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Porous media grain size distribution and hydrodynamic forces effects on transport and deposition of suspended particles

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ABSTRACT

The effects of porous media grain size distribution on the transport and deposition of polydisperse suspended particles under different flow velocities were investigated. Selected Kaolinite particles (2–30 μm) and Fluorescein (dissolved tracer) were injected in the porous media by step input injection technique. Three sands filled columns were used: Fine sand, Coarse sand, and a third sand (Mixture) obtained by mixing the two last sands in equal weight proportion. The porous media performance on the particle removal was evaluated by analysing particles breakthrough curves, hydro-dispersive parameters determined using the analytical solution of convection–dispersion equation with a first order deposition kinetics, particles deposition profiles, and particle-size distribution of the recovered and the deposited particles. The deposition kinetics and the longitudinal hydrodynamic dispersion coefficients are controlled by the porous media grain size distribution. Mixture sand is more dispersive than Fine and Coarse sands. More the uniformity coefficient of the porous medium is large, higher is the filtration efficiency. At low velocities, porous media capture Q2 all sizes of suspended particles injected with larger ones mainly captured at the entrance. A high flow velocity carries the particles deeper into the porous media, producing more gradual changes in the deposition profile. The median diameter of the deposited particles at different depth increases with flow velocity. The large grain size distribution leads to build narrow pores enhancing the deposition of the particles by straining.

Introduction

Understanding solid particle transport and deposition in porous media is important in several contexts. In the field of water and wastewater treatment, the filtration through granular media is largely used to remove micron-sized particles from liquid input streams (Aim et al., 1997; Sadiq et al., 2003). For problems involving artificial recharge of aquifers, the raw water containing solid particles increases the risk of clogging of well injection (Vigneswaran et al., 1985; Vigneswaran and Suazo, 1987; Q3 Bouwer, 2002; Kurki et al., 2013). Particle-facilitated contaminant transport aroused a growing interest (Kretzschmar et al., 1999; Kanti Sen and Khilar, 2006; Li and Zhou, 2010; Syngouna and Chrysikopoulos, 2013; Saiers, 2002). Solid particles play a determining role in soils and aquifers contamination and act as pollution carriers if they are transported easily in the flow, or in opposite, they remain a barrier to the migration of pollutants if their presence clogs the porous medium.

In natural subsurface systems, solid particles may exist in several types: inorganic, organic, and microbiological parti-

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cles. Initial investigations on particle mobilization and transport in porous media were focused on colloidal particles (≤1 μm) in aquifers (McCarthy and McKay, 2004; Elimelech et al., 1995; Hater et al., 2000). Colloidal particles have been studied most often because of their abundance in groundwater and their physical properties such as specific surface area, large adsorption capacity, and low settlement rates (McDowell-Boyer et al., 1986). Recently, the transport and deposition of suspended particles (SP) (>1 μm) has also attracted significant attention (Gohr Pinheiro et al., 1999; Masséi et al., 2002; Ahfir et al., 2009; Bennacer et al., 2013). During the flow of the suspension through a medium, particle transport and capture are the result of several forces and mechanisms depending on particle density and size (Herzig et al., 1970). For large SP (>10 μm), hydrodynamics, gravity, and inertial effects are dominant (Frey et al., 1999). The gravitational force plays an important role on transport and deposition of solid particles in porous media. Laboratory experimental results presented by Chrysikopoulos and Syngouna (2014) and by Chen and Bai (2015) show that the effects of gravity depend on the flow direction used. Horizontal position promotes the particles deposition by gravity compared to vertical column position with downward flow. Various restrictions on the movement of SP such as straining and filtration have been studied (Bradford et al., 2003; Xu and Saiers, 2009; Porubcan and Xu, 2011; Alem et al., 2013). The straining is sensitive to change in the ratio between particle diameter and grain diameter (Bradford et al., 2002). Brown et al. (2002) found that the shape of the sand grains (oblong versus rounded) significantly alters the bacterial transport, with the transport being dominated by the smallest dimension of the oblong grains. Results presented by Porubcan and Xu (2011) on the transport of monodisperse latex particles in heterogeneous porous media prepared from the mixing of uniform quartz sands (with strong repulsive interactions between the latex particles and the clean quartz sands) showed that the straining of the latex particles within heterogeneous sand mixtures increased when the fraction of finer sands increased.

Previous studies on solid particle transport and deposition have predominantly relied on experiments conducted with uniform sand packs and monodisperse particles (Bradford et al., 2003; Xu et al., 2008). However, natural soils are characterized with physical heterogeneity which may originate from the mixing of sand grains of various sizes that displays different grain size distribution and structured heterogeneity (porosity and hydraulic conductivity) (Saiers et al., 1994; Dong et al., 2002; Tillmann et al., 2008). In addition, most of mobilized and transported particles are heterogeneously sized. In literature, most of the studies were conducted in laboratory column with small dimensions (e.g., Foppen et al., 2007; Porubcan and Xu, 2011; Syngouna and Chrysikopoulos, 2011). Studies that investigate the influence of porous media structured heterogeneity on transport and deposition of polydisperse solid particles are important in advancing our understanding of particle transport within natural heterogeneous porous media.

The objective of this research is to investigate the effect of the porous media grain size distribution (GSD) on the transport and deposition of selected polydisperse SP under different flow velocities. Three porous media were tested. Two porous media with calibrated GSD were used. The third porous medium was the result of mixing the first two porous media. Transport experiments were performed in a column of 62 cm in length using the step-input injection technique. The porous media performance on the SP removal was analysed with the aid of SP breakthrough curves (BTCs), Q4 hydro-dispersive parameters of the porous media, SP deposition profiles, temporal changes in the particle-size distribution (PSD) in the effluent, and spatial changes in PSD of the deposited SP.

1. Materials and methods

1.1. Experiments

Transport experiments were performed in a horizontal column under constant flow conditions using the step-input injection technique (tracers were injected continuously for three pore volumes). A Plexiglas column with inner diameter of 4.4 cm and length of 62 cm was used. The column was equipped with 13 pressure sensors (Measurement Specialities (France)) for measuring the pressure variation along the column. The column was fed by reservoirs containing deionized water (pH of 6.7 ± 0.2) and the SP, using a Cole–Parmer Masterflex peristaltic pump with flow rate control. To prevent the deposition of particles on the interior surfaces of the reservoir, the particles were maintained in suspension with the help of a motorized stirrer. Fluorescein (uranine) was used as a dissolved tracer (DT) in order to compare solute transport behaviour with that of the SP. The detection system consists of a turbidimeter (Kobold Instruments) and a Spectrometer (AstraSagitta UV/Vis). The turbidimeter has a measurement range of 1–5000 NTU (nephelometric turbidity units). The SP concentrations in the effluent were determined with the help of correlations made a priori between measured SP concentrations in the water and values in NTU given by the turbidimeter. The spectrometer, placed at the immediate Q5 outlet of the column, measures DT concentrations (wave length absorbance equal 490 nm) in the effluent passing through a flow cell (continues measurements). The spectrometer, also, was calibrated to the DT concentrations in water effluent.

The porous medium that filled the column during the experiments consist of quartz sand collected from the Seine River (France), with grain size selection being performed by sieving. Two sands with different GSD were selected: Fine sand (315–630 μm), and Coarse sand (630–800 μm). A third medium (noted Mixture) obtained by mixing the two last sands in equal weight proportion was also tested. The uniformity coefficients (C_u) are 1.13, 1.37 and 1.80 for Fine sand, Coarse sand and Mixture sand, respectively. The sand was cleaned to remove all organic matter and fine particles attached to the grains. After repeated washing with deionized water, the sand was soaked within nitric acid at a concentration of 0.01 mol/L for 24 hr, followed by rinsing with deionized water. After that it was soaked in NaOH (concentration of 0.1 mol/L) for 6 hr. Finally, the sand was washed with deionized water until the electrical conductivity of the rinse

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