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Numerical modeling of deposition-release mechanisms in long-term filtration: validation from experimental data

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A numerical phenomenological filtration model based on the combination of existing modeling approaches for simulating the transport of suspended particles in saturated porous medium is presented. The model accounts for the decreased physical straining with the distance from the inlet and the amount of deposited particles in the deposition kinetics. The particle release flux is a function of the local shear stress exerted by the flow on the pore surfaces. The proposed model is validated by interpreting a series of experimental data, realized in a laboratory sand column. The results show that the present model allows simulating the presence of a plateau in the breakthrough curves in the light of the shear stress conditions, and the spatial profile of deposited particles in the porous medium in the light of the straining profile.

1. Introduction

Filtration is a term used to describe the deposition and capture of solid particles from the transport of a fluid suspension through a porous medium. Filtration processes are encountered widely in the natural and industrial systems. Granular filtration is one of the widely implemented treatment methods for dilute aqueous suspensions. In this method, grains of the porous medium adsorb a substantial fraction of the suspended particles transported by water inside the filter bed. It is necessary to understand filtration kinetics and to predict filter performance for ensuring a high quality of the tap water. For a long time, the retention of particles by passage through a filter bed was determined using the classical colloid filtration theory (CFT) [1,2]. This theory is based on the assumption that particles are retained at a constant rate. Recent research shows that the CFT with a spatially constant kinetic approach was insufficient to predict the observed particle deposition profile. Li et al. [3] and Tufenkji and M. Elimelech [1,2] reported a reduction of the coefficient of deposition rate with transport distance. Lutterodt [4] found out that deposition rate coefficients decreasing with the distance were needed to predict accurately the shape of the profile of the observed retained particles in laboratory sand columns. In order to describe the shape of the profile of the retained particles in column tests, Bradford [5,6] incorporated two empirical kinetic terms for estimating two particle-retention mechanisms: (i) attachment–detachment to the grains surfaces of the filter and (ii) straining, which is the retention of particles in the smallest regions of the soil pore formed adjacent to points of grain–grain contact. Detachment and re-entrainment of previously filtered particles is handled by introducing a detachment term in the attachment–detachment kinetic term. The use of a depth-dependent function in the straining term enables accurate description of their observed retained particle profiles. Bai and Tien [7] introduced a dimensionless

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function in the deposition kinetic term in order to account for time-dependent retention. El Ganaoui et al. [8] showed that the release of deposited particles is induced by the hydrodynamic forces applied to the throat pore of porous media. A function of the pore shear stress was used for simulating the release process. Long-term effects in the filtration process are important in natural environments where backwashing of filters is not possible. A series of filtration experiments were conducted on laboratory columns in order to analyze long-term effects. Indeed, in these experimental conditions, deposition and mobilization mechanisms are complex and change greatly over time and space. In the present study, we present a mathematical model developed in order to characterize, through our experimental data, the main effects of long term in filtration process. Based on previous models of transport, deposition and mobilization phenomena, the present model incorporates several changes to take into account the non-linear deposition and mobilization mechanisms as well as their dependence on time and space. The model predictions are compared with experimental data from our laboratory filtration experiments.

2. Mathematical models

The filtration tests in laboratory columns can be described by the transport equation [9]:

$$\frac{\partial(\omega_c C)}{\partial t} = D\frac{\partial^2(\omega_c C)}{\partial x^2} - u\frac{\partial(\omega_c C)}{\partial x} - f \quad \text{with} \begin{cases} \omega_c = \omega_o - \omega_p \\ D = \alpha|u| \end{cases} \tag{1}$$

where ω_c is the kinetic porosity, ω_o the initial porosity of the porous medium, ω_p the specific deposit (volume of deposited particles per unit volume of the porous medium), C the concentration of suspended particles in the aqueous phase, D the dispersion coefficient, α the dispersivity, u the aqueous phase velocity, and f the source term. In the case of step-input experiments, the initial and boundary conditions are given by:

$$C(x \geq 0) = 0 \quad \text{and} \quad \omega_p(x \geq 0) = 0 \quad \text{for } t = 0 \tag{2}$$

$$C(x = 0) = C_o \quad \text{and} \quad \partial C(x = L)/\partial x = 0 \quad \text{for } t > 0 \tag{3}$$

with C_o the concentration of injected particles and L the length of the porous medium. The source term f, describing the deposition and the release of fine particles, is the sum of two kinetics:

$$f = q_{dep} + q_{rel} = \rho_p\frac{\partial \omega_p}{\partial t} \quad \text{with} \begin{cases} q_{dep} = K_{dep}\omega_c C\phi(\omega_p)\theta(x) \\ q_{rel} = -K_{rel}\omega_p\rho_p\zeta(\tau) \end{cases} \tag{4}$$

where K_{dep} and K_{rel} are respectively the deposition and release coefficients, ρ_p is the density of fine particles, and ϕ is a dimensionless function to account for time local dependent retention. It is given by [7]:

$$\phi(\omega_p) = 1 + a(\omega_p/\omega_{pmax}) + b(\omega_p/\omega_{pmax})^2 \tag{5}$$

where ω_{pmax} represents the maximum volume of deposited particles per the unit volume of the porous medium, a and b are dimensionless coefficients estimated by means of a matching of experimental data, and θ is a dimensionless function to account for the depth-dependent retention given by:

$$\theta(x) = \left((L_p + x)/L_p\right)^{-\beta} \tag{6}$$

This function is similar to that reported by Bradford et al. [5], where L_p is a parameter for the pore length set equal to d_{50}. β is a fitting parameter allowing one to control the shape of the curve. In our experiments, we observed deeper clogging. Using the Bradford function does not allow us to correctly predict the experimental results. A characteristic length that is better suited was then used. The parameter L_p used characterizes the penetration depth of the transported particle and it is evaluated using the equation $L_p = u/K_{dep}$. For the same reason, β is taken equal to unity. Based on the shear stress function proposed by [8], we incorporate in the release kinetic term the dimensionless shear stress function ζ:

$$\zeta(\tau) = \begin{cases} (1 - \tau_{cr}/\tau)^n & \text{if } \tau \geq \tau_{cr} \\ 0 & \text{if } \tau < \tau_{cr} \end{cases} \quad \text{with } \tau = \Delta P/\Delta L(2k/\omega_c)^{0.5} \tag{7}$$

τ is the local hydraulic shear stress [10], and τ_{cr} is the critical shear stress. n denotes an empirical parameter which is estimated by means of numerical tests. $\Delta P/\Delta L$ represents the local pressure gradient in the porous medium and k is the intrinsic permeability of the porous medium. The deposition and release of fine particles change the geometry of the porous medium. Thus the hydraulic characteristics of the porous medium are modified during the filtration of suspended particles. In order to take into account this modification, a flow equation is coupled with the filtration model. Under the assumption of a constant flow rate, the flow equation is given by:

$$u = \frac{Q}{\omega_c \pi R^2} \tag{8}$$