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Dynamic Channeling of Flow and Transport in Saturated and Unsaturated Heterogeneous Media

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ABSTRACT

Dynamic channeling of flow and transport in strongly heterogeneous, saturated and unsaturated media is reviewed. Focusing or channeling of flow is dependent on both the permeability distribution and the pressure field. In the case of unsaturated media, it is also dependent on the degree of saturation. The emergence of flow channeling as a function of permeability variability (as measured by its standard deviation) and the spatial correlation range in three-dimensional porous systems is described. We also discuss the effects of channelized flow on two problems of practical interest for saturated and unsaturated heterogeneous media.

1. INTRODUCTION

Geologic formations consist of large scale heterogeneities, such as layering, regional zones, major faults and connected fractures, as well as smaller scale heterogeneities within each formation or region. We often assume that small scale heterogeneities can be smoothed, with its effects represented by a perturbation to the behavior of a homogeneous constant-property system. One well-known example is the problem of solute transport in a geologic formation. The solute velocity (advection) is calculated by assuming that the permeability of the medium is constant and the effect of heterogeneity caused by the presence of spatially varying permeability values is represented by a dispersion term which accounts for velocities greater and smaller than a mean velocity. This process is represented using the advective-dispersive equation, whose solution describes a solute plume migrating through a geologic formation with its boundaries smeared out due to the dispersion term. The tracer breakthrough curve (which is the solute or tracer concentration at an observation well or boundary, downstream from the source of the solute or tracer) displays a spread in time about the median tracer arrival time. The median arrival time can be calculated by assuming the medium to be homogeneous with constant properties.

The relationship between solute dispersion and the heterogeneity of the medium, characterized, for example, by the standard deviation around the geometric mean of permeability values, and the spatial correlation range, has been studied by many authors (Gelhar and Axness, 1983; Gelhar, 1986; Dagan, 1984, 1986, 1990; Neuman et al., 1987; Neuman and Zhang, 1990; Zhang and Neuman, 1990; Vomvoris and Gelhar, 1991; Graham and McLaughlin, 1990, 1991; Rubin, 1990, 1991a, 1991b; Tompson and Gelhar, 1990; Desbarats, 1990; Rajaram and Gelhar, 1991; Chin and Wang, 1992; Rubin and Dagan, 1992). In most of these studies, small variations in the hydraulic conductivities are assumed, and the applicability of results obtained is limited to moderately heterogeneous porous media. By moderately heterogeneous media, we mean that the standard deviation of log permeability $\log_{10}(k)$ is less than 1, or the standard deviation σ of natural log permeability, $\ln k$, is less than approximately 2.

The interest in strongly heterogeneous system was stimulated by the study of flow in single fractures as represented by a two-dimensional (2-D) porous medium, whose permeability k at

every point is proportional to the square of the local fracture aperture. Tsang, Moreno, and coworkers (Tsang et al., 1988; Moreno et al., 1988, 1990; Moreno and Tsang, 1991) found that flow in strongly heterogeneous systems becomes channelized; i.e., it seeks out paths of least resistance, with a small percentage of the flow region carrying the main portion of the flow. Further, the velocity of this channelized flow can be as large as an order of magnitude more than the average flow rate expected if the medium were uniform (Tsang and Tsang, 1987, 1989). Later, the study was extended to three-dimensional (3-D) strongly heterogeneous systems (Moreno and Tsang, 1994). This kind of flow channeling may be termed "dynamic channeling", because it depends on both the permeability distribution and the pressure field applied to the system. Subsequently, it was found that such channeling effects also occur for water flow in 2D unsaturated media (Birkhölzer and Tsang, 1997). In this last case, the strength of the channeling effect and the locations of preferred flow paths are also dependent on the degree of saturation. In the present paper, flow in 3D unsaturated system is shown to exhibit similar results.

Flow channeling effects have been seen in many field experiments in fractured rocks. A review of these experiments was given by Tsang and Neretnieks (1998). The channeling model has been applied to analyze data from some of these experiments (see, for example, Tsang et al., 1991). For porous media, channelized flow has been noted in soils (Ghodrati and Jury, 1990; Booltink and Bouma, 1991; Roth et al., 1991; Flury et al., 1994; Buchter et al., 1995). The present paper gives an overview of flow channeling effects, and it is hoped that it will serve to stimulate further field studies from the view of the flow channeling phenomenon. In the next section, the basic approach to the calculation of flow channeling is described. Then the emergence of the channeling effect as a function of permeability standard deviation and spatial correlation length is presented. Following this, flow channeling effect for 3D unsaturated systems is discussed, and it is shown to be also a function of the average saturation level of the medium. Finally, the occurrence of channeling effects in two problems of practical interest for saturated and unsaturated heterogeneous media are described and their implications discussed.

2. BASIC APPROACH TO CALCULATE FLOW CHANNELING EFFECTS

We use a numerical approach to investigate the flow-channeling phenomenon because the strong heterogeneity precludes simple theoretical methods, which often use a perturbation approach applicable to cases with small standard deviations. A porous medium block is divided into cubic cells or grid elements of dimensions L_x , L_y , L_z , where the three lengths are equal. These grid elements are assigned different permeability values according to a probability distribution. In our studies, we assume that the permeability values are lognormally distributed and correlated in space. An exponential covariance function is used, from which the permeability field can be generated using subroutines in a geostatistical software library (e.g. the SISIM module of GSLIB package by Deutsch and Journel, 1998). For each realization generated, the log permeability values in each grid element can be scaled about the mean, to obtain realizations with the same spatial correlation structure, but different standard deviations in permeability values (Tsang and Tsang, 1989). Thus, the probability distribution for lognormal permeability (k), with geometric mean k_0 , may be written as,

$$\begin{aligned} f(k)dk &= \frac{1}{(2\pi)^{1/2} \sigma k} \exp \frac{-(\ln k - \ln k_0)^2}{2\sigma^2} dk \\ &= \frac{1}{(2\pi)^{1/2} \sigma} \exp \frac{-(\ln k - \ln k_0)^2}{2\sigma^2} d(\ln k). \end{aligned}$$

If we replace $(\ln k - \ln k_0)$ by $\gamma (\ln k - \ln k_0)$ in this equation, we obtain again a lognormal distribution but with

$$\sigma \rightarrow \sigma/\gamma$$

where γ is a multiplicative factor to scale the standard deviation (σ) of the heterogeneous field. By choosing a range of γ values, we keep the same spatial structure but make the standard deviation vary over a wide range, from 0.5 to 6.0 in natural log. A standard deviation of 6.0 implies a very large variation in permeability over the porous medium block, so that 95% of the values are in an interval that covers about six orders of magnitude. We also use a range of values

for the spatial correlation length parameter in an exponential variogram model, from 0.025 to 0.2 times the transport distance. Note that for the exponential variogram, the effective correlation range is three times the spatial correlation length parameter.

Although the results presented in the paper are obtained using the particular geostatistical specifications as described above, similar results are also obtained with multiple realizations and alternative approaches, such as a non-parametric permeability distribution and spherical spatial correlation structures. Thus we believe that the conclusions presented in this paper on channeling as a function of permeability variance and spatial correlation length are independent of such specifics.

The flow calculations are based on steady-state flow conditions and followed the procedure used by Moreno et al. (1988), which was extended to three dimensions (Moreno and Tsang, 1994). In all the calculations, a pressure difference is assumed on two opposite faces of the rectangular porous-medium block with the remaining four sides closed to flow, and the porosity of the block is assumed to be constant. Then once the steady-state flow is calculated by, for example, a finite-difference method, the flow velocity at every point can be computed. Solute transport through the porous medium is simulated by a particle-tracking technique. Four thousand particles or more are introduced with the fluid at the high-pressure side of the porous block. The number of particles introduced in each inlet grid cell is proportional to the flow through that cell. They are randomly distributed on the inlet surface of the cell, and each particle is then followed through the porous medium. The particle tracking is carried out by calculating the velocity v of the particle in its actual location and then moving the particle a small distance $v\Delta t$. The time step Δt is set to be small enough to obtain consistent results. In most cases, Δt was set such that the travel distance is equal to 0.05 of the cell size. Using an even smaller time step increases the calculation time, but the accuracy of the results is only slightly improved.

Velocity is calculated using a three-dimensional linear interpolation scheme among the velocity vectors located at interfaces between the cell where the particle is located and all the adjacent cells. These velocity vectors are calculated from the pressure field computed earlier. No local dispersion within each path is considered in these calculations, but it may be included in a straightforward way (Tompson and Gelhar, 1990).

The particles are collected at the outlet surface, 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.

3. EMERGENCE OF FLOW CHANNELING WITH DEGREE OF HETEROGENEITY

Using the method described in the last section, we obtain results for both 2-D and 3-D flow in a heterogeneous medium. In Figures 1a–c, we show typical results for the 2-D case. In this case, a pressure difference is maintained between the upper and lower boundaries, while the side boundaries are closed to the flow. The flow domain is discretized into 200×200 grid cells and the spatial correlation length is chosen to be 0.05 of its linear dimension. Let us define λ and λ' as the ratios of, respectively, the spatial correlation length parameter and the effective correlation range to the flow dimension. Since the effective range is three times the correlation length parameter in exponential variogram, $\lambda = 0.05$ and $\lambda' = 0.15$ in these figures. The lines show the tracks of the fastest 90% of the particles. For a small standard deviation of natural log permeability, $\sigma = 0.5$, flow is essentially vertical. The travel time contrast is small among all the flow paths (see further discussions in Section 5 and Figure 8 below). However, as σ increases, this contrast greatly increases and flow is channelized (Figures 1b and 1c) with exit flow at the lower boundary concentrated at fewer and fewer locations.

Figures 1b and 1c may be compared with the experimental measurements by Bourke (1987) on a single fracture, which can be represented as a 2-D flow system with point permeability proportional to the square of the local fracture aperture. In his experiment, Bourke and his coworkers selected a fracture in the Cornish granite in England and drilled five boreholes in its plane with a length of about 2.5 m. Because the fracture plane undulates to a small extent, the five holes did not lie entirely in the fracture. Water was pressurized in one hole, and the holes on its two sides were divided into 7-cm intervals by the use of packers for measuring the flow rate into each of the different intervals. The process was repeated by pressurizing the five boreholes one at a time. Results showed that many of the packed intervals in the five boreholes did not receive inflows from the pressurized neighboring borehole. Figure 2 shows a sketch of the

connected flow pathways inferred from these measurements by Bourke (1987). As we can see, the flow areas occupy only about 20% of the fracture surface. This is mainly a result of the fracture apertures, and the corresponding permeability, not being uniform. Rather, the aperture varies over the fracture plane, and the pressurized water takes the easiest pathway from one drill hole to the other, resulting in channelized flow paths as shown.

Figures 3a–c show the results for 3-D, where the block is discretized into $40 \times 40 \times 40$ grid cells and $\lambda' = 0.075$. Here again, for small σ , flow is vertical (Fig. 3a) with little contrast in travel time between fast and slow flows. As σ is increased to 2.0 and 6.0, flow becomes highly channelized, with exit flow on the lower boundary concentrated at a few discrete locations: $(x \sim 22, y \sim 15)$, $(x \sim 5, y \sim 10)$, $(x \sim 15, y \sim 15)$ and $(x \sim 5, y \sim 35)$.

Flow channeling also depends on the spatial correlation range as a fraction λ' of the flow distance. If λ' is small, though channeling does occur, the channels are closely spaced, and there are many of them over the flow domain, its effect is “averaged out.” However, for λ' larger than ~ 0.3 , it is found that flow channeling is important and is not very sensitive to the exact λ' value. Some typical results are shown in Figures 4a–c for the same σ value of 2.0, but λ' of 0.015, 0.15, 0.3 respectively.

Note that these flow channels are not the same as, but are in addition to, the discrete and connected high-permeability paths that may be present and visually discernable in the permeability spatial distribution. These channels occur because flow seeks out paths of least resistance in the heterogeneous medium under the applied pressure gradient. Thus, different flow channeling patterns are obtained as the pressure gradient changes in direction. We may call this “dynamic channeling” to emphasize the fact that these fast flow paths are a function of both the permeability distribution and the pressure field.

4. FLOW CHANNELING IN UNSATURATED POROUS MEDIA

Flow channeling effects as shown above for saturated porous media are expected to also occur for unsaturated systems, as has been shown by Birkhölzer and Tsang (1997), Roth (1995), and Roth and Hammel (1996) for 2-D systems. In this section, we shall show the results for 3-D

unsaturated media. To calculate liquid flow in the unsaturated case, we consider percolation under gravity. An effective permeability can be defined as the product of the intrinsic (or saturated) permeability k and the relative permeability k_r . The pressure is the sum of a capillary pressure P_{cap} and the reference pressure.

Both the capillary pressure and relative permeability depend on the saturation, and characteristic functions are used to describe these relations. In our study, we use the well-known van Genuchten-Mualem capillary pressure and relative permeability model [van Genuchten, 1980; Mualem, 1978], given as

$$P_{cap}(S_e) = -\frac{1}{\alpha} \left\{ (S_e)^{-n/(n-1)} - 1 \right\}^{1/n}$$

$$k_r(S_e) = (S_e)^{0.5} \left\{ 1 - \left(1 - (S_e)^{n/(n-1)} \right)^{1-1/n} \right\}^2$$

with the effective saturation defined as

$$S_e = (S - S_r) / (1 - S_r) .$$

Here S_r is the residual saturation, α is a scaling factor for the capillary-pressure function, and n characterizes the distribution of pore sizes within each grid element ($1 < n < \infty$).

In a heterogeneous porous medium, the characteristic functions of capillary pressure and relative permeability are not spatially constant. Areas of high permeability are expected to drain faster, on account of the large pore sizes and less capillary strength. Likewise, areas of low permeability are expected to maintain larger water saturations, on account of smaller pore sizes and stronger capillary suction. Consequently, areas with different permeabilities in our model region have to be assigned different capillary pressure functions. This is done by using spatially varying scaling factors α for the capillary pressure function. Leverett (1941) proposed a model to calculate the scaling factor α at a given location with permeability k as follows:

$$\alpha = \bar{\alpha} (k / \bar{k})^{0.5}$$

where $\bar{k}$ and $\bar{\alpha}$ are reference values for the permeability and scaling factor, respectively. A number of investigators have shown that the above relationship holds for a variety of different soils (e.g., Davies, 1991; Wang, 1992).

In our study, we used the TOUGH2 code (Pruess, 1991), and the reference values for the scaling law are given as $10^{-12} \text{ m}^2 = 1 \text{ } \mu\text{m}^2$ for the permeability $\bar{k}$ (equal to the geometric mean) and 10^{-4} Pa^{-1} for the scaling factor $\bar{\alpha}$. For the sake of simplicity, we assume that the spatial variability of pore sizes does not change from cell to cell within the model area. Then, the pore-size distribution coefficient n is not modified, allowing the relative permeability function to be the same over the whole model area. Sensitivity studies made (Birkholzer et al., 1999) have shown that the results are not sensitive to the exact value of n . We choose a pore size distribution coefficient of $n = 2$ and a residual saturation of $S_r = 0.2$. Note that for an unsaturated medium, the effective permeability is the product of intrinsic (or saturated) permeability and the relative permeability, so that the effective permeability values may have a wide spread even though the saturated permeability may have less variability, because of the saturation-dependent relative permeability function. It is the variation in effective permeability that gives rise to the channeling phenomenon.

Again, using the SISIM module of the GSLIB Geostatistical library (Deutsch and Journel, 1998), a 3-D heterogeneous field is generated on a $40 \times 40 \times 40$ grid to model a $10 \times 10 \times 10 \text{ m}^3$ block. The four side boundaries are assumed to be closed to flow, and percolation inflow is imposed on the upper boundary at rates $1, 10^{-1}, 10^{-2}, 10^{-3}$, and 10^{-5} times the flow rate Q_s , where Q_s is a large inflow rate which would result in fully saturated block at steady state (Birkhölzer and Tsang, 1997).

Figures 5a–c show the heterogeneous field and the saturation distributions for percolation rates $10^{-5} Q_s$ (low infiltration case, U1) and $10^{-2} Q_s$ (moderately high infiltration case, U3) cases, respectively. For this set of calculations, the mean intrinsic permeability is $1 \text{ } \mu\text{m}^2$, $\lambda = 0.05$, and $\sigma = 4$ in natural log (which is the same as $\sigma = 1.737$ in log to the base 10). Note that high saturation (and hence high liquid flow) locations are found near low-permeability (and hence high capillary) areas for the low-inflow case U1 with a low overall saturation. However, at higher inflow, it is not as clear that the anti-correlation holds. Further, we know that if the

medium is fully saturated, most liquid flow will be by way of high permeability areas, which is complementary to the U1 case.

Flow lines for the cases are calculated using the particle tracking technique described above. Figures 6a–c show these flow lines respectively for low inflow case U1; intermediate inflow case U3; and large inflow case S, in which the flow rate is Q_s . In case S, the 3-D block becomes fully saturated and corresponds to the situation described in Section 3. For results shown in Figure 6, the intrinsic permeability distributions in all the cases are identical. Note that strong flow-channeling is seen in the saturated case S and also in the low-inflow, low-saturation case U1, but is less important in the intermediate mean saturation case. The occurrence of an intermediate mean-saturation case where channeling is minimal was pointed out by Roth and Hammel (1996) and by Birkhölzer and Tsang (1997), and further discussion is presented in these references. Tracer breakthrough curves for the unsaturated heterogeneous systems as a function of saturation are also presented in Birkholzer and Tsang (1997).

As to be expected, the flow channels in case S and case U1 do not coincide, but rather they are complementary, i.e., the flow channels in case S are found exactly where channels do not occur in case U1. This result is further illustrated in Figure 7, which shows the permeability probability distribution sampled by the flow lines in the heterogeneous medium under different conditions. The broken line shows the intrinsic permeability probability distribution over the block. For the saturated case, Case S, lowest figure, the flow mainly samples the large permeability values, while for the “dryer” Case U1, the flow samples the low permeability values where the capillary effects are stronger. For the intermediate saturation case, the flow samples the middle-range values of permeability. In all cases, the range or standard deviation of permeability values sampled is less than that of the intrinsic permeability.

The results presented in this section demonstrate that the dynamic channeling effect for the unsaturated heterogeneous system depends not only on the permeability distribution and the pressure field, but also on the degree of saturation.

5. IMPLICATION OF FLOW CHANNELING ON TRACER BREAKTHROUGH CURVES FOR SATURATED MEDIA

In this and the next section, we discuss two practical problems for saturated and unsaturated media where flow channeling can play an important role. The first example is tracer transport in saturated porous media.

Let us consider the flow fields presented in Section 3 and Figures 3a-c. Let solute be deposited at the upper inflow boundary at time $t = 0$ and let it be followed by particle or tracer tracking. The particles representing the solute are then collected as a function of time at the lower exit boundary, integrated over the lower boundary area. Summing the arrivals of the particles builds up the tracer breakthrough curves, which describe the arrival of the solute resulting from a unit release at the upper boundary.

Figures 8a-b show breakthrough curves for different standard deviations in the permeability distribution and for two different ratios of the effective correlation range to travel distance. For the large correlation range ($\lambda' = 0.30$; Figure 8b), the breakthrough curves for small heterogeneity show a clear peak at $t=1$, which is the time of arrival if the porous medium has uniform permeability. When heterogeneity increases, the peak is wider and moves in the direction of shorter travel time, with a longer tail towards large travel times. If the heterogeneity becomes extremely large ($\sigma = 4$ or 6), the curves show a narrow peak again, but at very short travel times, and a long tail. When a very short correlation range was used ($\lambda' = 0.075$ case, Figure 8a), a clear peak at $t=1$ is obtained for porous media with small heterogeneity. As σ is made larger, the peak of the breakthrough curves is wider, but no clear peak is observed for the very large heterogeneity values. In the case (not shown in Figure 8) where a very large ratio of correlation range to travel length is used ($\lambda' > 0.6$), a clear peak at a very short travel time is displayed for extremely large heterogeneity values, but no single peak dominates when the standard deviation is decreased to 0.5 or smaller.

The solution of the conventional advective-dispersive equation describes well the situation shown in Figure 8a or Figure 8b for very small σ values up to approximately $\sigma = 1.0$ (see curves labeled $\sigma = 0.5$ and $\sigma = 1.0$). The velocities peak around the mean flow velocity with arrival time

$t=1$ and are symmetric on either side of the mean flow velocity. The spread of velocities about the mean increases with σ . However, as σ becomes much larger, with $\sigma > 1.0$, flow begins to be focused in a few channels (see Figures 3b-c), and the breakthrough curves show a much earlier peak, quite distinct from the $t=1$ peak, and a long tail. The early peak arrives at possibly one-tenth the time of travel in a constant-permeability medium (see $\sigma = 6.0$ case in Figure 8b). Such a phenomenon is believed to be seen in a number of field experiments (see, for example, the review by Tsang and Neretnieks, 1998). In particular, the field experiment described by Hadermann and Heer (1996) clearly show such results for a 2-D case.

These results have important practical significance. First, because of flow channeling, the peak arrival of a contaminant plume could be as much as an order of magnitude sooner than expected. This is an important concern for evaluating the potential migration of a contaminant plume, and its possibility needs to be accounted for in safety assessment. Second, because of the emergence of flow channeling at strong heterogeneity, the use of the conventional advective-dispersive equation to analyze this class of tracer breakthrough curves is very much in question.

6. IMPLICATION OF FLOW CHANNELING ON SEEPAGE INTO AN UNDERGROUND CAVITY IN UNSATURATED MEDIUM

Philip et al. (1989) presented the general theory of water exclusion from, or entry to, subterranean openings in a homogeneous uniform medium from steady, downward flow; and developed an analytical solution of the exclusion problem for cylindrical cavities. The solution is based on the assumption of an infinite flow region and spatially uniform downward flow far away from the cavity. If no water enters into the cavity, the gravity-driven downward flux must be diverted around the obstacle. From Darcy's law, this diversion requires a saturation increase at the crown of the opening to provide a pressure gradient driving water sideways and downwards. Thus an upstream retarded region develops, which culminates in an upstream stagnation point at the crown where zero velocity and maximum pressure is found. As water is diverted sideways and around the cavity, it forms a "roof drip lobe", with higher saturation and thus higher relative permeability and flow velocity. The stagnation point at the crown is the most likely location for water to reach full saturation, $S = 1$, at which condition the capillary barrier

presented by the drift becomes zero and water begins to seep into the open cavity. Philip et al. (1989) give an approximate expression for seepage to occur. Consider the case where the radius of the opening $r = 5.0$ m, k for the uniform medium $= 10^{-13}$ m², $\alpha = 9.78 \times 10^{-4}$ 1/Pa, $n = 2.7$, and $S_r = 0.01$ (Birkholzer et al. 1999). This happens to be the set of parameters appropriate to the Yucca Mountain site in Nevada where a large research program is underway to evaluate its suitability as a host site for a potential nuclear waste repository. We then find from Philip's theory that the percolation influx from the top of the domain must be larger than 1200 mm/yr before sufficient saturation is built up at the crown of the opening for seepage to occur.

However, if heterogeneity is present, the findings are substantially different. Birkhölzer et al. (1999) examined the case where $\sigma = 2.1$ in natural log and the spatial correlation length is 2 m, using three realizations of the generated heterogeneous field. A series of percolation influx rates were used from 10 to 1000 mm/yr. To show the flow pattern, we present in Figure 9 the saturation contours in three horizontal slices and three vertical slices of the 3-D block for 1000 mm/yr percolation flux. This figure clearly indicates the disturbance of the saturation distribution because of the presence of the drift. Thus, in the horizontal plane just above the drift, liquid accumulates at the crown as the vertical gravity-driven flow is being diverted around it, while in the horizontal plane below the drift, a low-saturation shadow develops. In addition to this flow-perturbation effect, the saturation contours also reflect the heterogeneity of the model area, showing several locations where "channelized" flow accumulates to high saturation values dependent on local permeability contrasts. At locations where the channelized flow reaches the cavity walls, the flow accumulates and the saturation increases toward unity, at which time water begins to seep into the cavity at these locations. For the particular example here, we find that seepage occurs when the percolation influx is about 25 mm/yr, about 50 times less than the result (>1200 mm/yr) for a homogeneous medium in the absence of flow channeling.

7. SUMMARY AND REMARKS

Dynamic channeling of flow and transport in strongly heterogeneous porous media gives rise to fast and localized flow paths, which are dependent on both the permeability distribution and the pressure field, and, for the case of unsaturated media, also on the degree of saturation. These

fast flow-paths occur in addition to the usual fast flow associated with the presence of connected high-permeability zones, like faults or a series of connected fractures which can usually be traced visually in a fracture map. In this paper, we use a simple model to study the emergence of dynamic channelizing as a function of permeability variation and spatial correlation range, σ and λ' . Further, for an unsaturated medium, flow channeling is also shown to be dependent on the mean saturation of the medium, with the channeling effect strongest at low and full saturations, and a minimum effect at an intermediate mean-saturation value.

Dynamic channeling is a new area for study, requiring further investigation with respect to practical problems in the field. In this paper, two such problems are discussed as examples, (1) solute migration breakthrough curves and (2) potential seepage into an opening in unsaturated rocks. Studies of other problems that may be also affected by flow channeling are underway.

The study of flow channeling requires a stochastic approach because it is often difficult to have detailed deterministic data on spatial permeability distribution. The results obtained in such a study will also be stochastic. Thus, we have to consider multiple realizations, probabilities, and expectation. How to apply such results to practical problems of contaminant migration and safety assessment is still an open question.

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FIGURE CAPTIONS

Figure 1 a-c. Emergence of flow channeling, under a pressure step applied from the top to the bottom boundary, as a function of σ for a 2D heterogeneous medium. Tracer flow paths are shown for $\lambda' = 0.15$ and $\sigma = 0.5, 2.0$, and 6.0 in figures a, b, and c respectively. Numbers on the x and y axes indicate the number of grid elements so that the flow domain is 200×200 and the effective spatial correlation range is $200\lambda'$.

Figure 2. Flow channeling observed in the plane of a single fracture. The five boreholes are drilled in the fracture plane, which is, however, not entirely flat; thus some parts of boreholes are outside the fracture plane. Flow channels are found by cross-hole pressure-flow tests between isolated intervals (7-cm long) in the five boreholes. They are indicated as A, B, C, and D. (Taken from Bourke, 1987).

Figure 3 a-c. Emergence of flow channeling, under a pressure step applied from the top to the bottom boundary, as a function of σ for a 3D heterogeneous medium. Tracer flow paths are shown for $\lambda' = 0.075$ and $\sigma = 0.5, 2.0$, and 6.0 in figures a, b, and c respectively. Numbers on the x and y axes indicate the number of grid elements so that the flow domain is $40 \times 40 \times 40$ and the effective spatial correlation range is $40\lambda'$.

Figure 4 a-c. Emergence of flow channeling, under a pressure step applied from the top to the bottom boundary, as a function of λ' for a 2D heterogeneous medium. Tracer flow paths are shown for $\sigma = 2.0$ and $\lambda' = 0.015, 0.15$, and 0.3 in figures a, b, and c respectively. Numbers on the x and y axes indicate the number of grid elements so that the flow domain is 200×200 and the effective spatial correlation range is $200\lambda'$.

Figure 5 a-c. (a) Spatial distribution of intrinsic permeability in $\log_{10} (k/k_{\text{mean}})$. (b) Spatial distribution of water saturation for a low infiltration case (low mean saturation). (c) Spatial distribution of water saturation for a higher infiltration case (moderate mean saturation).

Figure 6. Flow paths are shown for a low infiltration, low mean saturation (a); intermediate infiltration and mean saturation (b); and large infiltration and fully saturated case (c). Note that flow channeling is strong for (a) and (c), but not so pronounced in (b).

Figure 7. Frequency distribution of intrinsic permeability for the flow channels (solid lines) and the entire flow domain (dotted line), for three cases of low, intermediate and full saturations, cases U1, U3 and S, respectively.

Figure 8 a-b. Breakthrough curves for different standard deviation σ values and for a ratio of correlation length to travel length λ' of .075 and 0.3 in figures a and b respectively. The x-axis gives the arrival time normalized to (i.e. in units of) the expected time if the medium were of constant permeability. The y-axis gives the concentration as a fraction of the input pulse concentration.

Figure 9. Saturation profiles in a 3D heterogeneous block with a drift, under percolation flux of 1000 mm/yr on the top boundary.

Figure 1 a-c. Emergence of flow channeling, under a pressure step applied from the top to the bottom boundary, as a function of σ for a 2D heterogeneous medium. Tracer flow paths are shown for $\lambda' = 0.15$ and $\sigma = 0.5, 2.0$, and 6.0 in figures a, b, and c respectively. Numbers on the x and y axes indicate the number of grid elements so that the flow domain is 200×200 and the effective spatial correlation range is $200\lambda'$.

Numbers on histograms are flows in ml/sec from adjacent holes

Figure 2. Flow channeling observed in the plane of a single fracture. The five boreholes are drilled in the fracture plane, which is, however, not entirely flat; thus some parts of boreholes are outside the fracture plane. Flow channels are found by cross-hole pressure-flow tests between isolated intervals (7-cm long) in the five boreholes. They are indicated as A, B, C, and D. (Taken from Bourke, 1987).

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