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Effect of connectivity of alluvial aquifers on groundwater flow and solute transport

A. Beaudoin^a, I. Colecchio^b and A. Boschan^b

a. Institute of PPRIME, University of Poitiers + anthony.beaudoin@univ-poitiers.fr

b. Grupo de Medios Porosos, Facultad de Ingeniería, UBA + icolecchio@fi.uba.ar

c. Grupo de Medios Porosos, Facultad de Ingeniería, UBA + aboschfi@gmail.com

Résumé:

Nous étudions le transport d'un soluté passif pour des écoulements monophasiques ayant lieu dans des échantillons de milieux poreux 3D composés d'un faciès à haute conductivité hydraulique (k^+) et d'un faciès à faible conductivité hydraulique (k^-). Le faciès k^+ est caractérisé par une proportion p , et également par deux paramètres de connectivité : un type de structure de connectivité (faible, intermédiaire, élevé), et une échelle d'intégrale l_c . Le temps de transit t_{mean} et la valeur asymptotique de la dispersivité longitudinale α_l des particules passives de soluté sont estimés numériquement à l'aide de simulations numériques parallèles Monte Carlo. Les résultats nous permettent d'analyser l'interaction entre le transport de soluté, la connectivité et la percolation. L'influence de la connectivité sur α_l est mise en évidence principalement par un déplacement du seuil de percolation p_c . Le maximum du temps de transit t_{mean} se produit pour $p \sim p_c$ (c'est-à-dire lorsque le faciès k^+ arrive à connecter le milieu dans le sens de l'écoulement), tandis que celui de α_l est obtenu pour p légèrement supérieur à p_c . Nous montrons que α_l présente un effondrement des données sur les paramètres étudiés (l_c , structure de connectivité) s'il est exprimé en fonction de $p-p_c$, démontrant que la forte influence de la connectivité et de la percolation sur les propriétés effectives de l'écoulement s'étend également au transport.

Abstract:

We study the transport of a passive solute for monophasic flows taking place in 3D porous media samples composed of a high hydraulic conductivity (k^+) and a low hydraulic conductivity (k^-) facies. The k^+ facies is characterized by a proportion p , and also by two connectivity parameters: a connectivity structure type (low, intermediate, high), and an integral scale l_c . The transit time t_{mean} and the asymptotic value of the longitudinal dispersivity α_l of passive solute particles are numerically estimated using Monte Carlo parallel numerical simulations. The results allow us to analyze the interplay among solute transport, connectivity and percolation. The influence of connectivity on α_l is evidenced mainly through a shift in the percolation threshold p_c . The maximum of the transit time t_{mean} occurs for $p \sim p_c$ (i.e. when the k^+ facies spans the media sample in the flow direction), while that of α_l is obtained for p slightly greater than p_c . We show that α_l presents a data collapse over the studied parameters (l_c , connectivity structure) if expressed as a function of $p-p_c$, demonstrating that the strong influence of connectivity and percolation over flow effective properties also extends to transport.

Keywords: Binary media, Connectivity, dispersion, Monte Carlo approach.

1 Introduction

The assumption that the heterogeneity of aquifers can be described by multiGaussian distributions has been widely used [1]. However, this is inappropriate in many types of coastal or alluvial aquifers [2]. Fluvial sediment systems containing paleochannels or sandstone/shale sequences frequently show flow channeling, whose features are not well-captured by the multiGaussian approach and traditional geostatistical tools [3].

Many authors have argued that, for alluvial aquifers, the connectivity of the high conductivity (k) facies might be more important than the k -point values themselves [4]. When the high- k facies gains connectivity, channeling (percolation) leads to a significant increase of average flow rates and even more significant reduction of contaminant transit times [5]. This is why alluvial aquifers can be well described by binary media, that are particularly well suited for addressing this situation. In 2017, Jankovic *et al.* [6] studied transport in continuous multiGaussian, connected and disconnected k -fields, firstly introduced by Zinn and Harvey in 2003 [2]. The authors showed the strong influence of connectivity in the breakthrough curves. On the other hand, Colecchio *et al.* [7] studied the percolative properties of flow in binary media samples analog to those of [6]. The objective of this work is to analyze the interplay among solute transport, connectivity and percolation in saturated isotropic binary media.

2 Numerical methodology

The first stage of our numerical approach consists in generating 3D binary media made of a high hydraulic conductivity ($k^+ = 100 \text{ m/day}$) facies and a low conductivity ($k^- = 0.01 \text{ m/day}$). Initially, MultiGaussian media are generated within a rectangular parallelepiped of dimensions $L_x=2048 \text{ m}$, $L_y=L_z=128 \text{ m}$ at the same grid resolution $\Delta x = 1 \text{ m}$ in all directions using a spectral method through the software FFTW [8], and following a standard normal distribution characterized by an isotropic gaussian covariance function.. The media sample obtained in the previous step is modified by a normal score transform to swap the intermediate classes of conductivity with the high (or the low) ones [2]. This made it possible to increase (or reduce) the connectivity of the k^+ facies without changing the spatial covariance function or the integral scale l_c . The resulting media samples have low, intermediate and high connectivity structure types, and different values of l_c . Then, this normal distribution is binarized using a threshold value k_t of conductivity, assigning to each cell a characteristic k^+ (high conductivity) or k^- (low conductivity) value, with a given proportion p of k^+ . The value of k_t controls the proportion p of high conductivity cells [2]. As p increases, the k^+ facies eventually reaches the critical value p_c at which percolation occurs [7].

The second stage of our numerical approach consists in simulating flow in the sample. Fixed hydraulic heads were applied on the two faces orthogonal to the flow direction, and periodic boundary conditions on the other faces were used to minimize the perturbation of the flow due to boundary conditions. As the fluid and porous media are considered incompressible and non-deformable, the flow is then governed by the mass conservation equation coupled with Darcy's law. The finite-volume method is used to discretize these equations on an uniform regular grid [9].

The third stage of our numerical approach consists in measuring the dispersivity of the solute. A pulse of the latter, consisting in five thousand particles, is injected on a plane orthogonal to the flow direction, located a few correlation lengths downstream from the inlet, to avoid border effects on the velocity statistics. Particle trajectories are estimated in the 3D binary porous media flow by using the random walk tracker method. The Péclet number, that characterizes the ratio of advection to diffusion, is $Pe \equiv l_c U_{mean} / d_m \sim 10^2$ in our work ($l_c \sim 1\text{m}$ is the correlation length, U_{mean} (1 m/day) the averaged flow velocity, and d_m ($0.01 \text{ m}^2/\text{day}$) the molecular diffusion coefficient). From the trajectories of the

particles, the longitudinal dispersivity α_l is estimated by performing the time derivative of the second spatial moment of the particle positions [10]. As we intend to analyze the effect of connectivity over α_l , the velocity field is normalized after stage 2 to have a unit spatial mean. In this way, the increase of α_l due to the increase of the mean flow velocity, that takes place as p increases (and while the imposed head gradient is kept constant) is decoupled from that related to a variation of the connectivity (that imply inhomogeneities of the flow velocity field) itself.

3 Numerical results

In Fig. 1, the mean transit time t_{mean} of particles along the media sample is presented as a function of the proportion p of the k^+ facies for low, intermediate and high connectivity structure types and two values of $l_c = 1 m$ and $2 m$. For $p < p_c$, particle velocities are rather homogeneous. As percolation is reached, few solute particles sample a very fast flow channel (spanning k^+ cluster) increasing the mean significantly, so most particles have small velocities, and the normalized mean transit time increases. As the spanning cluster increases in volume, the relative volume occupied by fast channels increases and the mean of the particle velocities increases (the mean transit time decreases).

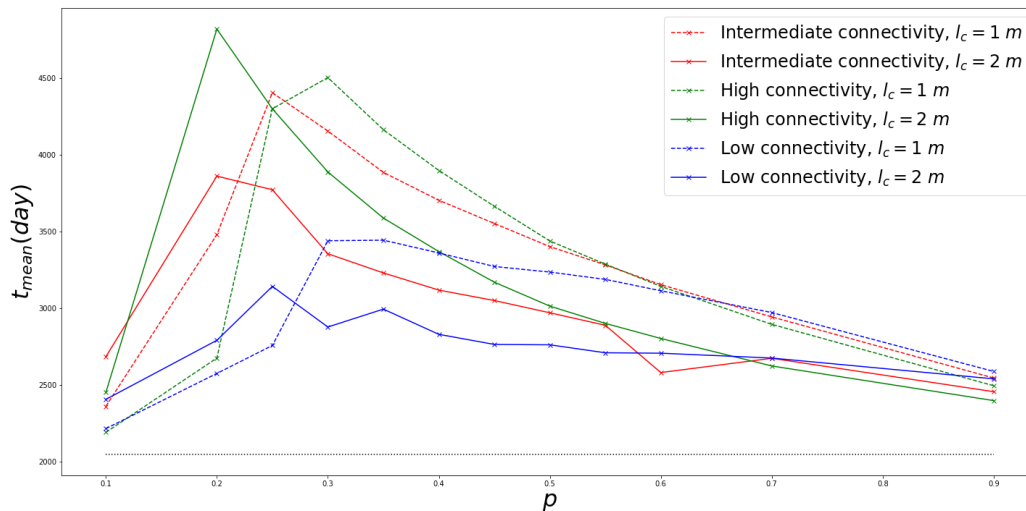


Figure 1. Evolution of the transit time t_{mean} of particles in the 3D binary porous media with respect to the proportion p of high conductivity facies for three connectivity structure types (intermediate, high and low) and for two values of correlation length l_c . Note that, as the flow velocity is normalized, for $p=0$ and $p=1$, the mean transit time should equal the length of the sample 2048 m (horizontal line).

In Fig. 2, the asymptotic value of the longitudinal dispersivity α_l is plotted as a function of $p-p_c$ for low, intermediate and high connectivity structure types, and two values of $l_c = 1 m$ and $2 m$. A steep increase of α_l is observed as p approaches p_c , while the maximum of α_l occurs just after percolation.

We interpret that, at $p-p_c=0$, only few solute particles sample the high velocities in the spanning cluster. We have studied numerically, and from the point of view of percolation, the transport and dispersivity of solutes in binary porous media. It is shown that much of the influence of the connectivity parameters over α_l is reflected by a shift of the percolation threshold.

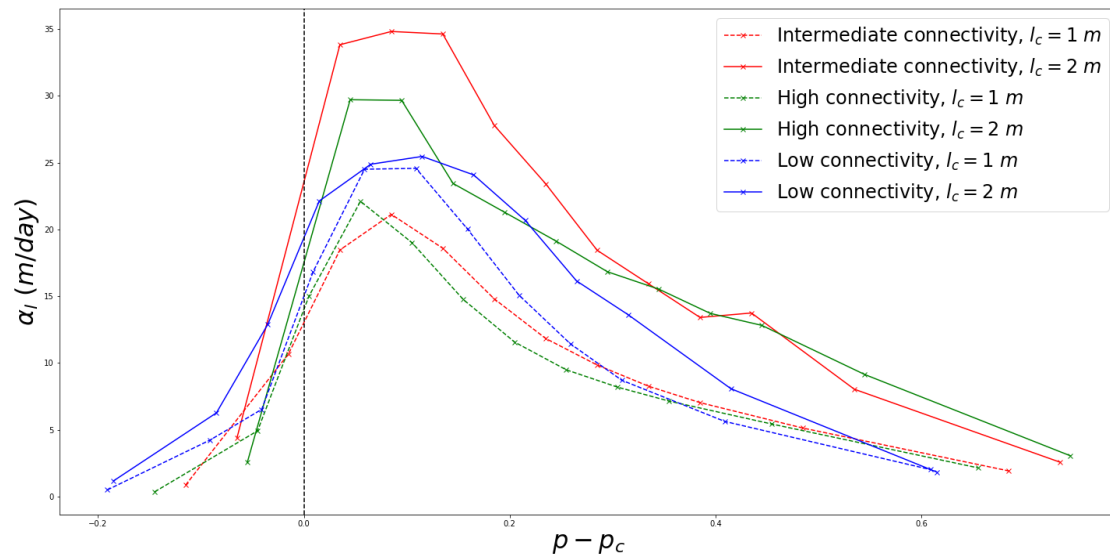


Figure 2. Evolution of the asymptotic value of the longitudinal dispersivity α_l as a function of $(p-p_c)$ for the three connectivity structure types (intermediate, high and low) and for two values of correlation length l_c . The vertical dashed line indicates p_c . Note that, as the flow velocity is normalized, α_l should equal zero for $p=0$ and $p=1$, since all particles travel at the same velocity. A collapse is observed, reflecting that all information in connectivity is reflected in the percolation threshold p_c .

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