resistive pathways or preferential "channels" in the porous medium. For a porous medium with strongly variable hydraulic conductivity this channeling effect may be very pronounced. Channeling is an especially important mechanism to be taken into account when solute transport is studied. The location of these channels is determined by the spatial distribution of the hydraulic conductivity and by the boundary conditions applied. If the boundary conditions are rotated the locations of the channels would change as well.

When particles flow through the porous medium, they seek the less resistive paths (or channels), and so they "see" a porous medium which has a hydraulic conductivity distribution that is different of the distribution used to generate the node conductivities. This new distribution will be called the channel conductivity distribution. One question of interest is whether the channel conductivity distribution is uniquely determined for a heterogeneous porous block or are they a function of, for example, the direction of the pressure gradient.

This question was studied by calculating the flow for the three orthogonal directions of the pressure gradient across the porous block. The particles are introduced at the inlet face and followed along their pathways in the porous medium and the hydraulic conductivity values of the porous medium through which the particles travel are recorded. From this, a new distribution of hydraulic conductivity is obtained (the channel conductivity distribution), which is then compared with the hydraulic conductivity distribution of the global porous medium. A typical distribution is shown in Figure 3, for a standard deviation in conductivity (global porous medium) of 4.0. The lighter lines show the conductivity distribution within the "channels" for the three orthogonal flow directions and the heavier line the conductivity distribution for the global porous medium. The porous medium through which the particles travel has properties which are very different of the properties of the global porous medium. The mean log conductivity is strongly increased and the standard deviation is decreased. It may then be expected that solute transport through this porous medium is characterized by the properties of this new porous medium (the channel porous medium)

If the direction of the pressure gradient applied to the grid is changed, then a new network of flow channels is formed. Figure 3 displays also the results of the three different flow directions for a particular realization. They show no significant difference between the properties of the channels when the three flow directions are compared with each other. The whole calculation was repeated for four additional realizations of the heterogeneous porous block, and similar results are obtained. Thus, it may be concluded that the properties of these channels (mean log conductivity and standard deviation of log conductivity) are independent of the specific location and geometry of these channels, but is unique for the heterogeneous porous block.

The relationship between channel properties and global properties is shown in Figures 4 and 5. Figure 4 shows the shift in the mean log conductivity (geometrical mean conductivity, K_G) between that for the channels and for the global porous medium as a function of the standard deviation of log conductivity. These shifts vary only slightly with the correlation length and the grid size. The statistical spreads of the results for 4 realizations with 3 directions each (12 cases) are indicated for two points and they are typical of the other points with the same standard deviation in the figure. They are large so that no conclusion on dependence of results on correlation length or grid size may be made. For comparison, the line in Figure 4 shows the results obtained by Tsang and Tsang (1989) for a two-dimensional heterogeneous porous medium. A horizontal line at $y = 0$ would correspond to the one-dimensional case where no variation is expected.

The shift in standard deviation between that for the global porous medium and the channels also increases with the standard deviation (Figure 5). For large standard deviations the spreading of the results over different realizations is large and no definitive conclusion on correlation length dependence may be obtained.

c) Longitudinal dispersion as a function of the heterogeneity of the porous medium.

If a solute is injected in the upstream zone of the heterogeneous porous block and collected at the outlet, its concentration will be spread by effect of the different velocities in various flow paths through which the solute is transported.

In addition to this velocity variation due to permeability heterogeneity there is also a smaller scale variation due to hydrodynamic dispersion in the porous medium. This would be added to the "macrodispersion" caused by various flow paths. In the direction of the flow, hydrodynamic dispersion smooths the breakthrough curves and increased slightly the spreading. In the traverse direction dispersion allows mixing of solute between two adjacent flow paths. This effect is not accounted for by the particle tracking technique used in the present simulations since we are interested to study only the macrodispersion caused by the different velocities in the various flow paths. However it can be straightforwardly added if needed.

The longitudinal macrodispersivity may be calculated from the stochastic theory (Gelhar and Axness, 1983; Gelhar, 1986). It is found that for isotropic porous medium the longitudinal dispersivity increases directly with the variance of log hydraulic conductivity and the correlation length:

$$\alpha = \frac{\sigma^2 \lambda}{\gamma^2} \qquad (8)$$

where α is the longitudinal dispersivity, σ^2 the variance of the log hydraulic conductivity, and λ the correlation length. The parameter γ is a flow factor defined as 1 by Neuman et al. (1987) and as $1+\sigma^2/6$ by Gelhar and Axness (1983). These two alternative expressions are approximately the same for small standard deviation in hydraulic conductivity.

Peclet Number may be used as a measurement of the dispersion and is defined in function of the dispersivity

$$Pe = \frac{u L}{D} = \frac{L}{\alpha} \tag{9}$$

where u is the fluid velocity, L the travel distance, D the dispersion and α the dispersivity

In our present investigation, we use particle travel times through the heterogeneous porous block to calculate the relative dispersivity as a function of the variance (Figure 6). Here the relative dispersivity is calculated using Equation (9) with the Peclet number calculated using equation (4). The upper line corresponds to runs with a correlation length of 0.20 L on the normal grid. The lowest line corresponds to the runs with the smallest correlation length (0.05 L). The lines between the earlier ones show the dispersivity for runs with correlation length of 0.10 L, using both the normal and fine grids. This means that the effect caused by the size of the grid used is negligible for this correlation length. For larger correlation length some effect of the grid size would be expected. The figure also shows that the dispersivity is increased by a factor of 1.6 - 1.7 when correlation lengths are increased by a factor of 2.0. Equation (8) predicts that the dispersivity would be increased proportionally with the correlation length.

The effect of flow channeling may be brought out by calculating the Peclet Number using three different ways (Equations (3) to (5)) and the results are shown in Table 1 for the runs with the normal grid and a correlation length of 0.1 L. If the dispersion caused by flow heterogeneity could be exactly described by the advection dispersion equation without strong channeled flow, then the three calculated Peclet Numbers would be equal. For a value of standard deviation of the hydraulic conductivity less than 1.0 the three Peclet numbers are similar. For large standard deviations and large dispersion, significant differences are found between the different ways to calculate the Peclet number. This means that, for heterogeneous porous medium with strong channeled flow, dispersion cannot be described by the advection dispersion equation.

We have based our calculations of the Peclet number on only the fastest 90 % of the particles which are collected. If the calculation is based on 100 % of the particles the dispersivity is increased by about 50 % for the range of standard deviation used in the simulations. The reasons for using 90 % of the particles in the calculations are that a) from the contamination point of view the species transported through the fast channels are more significant and b) radionuclides with travel time much longer than its half-life

may decay to low activity level. This is the situation in field tracer tests where the tracers with very long travel time are usually not recorded. If radioactive tracers are used the activity level would be too low after a very long time. Calculations were also made using only the fastest 50 % of the particles and then the dispersivity was decreased by a factor of about 2.

In Figure 7 the dispersivities are normalized with respect to the value of the dispersivity for the smallest variance. For a small variance the simulated values and the calculated values using the Equation (8) are equal regardless the approach used to calculate γ. The lines in the figure show the dispersivity for the two alternative expressions, i.e. $\gamma = 1$ and $\gamma = 1 + \sigma^2/6$. The values of dispersivity from the numerical simulations are located between the two lines. There is an indication that for small correlation lengths (0.05 and 0.10 L) these values are close to the $\gamma = 1$ case.

The slopes of these lines should be 1.0 in the log-log diagram according to Equation (8), but they are found to be less than 1.0 as shown in Table 2. These slopes are in the interval 0.95 to 0.98 for standard deviation of hydraulic conductivity from 0.1 to 2.0. Now Figure 5 gives the difference in the standard deviation of the conductivity of the flow channels relative to that corresponding to the global porous medium. When the standard deviation is corrected by this effect, a better agreement is found between Equation 8 and the simulations results (Table 2).

Figure 8 shows the simulated breakthrough curves for a pulse tracer injection through the heterogeneous block with different standard deviations, σ, in hydraulic conductivity. The geometrical mean is fitted to yield the same total flow rate through the porous block. It may be observed that for small standard deviation of the hydraulic conductivity distribution, a peak is found which spreads out around its peak value as the standard deviation is increased. However as the standard deviation is increased further, a new peak at much earlier time emerges. This may be due to increasing channeling effects at large standard deviation. The curves give an interesting transition from condition corresponding to a small standard deviation σ to strong channeled flow condition at large σ values. Such a channeling effect may be observed in Figure 2 where for $\sigma = 4.0$ the particles are transported by 2 - 3 channels, and for small σ the solute is transported by many almost vertical channels. From the breakthrough curves at very large σ, one notes that the tracer peak travel time is very short, which may be

fast channeling effect. The term fast channel was also introduced to describe early peak in calculated tracer breakthrough curves for the case of fractured media by Dverstorp et al.(1992). These early peaks for large σ have a width less than those for cases of intermediate σ values and similar to those of small σ case. This behavior deserves further study and consideration.

The usual practice in the field is to record the outlet concentration for a time long enough to obtain the main peak (or the first peak) and a part of the tail. When the concentration is low compared with the peak value the experiment is stopped. Then, the modeller fits some known models to the main peak and part of the tail of the curve. In many studies the tail of the curve is completely ignored and the fit is concentrated only on the main peak because many models are unable to describe the tail of the curve. The above simulation results, however, point out strongly that to determine dispersivity and hydraulic conductivity distribution of a strongly heterogeneous porous medium from experimental breakthrough curves, detailed careful study has to be made. If dispersivity is calculated using the width of the peak and the time to reach the peak, then the same value would be obtained for different standard deviations in hydraulic conductivity. Thus the value of the standard deviation is not unique. Straightforward application of conventional methods may lead to completely meaningless results, due to the channeling phenomenon.

d) Flow and solute transport for divergent/convergent flow.

Divergent/Convergent flow was simulated by modifying the boundary conditions. At one corner of the porous block, the corner node is chosen for flow and tracer injection (or production) at pressure P_2. On the three sides of the block defining the corner, no flow conditions are imposed and on the remaining three sides a constant pressure is imposed to be the outlet pressure P_1. Note that the size of the injection node is smaller than one correlation length, and thus it may be expected that this node and the nodes adjacent to it have similar hydraulic conductivities.

For a homogeneous porous medium represented by a cubic block with these boundary conditions the flow is not exactly convergent/divergent because there are paths with

different lengths and resistances. If the block has a dimension of L in each side, then the lengths of the paths vary from L to $L\sqrt{3}$. To simulate a convergent/divergent flow, a prescribed high hydraulic conductivity value is assigned to all nodes located at distances greater than L from the inlet. That the flow for the case of a homogeneous porous medium is really convergent/divergent was checked by performing simulations with very small standard deviation. Very high values of Peclet numbers were obtained (above 3 000). This shows that the boundary conditions used define a convergent/divergent system very well.

The calculational model as described above can simulate injection (divergent flow) or production (convergent flow) from a packered interval in a borehole in an heterogeneous medium. For steady state conditions convergent and divergent flows are equivalent. This means that exactly the same flow rates and the flow paths are obtained for both cases. As the particle following technique used in these simulations does not include local dispersion, the particles follow exactly the paths corresponding to the stream lines and the results obtained for convergent flow would be exactly equivalent to the results for the divergent flow. For practical reason, fluid flow and solute dispersion are calculated for convergent flow, but the results are completely applicable for the divergent case.

When parallel flow is studied the flow through the block increases with the standard deviation of the hydraulic conductivity (Equation 7). This behavior is not always observed for convergent/divergent flow. In some realizations the flow decreased with the standard deviation of conductivity. To explain this, it must be remembered that the flow is strongly influenced by the nodes near the injection/production node. So given a particular realization, if the hydraulic conductivity of the nodes adjacent to it is smaller than the geometrical mean, K_G, then these hydraulic conductivity values would decrease with increasing standard deviation. Thus injection/production flow rates will also decrease.

The difference between the hydraulic conductivity of the global porous medium and of the channels is also studied for convergent/divergent flow. For convergent/divergent flow, the differences in the value of the mean log conductivity (K_G) are slightly smaller. The reason of these smaller differences for convergent/divergent flow is that the particles are all forced to flow through a relatively small number of nodes adjacent to the

inlet. If the conductivities of the nodes around the injection node are smaller than K_G, then the increase of log K will be smaller due to the large weighting of these nodes with small conductivities. In other words, the hydraulic conductivity of the nodes located around the injection/production point at distances smaller than 1 - 2 correlations lengths play an important role in the determination of the channel properties.

The differences between the standard deviation of the global porous medium and of the channels do not show a clear relationship for convergent/divergent flow. In some runs, it is found that the standard deviation of the channels is equal or somewhat greater than the standard deviation of the global porous medium even for larger standard deviation in conductivity. Again these results could be explained as above, that convergent/divergent flow is anomalous as compared with the parallel flow case since the zone very close to the injection point is over-emphasized because all particles are forced to go through there

We also explore the type of flow in the present point injection/production case. We anticipate that for a strongly heterogeneous porous medium with large σ some important channels would be created in the flow field. These channels would behave as one-dimensional flow paths, rather than as the convergence/divergence flow pattern.

To study this, we analyze the simulations results. Let the distance traveled by the solute from the inlet to the recollection zone to be L and the travel time to be T. Then for a convergent/divergent system the travel time for the particle to go from the inlet to a distance L/2 is much smaller than T/2. In the case of tracer injection into a homogeneous porous medium, from the relationship between flow velocity and geometry one expects that time to reach L/2 was T/8 for 3-D (spherical); T/4 for 2-D (cylindrical); and T/2 for 1-D (linear) flow case. Simulations were done for different distances between 0.5 to 1.0 L, and the results shown in Figure 9. The lines show the theoretical results for linear flow, 2-D divergent flow and 3-D divergent respectively. From this figure, it is seen that for small standard deviation (less than about 1.0), the flow is 3-D divergent. However for very large standard deviation, in some cases, the flow behaves as a linear flow. For intermediate standard deviation the flow would be described as a 2-D divergent flow. These results are confirmed by additional calculations with other realizations. The linear flow behavior at large standard deviation may be understood by the onset of 1-D channeled flow as σ is increased.

4 SUMMARY AND CONCLUSIONS.

Fluid flow and solute transport properties of porous medium with strongly variable permeability have been investigated by numerical simulations. Results from these simulations have been compared with some theoretical relationships derived for the case of small variations in permeability. Effects of flow channeling on transport are studied and implications on experimental observations discussed.

For regional parallel flow through porous media, it was found that the theoretical relationship (Equation (7)) may be used only for standard deviation of the hydraulic conductivity less than 2.0 (in natural log). For larger standard deviation the flow do not follow this relationship. It is much larger than that predicted by Equation (7) because of the onset of flow channeling.

The solute transported through a porous medium seeks the less resistive paths or channels. The channels have different properties than those of the global porous medium. The geometrical mean of hydraulic conductivity of these paths is larger and the difference increases with the standard deviation. The spreading or standard deviation of the conductivity, on the other hand, is less when compared with the conductivity distribution for the global porous medium. The channel properties are independent of the actual location of the channels. This means that for a specific porous medium the properties of the paths or channels are determined by well-defined shifts on the properties of the global porous medium, regardless the direction of the pressure gradient applied to the system.

When solute transport was studied, it was found that the calculated dispersivities are located between two lines corresponding to the two alternative expressions for γ in Equation (8). The breakthrough curves obtained from the simulations for small and large standard deviations show a very clear peak. For intermediate values the main peak is wide and diffused. The results (Figure 8) for small σ are typical for small dispersion (clear peak and quite long peak time). However as σ increases, flow is channelized and a peak at a much shorter travel time emerges. The transition from one type of flow to the other is quite dramatic, and shall be studied in more detail in the future. In field tracer tests, the usual practice is to record only the main or early peak and a part of the tail. Thus if the hydraulic conductivity distribution of a porous medium is based on

dispersivity values determined from such experimental breakthrough curves, the results may be misleading. The same dispersivity value may be obtained for two different standard deviations in conductivity distribution of the porous medium.

When convergent/divergent flow was studied, it was found that the flow is strongly controlled by the hydraulic conductivities of the nodes adjacent to the injection/production point. This is especially true for injection or withdrawn of water in a borehole between a packered interval. The impact of the heterogeneities resulting in channeling in the convergent/divergent flow field was studied by calculating the travel time for different travel distances. It was found that for small heterogeneities the flow behaves like to a three-dimensional divergent flow from the injection point. But for large standard deviation the flow tends towards the case of 1-D flow channels.

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Table 1 Peclet number calculated using different expressions, for the 90 % of the particles. For the normal grid and a correlation length of 0.1 L

Standard Deviation	Peclet (Eq. 3)	Peclet (Eq. 4)	Peclet (Eq. 5)
0.1	2076	2057	2057
0.2	522	520	514
0.5	84	88	82
1.0	21	23	20
2.0	5.8	6.6	6.1
4.0	1.9	2.1	2.8
6.0	0.9	0.5	2.7

Table 2 Slope in the log-log plot (Figure 7) of dispersivity as a function of hydraulic conductivity variance without and with correction for the shift in variance (Figure 5) due to flow channeling.

Run		Slope of line	
# Nodes	λ/L	Without correction	With correction
20	0.10	0.96	0.98
20	0.20	0.95	0.98
40	0.10	0.95	0.98
40	0.05	0.98	1.00

FIGURES

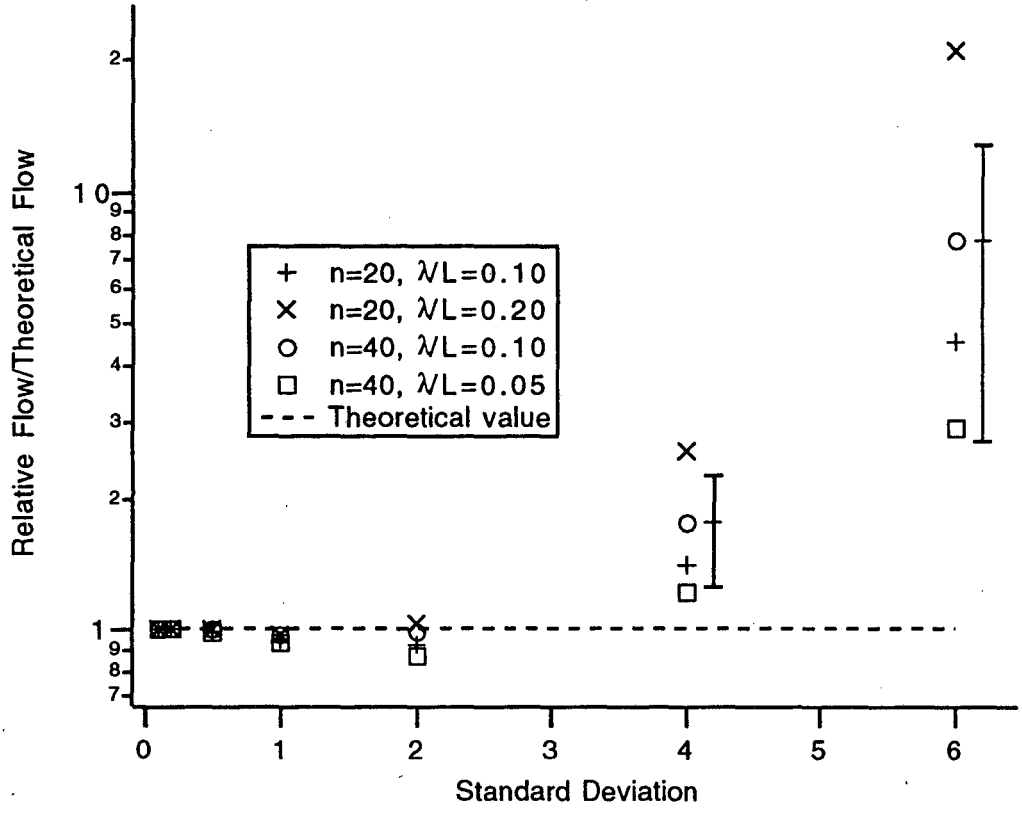

Figure 1 Flow through the porous block for different standard deviations in hydraulic conductivity. The broken line shows the flow calculated using Equation (7). Error bars representing statistical spreads over 12 realizations are shown for two cases ($\lambda/L = 0.10$, n =40 and $\sigma = 4$ and 6).

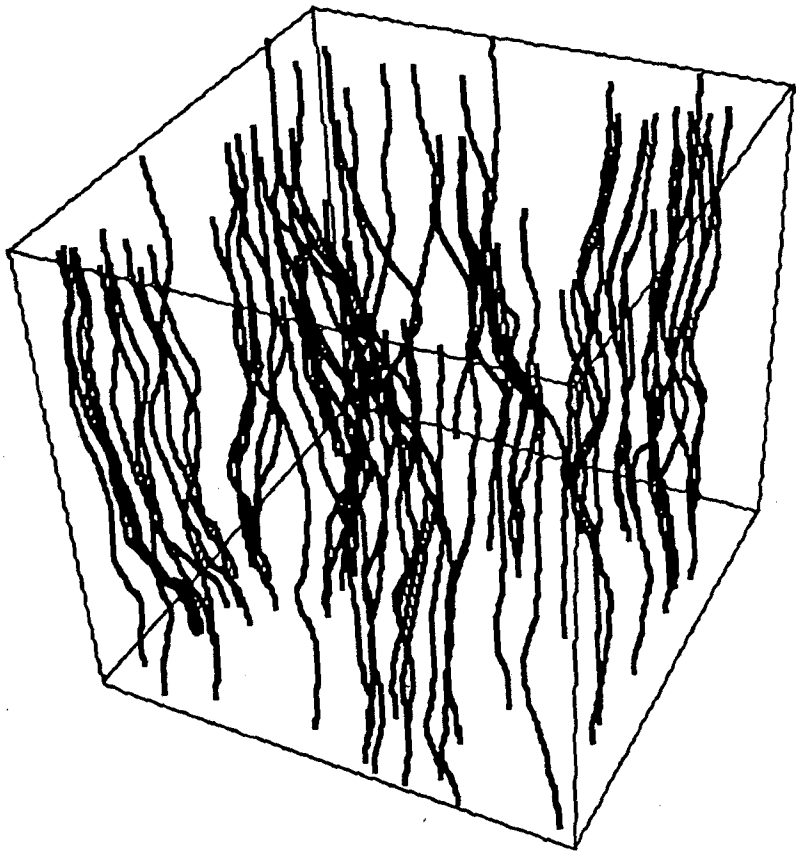

Figure 2a Flow in a vertical section of the porous block for $\sigma = 1.0$

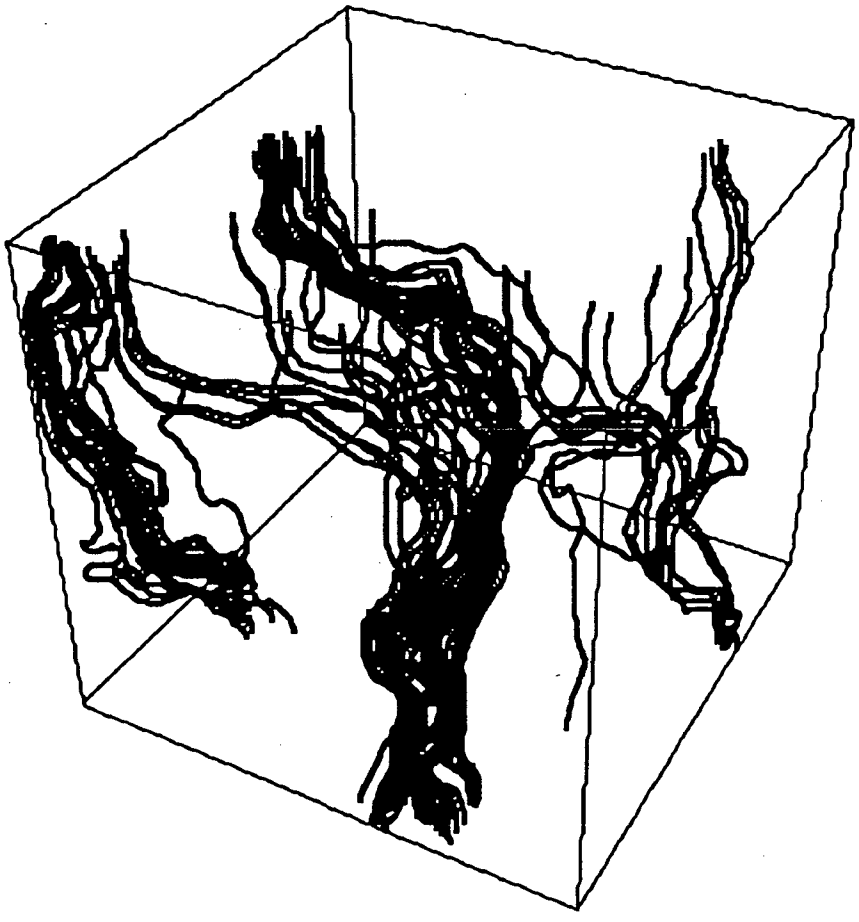

Figure 2b Flow in a vertical section of the porous block for $\sigma = 4.0$.

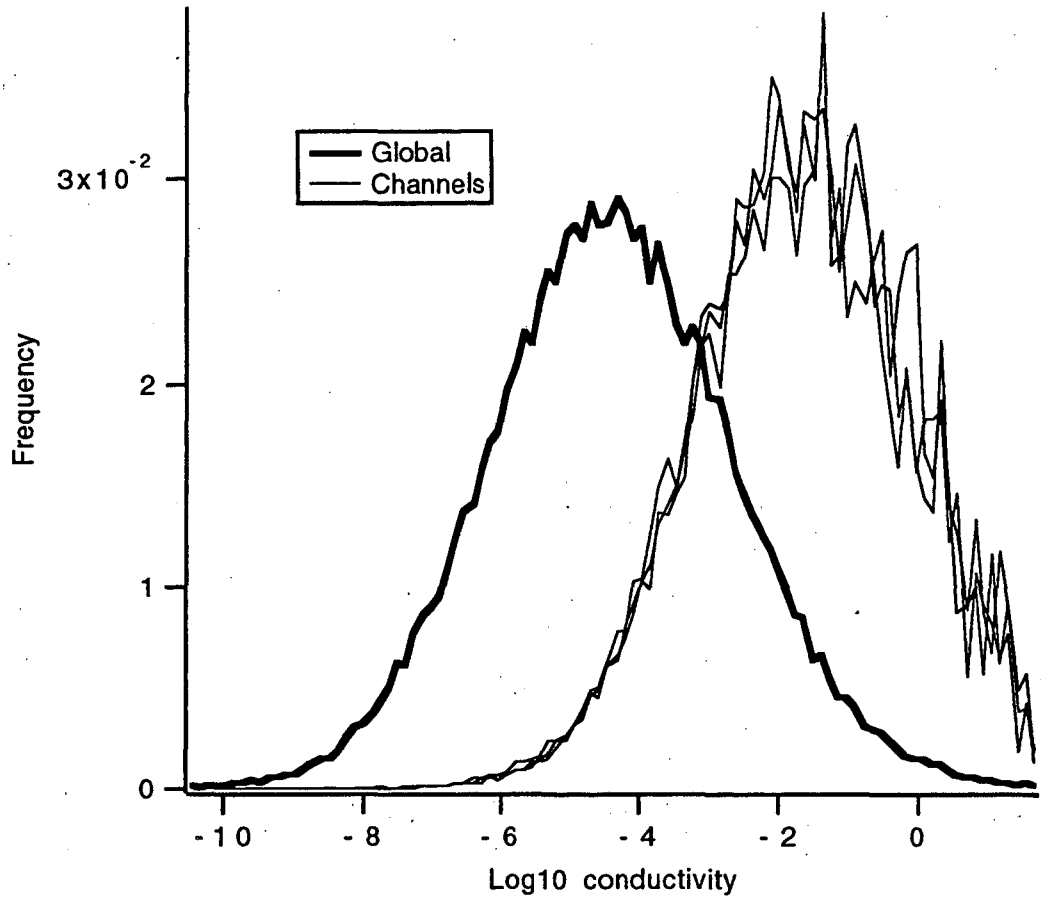

Figure 3 Hydraulic conductivity distribution for the channels (lighter lines) and for the global porous medium (heavier line). The three light lines correspond to distributions of channeled flow in three orthogonal directions (V, H1, and H2). Results are for a standard deviation in conductivity of 4.0.

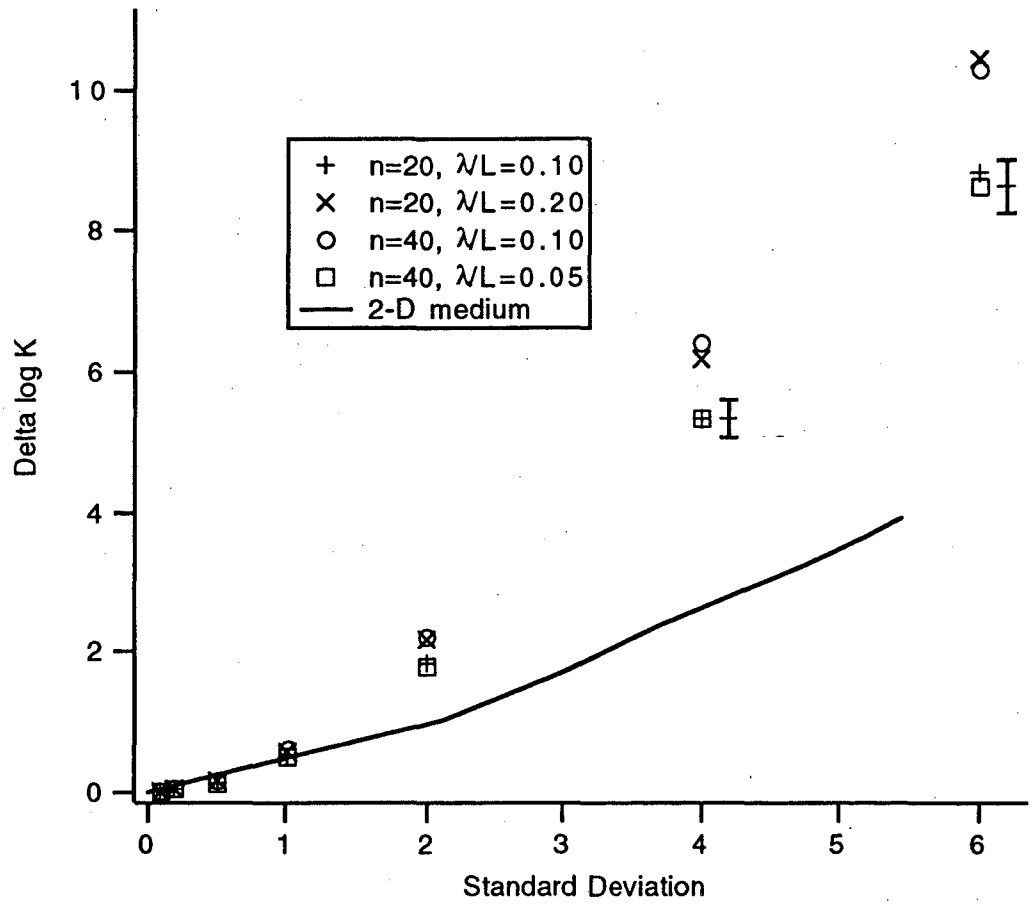

Figure 4 Difference between the mean log conductivity for the channels and the global porous medium, as a function of the standard deviation of the porous medium. Error bars representing statistical spreads over 12 runs are shown for two cases, as typical of the others. For comparison, the line is for the two-dimensional case taken from Tsang and Tsang (1989).

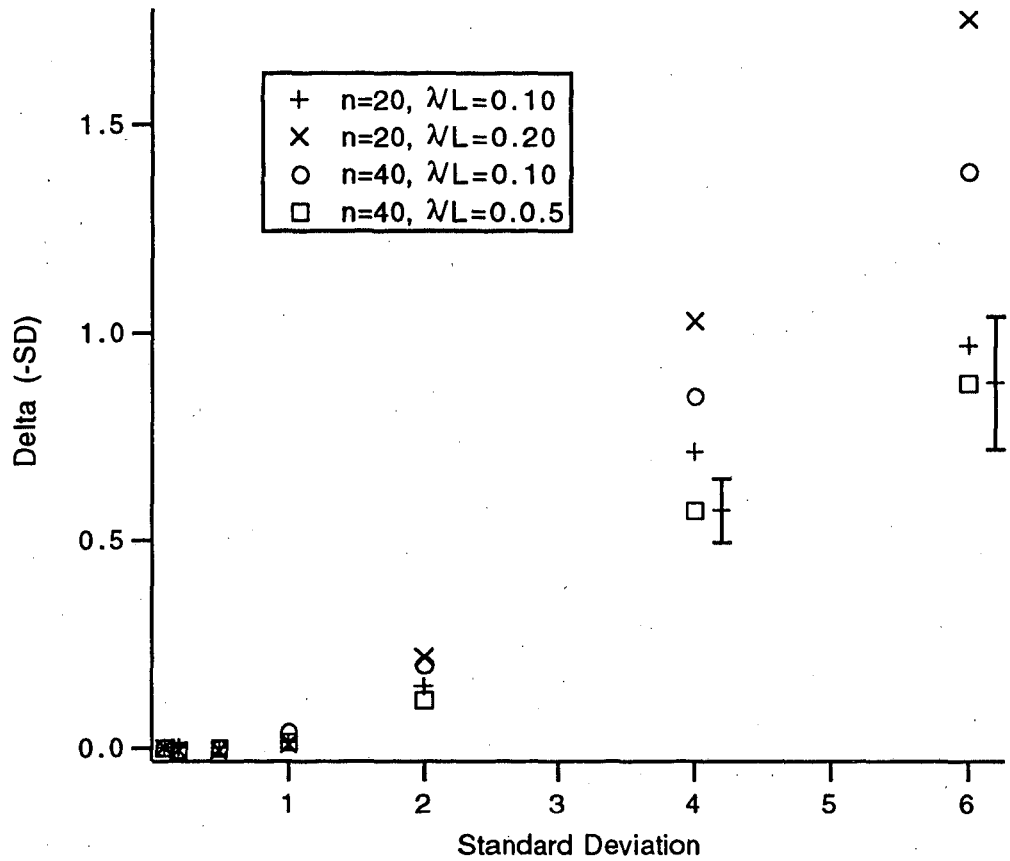

Figure 5 Difference between the standard deviation in conductivity for the channels and the global porous medium, as a function of the standard deviation of the porous medium. Error bars representing statistical spreads over 12 runs are shown for two cases, as typical of the others.

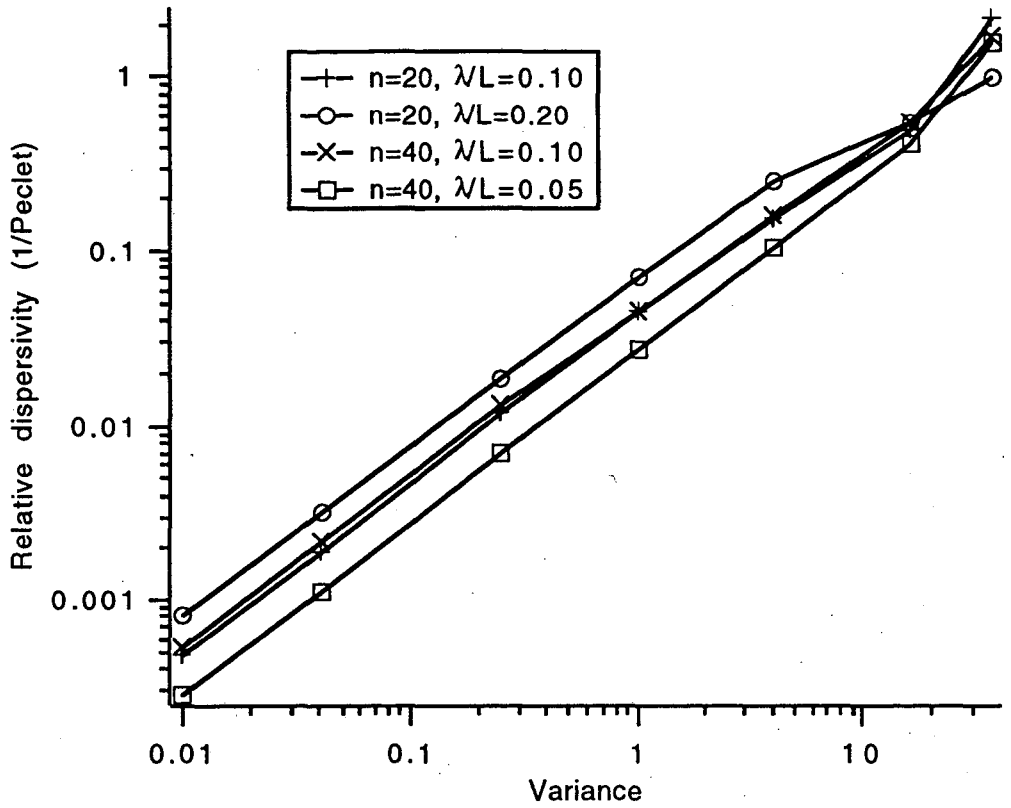

Figure 6 Relative dispersivity as a function of the variance of the log hydraulic conductivity for different cases.

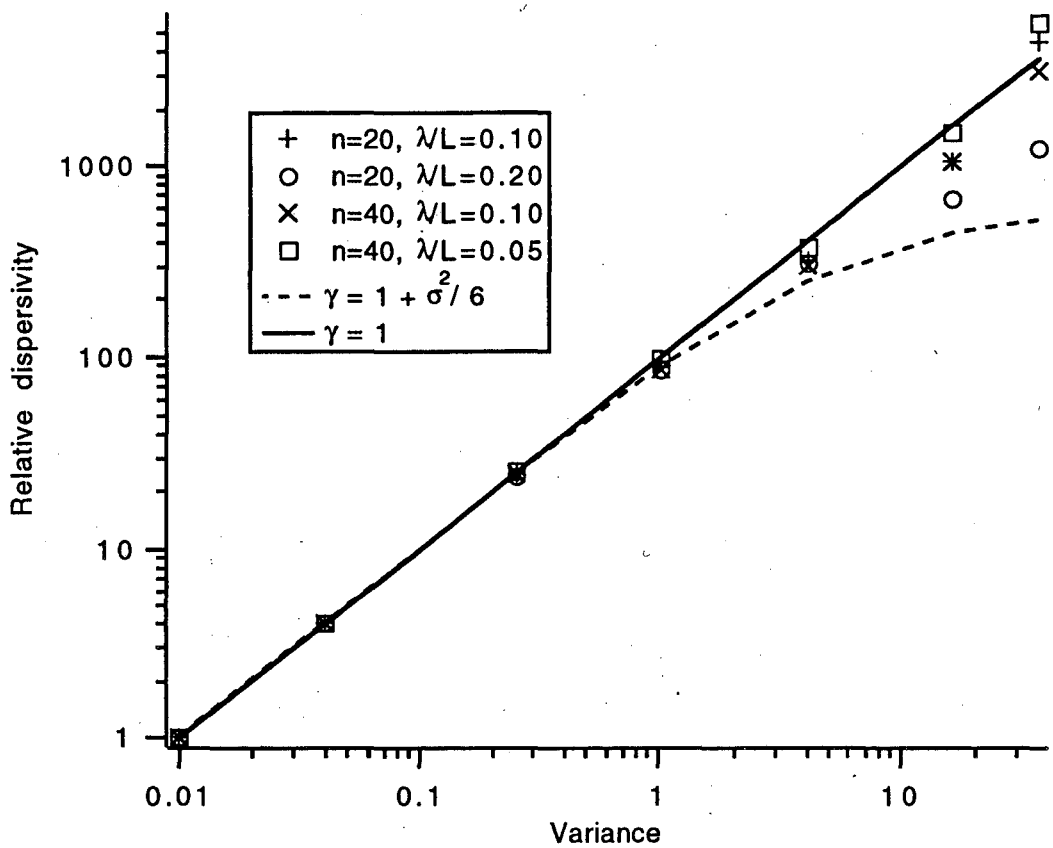

Figure 7 Dispersivity normalized for the lowest variance as compared with Equation (8) using $\gamma = 1 + \sigma^2/6$ (dashed line) and $\gamma = 1$ (solid line).

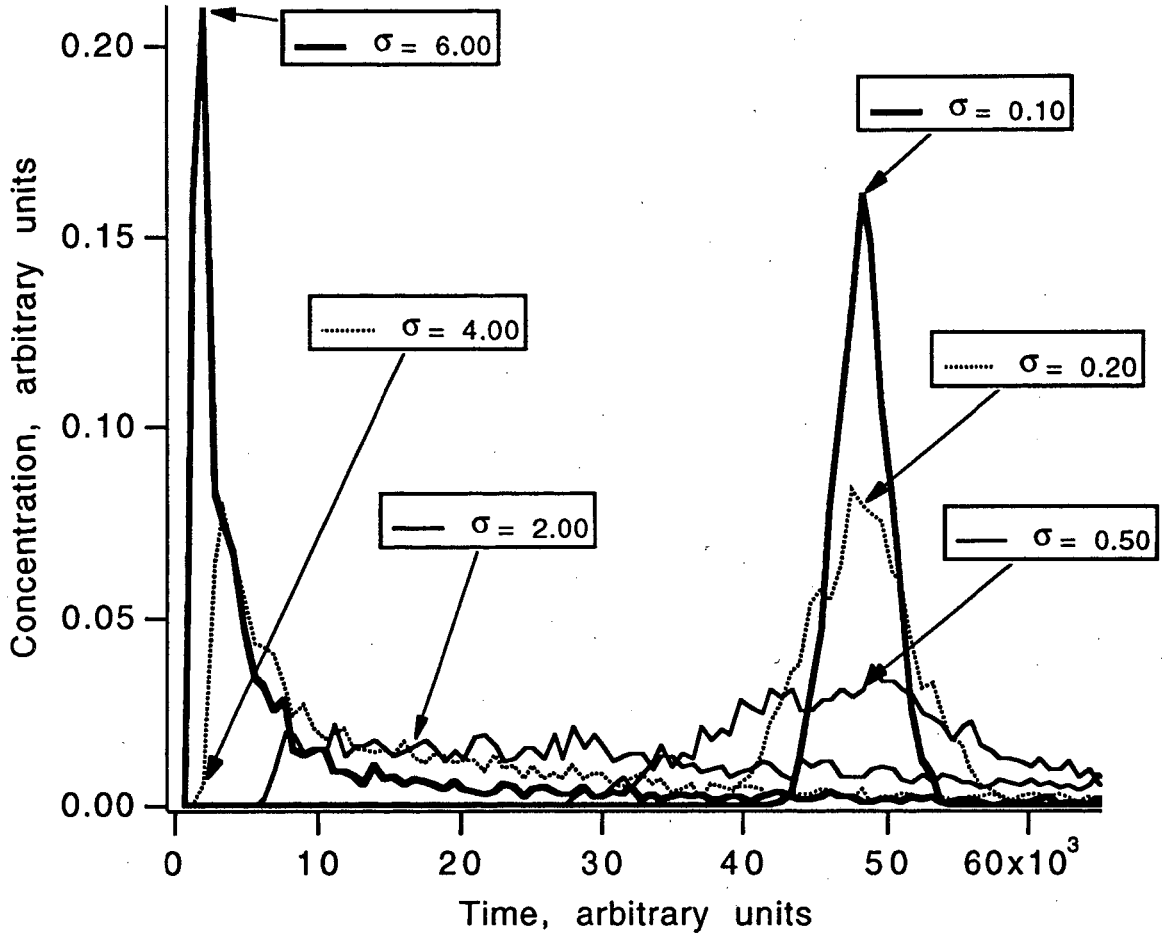

Figure 8 Breakthrough curves for a pulse tracer injection through the block with different standard deviations in hydraulic conductivity

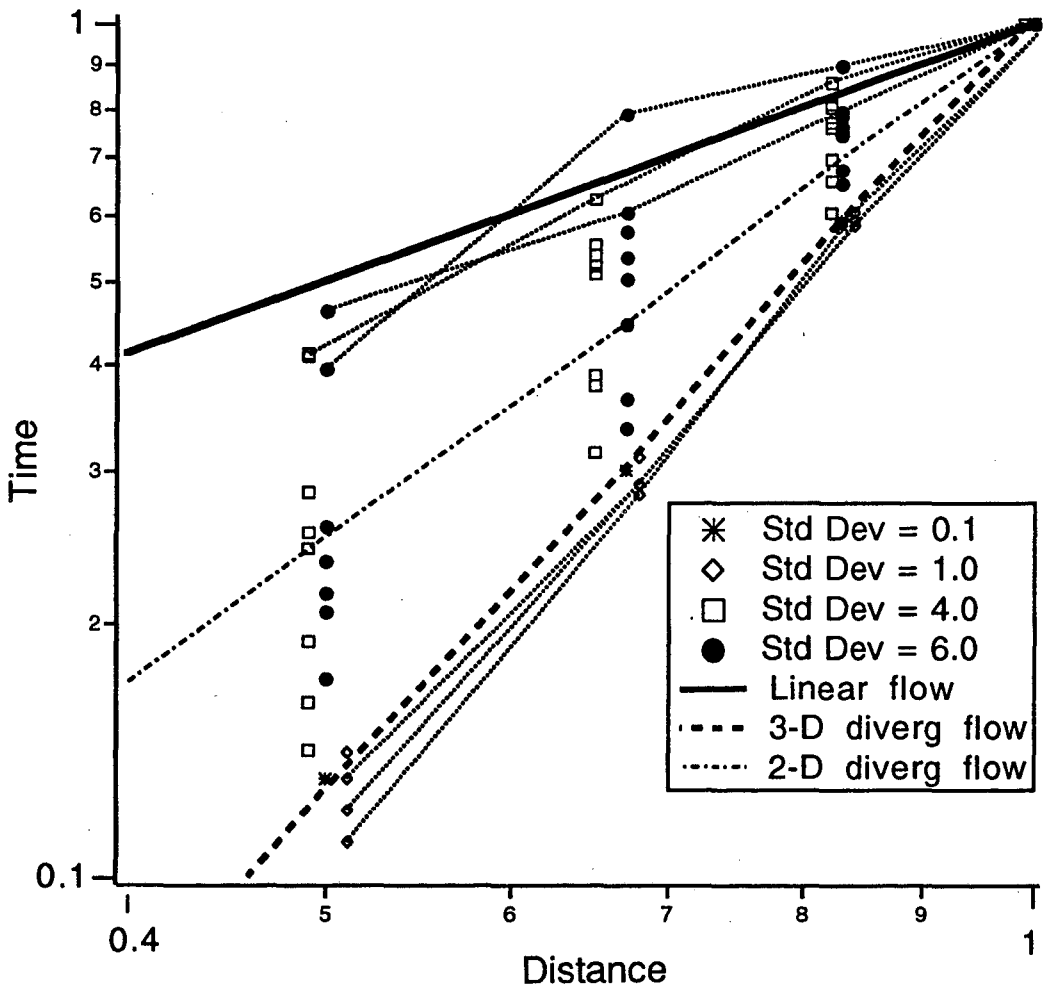

Figure 9 Travel time as a function of travel distance for different standard deviations in hydraulic conductivity. The heavy fill line show the results for a linear flow, the dashed line for a 3-D divergent flow, and the light line for a 2-D divergent flow. Results of 4 - 8 realizations are shown for each case calculated. As examples, points of 3 cases with the least and largest slopes, for $\sigma = 6.0$ and 1.0 respectively, are joined to illustrate the range of slope change.

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