Transport and deposition of suspended particles in saturated porous media: effect of hydrodynamic forces and pore structure
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ABSTRACT
In order to investigate the effects of pore structure and hydrodynamic forces on particle transport and deposition, an experimental study on the transport and deposition of suspended particles (SP) in saturated porous media (quartz sand and glass beads) was conducted under five different flow velocities at room temperature (22–25 °C). Silt particles with a mode of 10.7 μm diameter and fluorescein (as the dissolved tracer (DT)) were injected into the columns in short pulses. The SP transfer parameters were compared to the DT one. All the parameters (dispersivity, recovery rate, and deposition rate) obtained from the breakthrough data varied with the flow rate. The breakthrough curves were well described by an analytical solution of the advective-dispersive equation with a first-order deposition kinetic. The results showed that the transport of the SP was faster than the DT when the flow velocity reached a critical value which was different between the glass beads and quartz sand. The mean diameter of the recovered particles and the longitudinal dispersivity increase with flow rate; in addition, the recovery rate of SP is higher in the glass beads than in the quartz sand even under similar porosities. This study highlights the significance of pore structure and hydrodynamic forces in transport and deposition processes of SP.

Key words | breakthrough curves, hydrodynamic forces, pore structure, saturated porous media, suspended particle

INTRODUCTION
Particle transport and deposition in water is of great interest in many aspects. Among them are the industrial fields that focus on different techniques for particle separation and filtration and hydrogeology where particles play a significant role in the pollutant transfer of subsurface systems. Colloid (≤1 μm) and microorganism transport, deposition and release mechanisms have been investigated by many researchers (Sen & Khilar 2006; Li et al. 2013; Du et al. 2015). The role of colloids in groundwater contaminant transport has been studied most due to their abundance in groundwater and their physical properties such as specific surface area, large adsorption capacity, and low settlement rates (Xu et al. 2006). The transport of some large viruses, protozoa, and bacteria, which fall into the colloidal size range and are called biocolloids, is quite similar to colloidal particle transport (Kim & Walker 2009; Schinner et al. 2010). System hydrodynamics, colloid and collector grain size, ionic strength, and ratios of the colloid to the median grain diameter have significant effects on colloid transport and deposition (Bradford et al. 2007). Experimental and theoretical work has demonstrated that pore space geometry and hydrodynamics play an important role in colloid retention under unfavourable attachment conditions (Bradford et al. 2009). However, the majority of research findings have been focused on colloids (≤1 μm), bacteria and microorganisms. Suspended particles (SP) (>1 μm) because of their relatively large capacity to adsorb pollutants and their long settling time in water, also play a significant role.
in the transport of pollutants (Benamar et al. 2005; Ahfir et al. 2007, 2009; Chen et al. 2012; Alem et al. 2013). For large SP (>10 μm), hydrodynamics, gravity and inertial effects are dominant (Frey et al. 1999), while all forces and mechanisms can contribute to particle deposition for small SP whose sizes are between 0.1 and 10 μm (Gohr Pinheiro et al. 1999). A limited number of experimental studies have been carried out to study the effect of pore structure and hydrodynamic forces on the transport and deposition of SP, especially those with diameters ranging from 10 to 50 μm. Understanding the fate and transport of SP in a porous medium can better prevent the risk of drinking-water-supply contamination.

This paper presents an experimental study of the transport of SP in a saturated porous medium (glass beads and quartz sand), in order to investigate the effects of the pore structure of a porous medium and hydrodynamic forces on particle transport and deposition. The experiments on transport and deposition of SP were performed on two porous media that were different in pore structure under saturated flow conditions. In this study the mechanisms governing the transport process of SP are discussed. A horizontal laboratory column packed with quartz sand or glass beads was used to carry out the injection experiment under water-supply contamination. A large number of column experiments were performed under five different flow velocities at room temperature (22–25 °C). SP breakthrough curves (BTCs) and dissolved tracer (DT) BTCs were measured by turbidity and fluorescence sensors.

**MATERIALS AND METHODS**

Transport experiments were performed in a horizontal column under steady state and saturated-flow conditions using the short-pulse injection method in this paper. The short-pulse method, which can avoid blocking or filter ripening effects, has been used widely in recently years by many investigators (Massei et al. 2002; Chen et al. 2012). A Plexiglas column with an inner diameter of 8 cm and a length of 30 cm was used. The column was equipped with two equally spaced (12 cm) piezometers, which were used to measure pressure variations during SP injection in the porous medium. The average hydraulic conductivity values of the quartz sand and glass beads were 2.34 × 10⁻² m/s and 2.08 × 10⁻² m/s, respectively. The column was fed by a reservoir containing deionized water (pH of 6.9 ± 0.1) using a peristaltic pump (Longer Pump BT600-2J, Baoding, China) and equipped with a digital numeric flow-meter installed between the peristaltic pump and column inlet to measure the flow rate. A 30 ml syringe was used to perform pulse injections. The detection system consisted of a turbidity meter (HACH 2100AN, USA, calibrated with respect to the SP concentrations) and a fluorometer (F95S, Shanghai, China, calibrated with respect to the fluorescein concentrations). The measurement range of the turbidimeter was from 0 to 4,000 NTU. The particle concentrations in the effluent were determined with the help of correlations made a priori between SP concentrations in water and turbidity (NTU) (Chen & Bai 2012). The fluorometer measured fluorescein tracer concentrations of the effluent passing through a sample chamber which required a daylight white mercury vapour lamp and an excitation (455–500 nm) and emission (510–700 nm) filter. The F95S fluorometer was able to detect a fluorescein (excitation wavelength 250–850 nm, emission wavelength 200–900 nm) concentration of 0.1 ppb (parts per billion, i.e. 10⁻⁴ g/l). To determine the size of particles transported out of the porous medium, the samples were collected for grain size analysis using a laser device (Malvern Multisizer, 3000, England). The experiment set-up is shown in Figure 1. The material used as the porous medium was quartz sand and glass beads with quite similar porosity but different pore distribution and structure. The total porosity was 47% (±1%) for the quartz sand and 44% (±1%) for the glass beads. The average values of specific density of the glass beads and quartz

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**Figure 1** | Schematic diagram of the experimental set-up.
sand were 2.58 g/cm³ and 2.41 g/cm³, respectively. The median of the quartz sand medium grain diameter \(d_{50}\) is 2.5 mm, in which 75% of the quartz sand particles range between 2.00 and 3.50 mm in size, and 25% range from 1.00 to 2.00 mm in size. The glass beads are 2–5 mm in diameter. The main characteristics of silt (suspended particles) are reported in Table 1. The SP are silt which was collected from surface formations in the Miyun Reservoir (Beijing, China) with a median diameter of 10.7 μm and size ranging from 2 to 47 μm. The size distribution of the injected SP is shown in Figure 2. A solution of fluorescein (uranine) was used as the solute tracer in order to compare the solute transport behaviour with that of the SP. For each injection, the injected mixture consisted of 0.2 g/l SP and 1 mg/l fluorescein. The injected volume of 30 ml was very small compared to the column’s pore volume, thus it could avoid disturbing the water flow in the column (Kretzschmar et al. 1997). The tested flows varied from 0.1 to 0.8 l/min, corresponding to Darcy’s velocities ranging from 0.033 to 0.265 cm/s. These values exceed natural flow velocities in aquifers, but are moderate for forced flows such as the artificial recharge of aquifers (Bradford et al. 2002). The Reynolds number is defined as 
\[
\text{Re} = \frac{U d_{50} \rho}{\nu}
\]
where \(d_{50}\) is the mean size grain of the medium, \(\rho\) is the fluid density, and \(\nu\) is the dynamic viscosity. The values of Re obtained from the tested porous medium range from 0.39 to 3.13 for quartz sand, and the values of Re for glass beads are between 0.81 and 6.5, which confirms that the experiments were conducted under laminar flow conditions (de Marsily 1986). Thus, Darcy’s law remains applicable in this study. The molecular Péclet number is defined as \(P_e = U \rho d_{50} / D_0\), where \(U\) is the pore velocity and \(D_0\) is the molecular diffusion coefficient. For \(D_0 = 10^{-9}\) m²/s (diffusion of fluorescein in water), \(P_e\) values for the glass beads column ranged between 726 and 5,830 and for the quartz sand column ranged from 349 to 2,807. Also, these experiments conform to regime IV (300 <\(P_e\) <105), indicating that mechanical dispersion is the dominant process and that molecular diffusion can be neglected (Ahfir et al. 2009). For each injection, the flow rate was kept constant (controlled by a peristaltic pump). In each fresh packed column, five short-pulse injections were performed, starting from the highest flow rate to the lowest one. This technique was chosen by previous studies in order to avoid a likely release of the SP initially deposited in the porous medium, i.e. second-order deposition kinetics can be neglected (Benamar et al. 2007).

After each test series, the column was repacked with the same material after washing by the deionized water in order to remove any SP and being dried at 105 °C. In each test, the duration of the injected pulse was sufficiently short to be considered instantaneous. In this study, the chemical mechanisms were excluded from the assessment of processes because of the high velocities tested (mean pore water velocities ranged from 0.576 to 0.07 cm/s), the low ionic strength (deionized water), larger suspended particle size (a median diameter of 10.7 μm), and neutral water pH. Thus, the present study focuses on the physical mechanisms (hydrodynamic forces and pore structure) involved in SP transport and deposition.

### MATHEMATICAL MODELLING

Under steady-state and saturated flow conditions, the transport of particles through porous media can be described with a convection–dispersion equation including a term for the first-order deposition rate (Wang et al. 2000; Benamar et al. 2007; Ikni et al. 2013):

\[
\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} - K_{dep} C
\]

where \(C\) is the suspended particle concentration in the solution [M/L³]; \(D_L\) is the longitudinal dispersion coefficient [L²T⁻¹]; \(K_{dep}\) is the kinetic dispersion coefficient [T⁻¹]; \(u\) is the average pore water velocity [LT⁻¹]; \(t\) is the time [T]; \(x\) is

<table>
<thead>
<tr>
<th>Particles</th>
<th>Median diameter (μm)</th>
<th>Monodisperse index (dimensionless)</th>
<th>Particle density (g/cm³)</th>
<th>Tap density (g/cm³)</th>
<th>PH (dimensionless)</th>
<th>Specific surface (m²·kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>10.7</td>
<td>6.18</td>
<td>2.26</td>
<td>0.859</td>
<td>6.9 ± 0.1</td>
<td>335.02</td>
</tr>
</tbody>
</table>

Table 1 | Selected properties of the SP
the distance the particle travels from the inlet \([L]\). A short pulse is mathematically considered as an instantaneous injection. The initial and boundary conditions for a semi-infinite medium are given in Equations (2)–(4):

\[
C(x, 0) = C_0 \tag{2}
\]

\[
C(0, t) = \frac{m}{Q} \delta(t) \tag{3}
\]

\[
\frac{\partial C(\infty, t)}{\partial x} = 0 \tag{4}
\]

where \(C_0\) is the constant initial concentration in the porous medium \([M/L]\); \(m\) is the mass of particles injected \([M]\); \(Q\) is the flow rate \([L^3T^{-1}]\); \(\delta(t)\) is the Dirac delta function. In Equation (1), the release of deposited particles is neglected. Equation (4) assumes that the concentration is constant at infinity. This is not realistic for limited column length, but it is necessary to provide an analytical solution. The analytical solution for Equation (1) according to Equations (2)–(4) is given as follows (Wang et al. 2000):

\[
C(x, t) = \frac{mx}{2Q\sqrt{\pi D_t t^3}} \cdot \exp \left[ -K_{\text{dep}} \cdot t - \frac{(x - ut)^2}{4D_t t} \right] \tag{5}
\]

when there is no deposition phenomenon, i.e. \(K_{\text{dep}} = 0\).

Equation (5) directly gives:

\[
C(x, t) = \frac{mx}{2Q\sqrt{\pi D_t t^3}} \cdot \exp \left[ -\frac{(x - ut)^2}{4D_t t} \right] \tag{6}
\]

This can be considered the analytical solution for the transport of a DT. The recovery rate \((R)\) is estimated by integrating the experimental BTCs given as follows:

\[
R = \int_0^\infty QC(t)dt/m \tag{7}
\]

**RESULTS AND DISCUSSION**

**Influence of flow velocity on particle dispersion**

The longitudinal dispersion coefficient \(D\) can be derived by fitting the experimental BTCs using Equation (5). The hydrodynamic dispersion can be expressed by Equation (8):

\[
D = \alpha u^m \tag{8}
\]

where \(\alpha\) is the longitudinal dispersivity \([L]\), \(u\) is the pore flow velocity and \(m\) is the power coefficient. Different values of \(m\) have been determined by different researchers (Hu & Brusseau 1994; Ahfir et al. 2009). Figure 3 presents the variation of the longitudinal coefficient of DT and SP with the pore water velocity within the two tested media (quartz sand and glass beads). The results show that the longitudinal dispersion coefficient increases with pore water velocity. The same trend was observed for the two different media. The relationship between \(D\) and \(u\) is described by a power law for both quartz sand and glass beads. The values of \(m\) are 1.24, 1.54 for SP and 1.11, 0.98 for DT, respectively, as displayed in Figure 3. Bennacer et al. (2013) pointed out that as long as \(m = 1\) the longitudinal dispersivity \(\alpha\) has the dimension of length. Thus, by setting the power coefficient \(m = 1\) in Equation (8), the average values of the longitudinal dispersivity \(\alpha\) of the quartz sand medium were approximately 1.28 times those of the glass beads. The results further demonstrate that the dispersivity of the DT with the value of \(\alpha\) ranging from 0.47 to 0.53 cm is smaller
than that of SP with the value of $\alpha$ ranging from 0.68 to 0.82 cm over the investigated medium (Figure 3). This behaviour can be explained by the large size distribution of the SP (2 to 47 $\mu$m), which leads to a large dispersion of the flow velocities of SP. This difference in behaviour is more obvious for large flow velocities (Ikni et al. 2015), where the size exclusion effect is more significant (Benamar et al. 2007). In addition, the longitudinal dispersivity values obtained from the quartz sand columns are larger than those of the glass beads columns (Figure 3). This phenomenon can be explained by the large pore size distribution of quartz sand and the quite uniform pore distribution of glass beads caused by the single size of the glass beads.

**Particle transport behaviour**

The transport experiments have been interpreted by the mathematical model presented above. The breakthrough behaviour curves of the SP with 10.7 $\mu$m median diameter in the two porous medium with different flow velocities are shown in Figure 4. Noting that, the relative concentration $C_R$ in Figure 4 is given by the following equation (Ahfir et al. 2007):

$$C_R = \frac{C V_P}{m}$$

(9)

where $C$ is the particle concentration in the solution [M/L³], $V_P$ is the pore volume of the entire soil column [L³], and $m$ is the mass of the particle in each injection [M]. Figure 4 shows fitted experimental breakthrough behaviour curves (BTCs) of both SP and DT according to Equation (5). The experimental data are well described by the model at high, medium, and low velocities. Figure 4 also shows markedly the difference in the transport behaviour of DT and SP. BTCs show earlier transport of SP than of DT in both porous media at high velocity. This result is similar to that in the previously published literature (Ahfir et al. 2007). The peak of the SP BTCs decreases when the flow velocity decreases. SP are more dispersive than DT according to the shapes of the BTCs. In order to quantify the earlier breakthrough of SP compared to the DT, a relative velocity factor, denoted $u_r$, was defined as the ratio$(u_{SP} - u_{DT})/u_{DT}$, where $u_{SP}$ and $u_{DT}$ are the velocities of SP and the DT, respectively. Figure 5 presents the variation of the relative velocity as a function of Darcy’s velocity. The earlier breakthrough of SP is thus described by the positive values of $u_r$. The earlier breakthrough ($u_r$ positive) of the SP occurred at a lower velocity in the glass beads than in the quartz sand columns, i.e. 0.08 cm/s and 0.12 cm/s, respectively. These values are different from those in previous studies (Ahfir et al. 2007, 2009; Ikni et al. 2015). This discrepancy could probably be attributed to the differences of the physical properties of the used porous medium and the injected silt. Figure 5 also shows the existence of a critical velocity beyond which SP travel faster than the DT does. The critical velocity is different between quartz sand and glass beads since the pore geometries and distributions of the two porous media are different. Indeed, according to Figure 4 SP transport in the glass beads medium was facilitated by a homogeneous pore distribution. The behaviour of the faster transport of SP is mainly due to the size exclusion effect.
where the SP are transported along preferential pathways (Grollmund et al. 1998). According to Bennacer et al. (2015), the larger the particle, the larger its velocity is. The large particles are the first to appear at the column outlet. The fast transport of the SP is also attributed to the velocity of distribution in a pore. This explanation was highlighted by Dodds (1982) in a chromatographic tube and named ‘hydrodynamic chromatography’, within a cylindrical tube, and in a laminar flow regime, the microscopic velocity profile is parabolic, with the maximum velocity at the axis of the tube. Dodds (1982) also observed that the large particles are only transported by higher velocities near the tube axis.

**Figure 4** | Fitting of experimental BTCs of DT and silt SP with the mathematical model, for the glass beads column at (a) high, (c) medium and (e) low Darcy’s velocity and for the quartz sand column at (b) high, (d) medium and (f) low Darcy’s velocity.
whereas the solute can approach the wall (at lower velocities). At lower flow rates, a little retardation of the peaking of the SP concentration was observed (Figures 4(e) and 4(f)) because dispersion might be more important for the transport of smaller SP compared with the DT. At lower flow rates, the transport paths of smaller SP were longer, caused by detours in the porous medium before reaching the outlet. In contrast, a higher flow rate enhanced the transport of the larger SP, but with a pronounced size exclusion causing the preferential transport. At a lower flow rate, there was a larger SP entrapment within the porous media owing to settlement in narrower pores and gravity effects.

Effect of flow velocity on particle recovery rate

The recovery rate is obtained by integrating the experimental BTC area. The recovery rate $R$ as a function of Darcy’s velocity in the two porous media is shown in Figure 6. Results show that the recovery rate increases when the flow rate increases. Benamar et al. (2007) reported that decreasing flow rates result in decreased particle concentrations in the column effluents and decreased total particle recovery. When the flow velocity is lower than 0.033 cm/s the recovery rate is close to zero, which means that SP with a median diameter of 10.7 μm have a critical velocity of 0.033 cm/s, below which the hydrodynamic forces are too low compared to the gravity forces to prevent the deposition of the SP in the porous medium. Figure 6 also illustrates that at a given Darcy velocity, the SP recovery from the glass beads column is larger than that from the quartz sand column. It was known from Bradford et al. (2007) that SP recovery rate is sensitive to the geometry of the pores and their distribution. Ahfir et al. (2007, 2009) showed that for high flow rates, the recovery of coarser particles is more important in a gravel than in a glass beads column. The pore structure of the medium and their distribution in the porous medium are considered to cause the large recovery of SP in the quartz sand column. In the quartz sand column, there are narrow and wide grain sizes, leading to a wide range in pore size distribution and then to the existence of many retention sites, such as constrictions, crevices, and caverns, which participate in particle trapping. On the other hand, the single size of the glass beads leads to a quite uniform pore distribution. The existence of unconnected pores in the quartz sand medium may be another factor giving rise to the lower recovery rate of SP.

The size distribution of SP is measured at the column outlet at about the peak of the BTCs. The $d_{50}$ of the recovered particles at the outlet of the porous medium, for each tested population, is shown in Figure 7. It is shown that for the higher flow rates (e.g. 0.265 cm/s), the recovery of coarser SP is more significant in the quartz sand than in the glass beads. The diameter mode of the recovered particles is 9.1 μm for the quartz sand but only 7.2 μm for the glass beads at the velocity of 0.265 cm/s. This phenomenon can be explained by the existence of macropores in the quartz sand medium leading to favourable transport of the larger SP. It is worth noting that the modal size of the recovered particles increases with flow rate for both the quartz sand and
glass beads medium. At low velocities, the recovered particles are mainly the smaller ones, because the hydrodynamic force exerted by the flow on the particles is insufficient to mobilize the larger particles, which remain trapped.

**Deposition kinetics behaviour**

The SP deposition kinetics coefficient $K_{dep}$ is determined by fitting the experimental BTCs with the analytical solution in Equation (5). The SP deposition rate as a function of flow velocity for the quartz sand and glass beads columns is depicted in Figure 8. The results show that deposition rate is more obvious in the quartz sand medium at all the tested flow rates. The existence of many retention sites, such as constrictions, crevices, and caverns in the quartz sand column leads to a better deposition of SP. The SP deposition kinetics coefficient increases with flow rate until a critical velocity, beyond which it decreases. This result is similar to those in the published literature (Ahfir et al. 2007, 2009). Usually, the deposition rate is described by a power law ($K_{dep} = aU^n$). Different authors have proposed a different power value $n$. Massei et al. (2002) found a power value $n$ of 0.7 for silt particles. Kretzschmar et al. (1997) found a power value of 0.31 for carboxyl latex colloids and 0.18 for humic-coated hematite colloids. Ahfir et al. (2007) found a power value of 0.67 and 0.62 below the critical velocity within gravel and glass beads. Ahfir et al. (2009) found that the values of $n$ ranged from 0.44 to 0.56. Bennacer et al. (2013) found that the values of $n$ ranged from 0.26 to 0.66 for SP. In the present study, the deposition rate is well described by a power law with values of 0.30 and 0.40 within the quartz sand and glass beads columns, respectively. At low flow rates, the deposition of large SP is mainly governed by sedimentation (gravity effect) and their velocity is smaller than that of the fluid; thus, they can be captured at constriction and cavern sites. However, at high flow velocity, hydrodynamic forces, especially the drag force, are significant and dominate the gravitational forces on the SP. According to these results, it can be concluded that both hydrodynamic forces and pore structure of the porous medium play an important role in the SP deposition kinetics rate.

**CONCLUSIONS**

Experimental studies were conducted to investigate the influence of hydrodynamic effects and pore structure on SP transport and deposition in different porous media under various flow conditions at room temperature (22–25 °C). The ratio of SP diameter ($d_p$) and quartz sand grain size ($d_{50}$) is 0.0043 in the present study. Column transport experiment results were given based on the SP used (with a median diameter of 10.7 μm), quartz sand (the median of the quartz sand medium grain diameter $d_{50}$ was 2.5 mm) and glass beads (2–3 mm in diameter). Specific findings are highlighted as follows.

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**Figure 7** | Median diameter $d_{50}$ of the recovered particles at the outlet of the porous medium versus Darcy’s velocity ($U$).

**Figure 8** | Influence of flow velocity on deposition kinetics coefficient $K_{dep}$ of the SP.
The BTCs were well described by analytical solutions of a convection–dispersion equation with first-order deposition kinetics. All the transport parameters calculated by fitting the model indicate a complex influence of flow rates and pore structure on particle transport and deposition.

Both quartz sand and glass beads columns provided sufficient evidence that SP can be transported through porous media, under certain hydrodynamic conditions, faster than the DT due to the large size distribution of the SP (polydisperse). The recovery rate increases with flow rates. The amount of SP recovered from the quartz sand column is less than that from the glass beads column. This discrepancy in recovery rate is mainly attributed to the pore structure where the throat dimension, tortuosity, and path connections are the main parameters governing particle transport and straining.

The larger SP were most recovered at high velocities in the quartz sand compared to the glass beads column. A size exclusion effect is observed at high flow rates leading to rapid transport of SP with respect to the DT. The deposition rate increases with flow rate until a critical velocity beyond which the deposition rate and the recovery rate are, respectively, close to zero and 100%. This behaviour can be explained through the fact that the hydrodynamic forces applied to the SP at high flow rates dominate the gravitational forces, leading to reduced deposition kinetics of the SP.

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