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Surface clogging process modeling of suspended solids during urban stormwater aquifer recharge

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Abstract

Aquifer recharge, which uses urban stormwater, is an effective technique to control the negative effects of groundwater over-exploitation, while clogging problems in infiltration systems remain the key restricting factor in broadening its practice. Quantitative understanding of the clogging process is still very poor. A laboratory study was conducted to understand surface physical clogging processes, with the primary aim of developing a model for predicting suspended solid clogging processes before aquifer recharge projects start. The experiments investigated the clogging characteristics of different suspended solid sizes in recharge water by using a series of one-dimensional fine quartz sand columns. The results showed that the smaller the suspended particles in recharge water, the farther the distance of movement and the larger the scope of clogging in porous media. Clogging extents in fine sand were 1 cm, for suspended particle size ranging from 0.075 to 0.0385 mm, and 2 cm, for particles less than 0.0385 mm. In addition, clogging development occurred more rapidly for smaller suspended solid particles. It took 48, 42, and 36 hr respectively, for large-, medium-, and small-sized particles to reach pre-determined clogging standards. An empirical formula and iteration model for the surface clogging evolution process were derived. The verification results obtained from stormwater recharge into fine sand demonstrated that the model could reflect the real laws of the surface clogging process.

Key words: stormwater; aquifer recharge; suspended solids; clogging

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Introduction

Under the stress of global climate change and water shortage, urban stormwater is quickly becoming a potential water resource (Bloetscher et al., 2010). Aquifer recharge using stormwater has many advantages. Aquifer recharge deduces the side effects of groundwater over-exploitation, such as land subsidence and seawater intrusion, and reduces the pressure on urban flood control and drainage (Datry et al., 2003). However, it cannot be widely adopted because of clogging problems. Survey data from aquifer recharge engineering practices around the world indicated that most aquifer recharge facilities encountered serious clogging problems within a short operation period. For example, about 33% of 207 infiltration systems in Maryland, USA, including facilities using recharge water with pre-treatment, encountered serious clogging problems within 2 years (Lindsey et al., 1992). Clogging problems are the most critical issues concerning the efficiency of recharge plants (Alfredo, 2000).

Clogging refers to the decrease in permeability of a porous medium because of physical, biological, and chemical processes (Alfredo, 2000; Bouwer, 2002). Physical clogging is dominant in practical engineering and is always observed firstly (Pavelic et al., 1998; Rinck et al., 2000). In a survey of 40 injection wells, 80% of the facilities showed clogging phenomena, of which 70% were caused by suspended solids (SS) and bubbles, 10% by chemical reactions, 15% by microbial growth, and 5% by other reasons (Dillon et al., 1994). The infiltration media are very prone to clogging by urban stormwater runoff with high concentrations of suspended solids. Thus, studies on the characteristics and evolvement laws of surface suspended solids clogging are important in improving aquifer recharge technology.

The study of suspended solids clogging in aquifer recharge includes two aspects: the clogging mechanism and clogging prediction. The study of clogging mechanisms focuses on the clogging process and its influencing factors through laboratory experiments. Suspected solid clogging always concentrates at the top of the infiltration media, especially in fine infiltration media with mini pores (Platzer and Mauch, 1997; Goss et al., 1973; Caselles et al., 2007; Deo et al., 2010; Hua et al., 2010). Field data also demonstrate that 50% of the particle mass in recharge water is retained in the top several centimeters of soil.
Infiltration medium size determines the distribution of internal pores and influences the migration conditions of suspended solids. Suspended solid concentration is another important governing factor of clogging, with high concentrations of suspended solids leading to more severe clogging problems.

Many previous publications have demonstrated the existence of a critical concentration causing clogging. Rice (1974) stated that adequate infiltration rates were reached by keeping the suspended solids concentration below 10 mg/L. Okubo and Matsumoto (1983) showed that to avoid physical clogging, the suspended solids concentration in recharge water used for aquifer recharge should less than 2 mg/L. It was also reported by one group that particle loads in infiltrated water less than 150 mg/L would not cause considerable blockage during their measurements (Dillon and Pavlic, 1996; Dillon, 2002). In some countries (e.g., the Netherlands, UK, USA), water with opacity degrees of more than 2 to 5 NTU is not allowed to infiltrate (Holländer et al., 2005). Research on the critical suspended solids concentration yields different results because of its dependence on specific field conditions.

Grain-size characteristics of suspended solids are also a significant factor in clogging. However, very few researchers have focused on this matter. The grain size distribution of a porous medium plays a significant role in the change of hydraulic properties during the clogging evolution. A laboratory scale study indicated that clogging occurred at the interface between a gravel filter and underlying soil (Siriwardene et al., 2007). Clogging of fine-grained porous media resulted in a final hydraulic head build up 2.8 times greater than that observed in medium-grained sand, whereas the infiltration medium of coarse sand can prevent or delay clogging (Wood et al., 2005; Hua et al., 2010). Siriwardene et al. (2007) indicated that physical clogging is mainly caused by the migration of sediment particles of less than 6 μm in diameter, through a series of one dimensional (1-D) laboratory experiments. Kovenya et al. (1972) found that suspended solids with diameters of 1–10 μm were deposited at the surface of the infiltration medium, the smallest particles of diameter 0.1 μm were adsorbed, and the suspended solids with diameter of 0.5 μm were transported the longest distance.

The Membrane Filtration Index (MFI), a method for estimating the fouling rate of reverse osmosis membranes used in the drinking water industry, is used to predict clogging potential (Dillon et al., 2001). Clark and Pitt (2009) used the equation of infiltration rate and particle concentration (Urbonas, 1999) to express the relationship between suspended solids concentration, particle size, and outflow rate. Herzig et al. (1970) proposed a movement model of suspended solids in porous media based on the advection-dispersion equation. Osei-Bonsu (1996) put forward a hydrostistical model of physical clogging, which described laws of media conductivity variation under different conditions.

The aims of the present study are to determine the relationship between suspended solids characteristics and the clogging process and derive a practical mathematical forecasting model based on the experimental data.

1 Materials and methods

1.1 Lab-based approach

A 1-D aquifer recharge rig system included four parts: water tank with circulation function, upper and lower constant-head controller, seepage column (50 cm in height and 8 cm in diameter and made of plexiglas), and observation board (Fig. 1). Five piezometric tubes were distributed along the column at 10 cm intervals from top to bottom. During the operation period, a submersible pump was used to continuously supply water to the constant-head controller and circulate water in the tank.

Fine quartz sand (diameter of 0.1–0.25 mm) was adopted as the infiltration medium. X-ray diffraction (XRD) patterns of the sand showed that the predominant mineral composition was quartz, followed by a small amount of feldspar (Table 1). The suspended solids samples were collected from a field site and were separated into three groups in diameter as follows: 0.075–0.05 mm, 0.05–0.0385 mm, and < 0.0385 mm. The mineralogy of the suspended solids is shown in Table 1. The recharge water was prepared by mixing tap water and suspended solids with different diameters.

The piezometric head and infiltration rates were monitored every 2 hr during unsteady stages of infiltration and every 4 hr at quasi-steady stages. The water flow was assumed to be in a steady state within every measurement interval. The time-varying hydraulic conductivity in different locations of sand columns is calculated by Darcy’s law (Eq. (1)):

$$K = \frac{Q \times l}{\Delta h \times \pi r^2}$$

where, $Q$ (m$^3$/day) is the flow rate, $l$ (m) is the length between any two piezometric tubes along the column, $\Delta h$...
(m) is the hydraulic head difference in distance of \( l \), and \( r \) (m) is the inner diameter of the column.

Three experiments were conducted to determine the influence of suspended solid size on the clogging process. The experimental conditions were as follows: the infiltration media was fine sand (diameter of 0.1–0.25 mm) with bulk density of 1.6 g/cm³, the hydraulic gradient was 1, the suspended solids content was 1 g/L, and the suspended solids diameter was 0.05–0.0385 mm, 0.075–0.05 mm and < 0.0385 mm respectively in each experiment.

1.2 Modeling the surface clogging processes

The vertical equivalent hydraulic conductivity theory was adopted for calculating the total conductivity from the conductivity and thickness of each observed layer (Eq. (2)).

\[
K_v = \frac{\sum_{j=1}^{m} M_j}{\sum_{j=1}^{m} \frac{M_j}{K_j}}
\]

where, \( K_v \) (m/day) is the vertical equivalent hydraulic conductivity of the infiltration sand, \( K_j \) (m/day) is the hydraulic conductivity of layer \( j \), and \( M_j \) (m) is the thickness of layer \( j \).

The critical factor governing the overall conductivity is the layer with smallest \( K_j \). According to this theory, the infiltration sand vertical equivalent hydraulic conductivity is mostly affected by the hydraulic conductivity values of surface clogging layers.

The assumption is that all the suspended solids concentrate on the infiltration sand surface as a clogging cake; thus, the sand column can be divided into two parts: clogging layer and sand layers. The vertical equivalent hydraulic conductivity equation is written as Eq. (3):

\[
K_v = \frac{M_{CL} + \sum_{j=1}^{m} M_j}{\frac{M_{CL}}{K_{CL}} + \sum_{j=1}^{m} \frac{M_j}{K_j}}
\]

where, \( M_{CL} \) (cm) is the accumulative thickness of the clogging layer on the infiltration sand surface, and \( K_{CL} \) (m/day) is the hydraulic conductivity of clogging layer.

In theory, the clogging layer conductivity (\( K_{CL} \)) represents the infiltration permeability, the value of which should remain constant (\( K_{CON} \)). However, under real conditions \( K_{CL} \) was a function of \( M_{CL} \): \( K_{CL} \) decreased with increasing \( M_{CL} \), until \( M_{CL} \) reached a critical thickness of clogging layer (\( M_{CT} \)). This may be due to other clogging processes. The empirical equation, obtained by batch experiments, is expressed as Eq. (4):

\[
K_{CL} = \begin{cases} 
K_{CON} + K_i (1 - M_{CL}/M_{CT})^5 & M_{CL} \leq M_{CT} \\
K_{CON} & M_{CL} > M_{CT}
\end{cases}
\]

where, \( K_{CL} \) is hydraulic conductivity of the clogging layer at time \( t \), \( K_{CON} \) (m/day) is the stable hydraulic conductivity of the clogging layer, and can be calculated by Eq. (3) according to the stable segment data of experiment curves. \( K_i \) (m/day) is the initial hydraulic conductivity of the clogging layer, and can be calculated by the Sauerbrei formula of Eq. (5) (Kasenow, 2002).

\[
K = 2.436n^3(d_1)^2/(1-n)^2
\]

where, \( K \) (cm/sec) is hydraulic conductivity, \( n \) is porosity, and \( d_1 \) (mm) is the effective grain diameter with 17% finer by weight.

\( M_{CT} \) (cm) is the critical thickness where the hydraulic conductivity of the clogging layer can stay constant, and also can be derived from experimental curves. \( M_{CL} \) (cm) is the clogging layer thickness at time \( t \). It is hard to measure but can be calculated by Eq. (6).

\[
M_{CL} = \frac{\sum_{i=1}^{n} Q_i \times \Delta t \times C_{SS}}{A \times \rho}
\]

where, \( Q_{i-1} \) (L/sec) is the flow rate in time \( t-1 \), \( \Delta t \) (sec) is the time interval from \( i-1 \) to \( i \), \( C_{SS} \) (g/L) is the concentration of suspended solids in recharge water, \( A \) (cm²) is the area of cross section, and \( \rho \) (g/cm³) is the density of the suspended solids.

Based on Eqs. (2)–(6), the vertical hydraulic conductivity of the whole infiltration medium (including clogging layer and infiltration sand) at time \( t \) can be iterated by Eq. (7):

\[
K_{vt} = \frac{\sum_{i=1}^{n} Q_{i} \times \Delta t \times C_{SS}}{\rho \times A \times K_{CL}} + \sum_{j=1}^{m} \frac{M_j}{K_j}
\]

when \( t = 1 \), \( Q_1 = Q_0 \) presents the initial recharge flow rate of the infiltration medium without clogging, which should be obtained by lab experiment. After \( K_{vt} \) was calculated, the flow rate at time \( t \) (\( Q_t \)) could be calculated by Darcy’s law Eq. (1):

\[
Q_t = K_{vt} \times I_t \times A
\]
Table 2 Characteristics of stormwater

<table>
<thead>
<tr>
<th>pH</th>
<th>Electrical conductivity (μS/cm)</th>
<th>Na⁺ (mg/L)</th>
<th>K⁺ (mg/L)</th>
<th>Ca²⁺ (mg/L)</th>
<th>Mg²⁺ (mg/L)</th>
<th>HCO₃⁻ (mg/L)</th>
<th>Cl⁻ (mg/L)</th>
<th>SO₄²⁻ (mg/L)</th>
<th>NO₃⁻ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.77</td>
<td>100</td>
<td>3.03</td>
<td>0.88</td>
<td>18.48</td>
<td>1.16</td>
<td>20.87</td>
<td>6.51</td>
<td>25.08</td>
<td>13.56</td>
</tr>
</tbody>
</table>

The change of hydraulic gradient with time \(I_t\) can be neglected, because the clogging layer thickness is usually very thin (less than 1 cm in experiments); thus Eq. (8) can be simplified as:

\[ Q_t = K_{st} \times I \times A \]  

(9)

1.3 Case verification

To verify the applicability and accuracy of the model, stormwater obtained from urban green areas with simple precipitation was used to recharge fine quartz sand in a bench scale experiment. The main characteristics of the stormwater are shown in Table 2. The experimental installation was 100 cm in height and 10 cm in diameter, and 28 piezometric tubes were distributed along the column, which were divided into three parts with varying measuring tube intervals of 2, 3, and 5 cm.

The experimental conditions were identical to the previous conditions except for the suspended solid content, which averaged 424 mg/L. The characteristics of suspended solids in recharge water are shown in Fig. 2. Particles less than 0.1 mm in size were the main components of suspended solids; these had a non-uniform coefficient \(C_u\) of 44.55 and poor grading. XRD results for the suspended solids indicated that quartz, at 68%, was the primary component of the matter. Feldspar was 25% and calcite was 7%. During the experiment, the piezometric level, flux, total dissolved solids (TDS), and suspended solids concentrations of inflow and outflow were monitored every 2 hr during the initial stage and once every 4 hr during later stages.

2 Results and discussion

2.1 Influence of suspended solids size on clogging formation

Suspended solids size is a key factor that influences the degree and position of clogging. Fine sand, which tends to clog surfaces, was selected for the experiments. Figure 3 shows the clogging degree using the ratio of the instantaneous monitoring value of the hydraulic conductivity \(K\) and the initial value \(K_0\) of the infiltration media.

The results show that for suspended solids with particle diameters of 0.075–0.05 mm and 0.050–0.0385 mm, clogging occurred only on the surface layer. Suspended solids with particle diameters of < 0.0385 mm infiltrated to a depth of about 2 cm into the column. The observed infiltration media permeability of 1–10 cm was affected mainly by the clogging layer. Therefore, the smaller the suspended solids in the recharge water, the deeper the clogging depth in the porous media.

The clogging rate of suspended solids with small diameters is faster than suspended solids with large diameters. Less time was needed to reach the stable state of total hydraulic conductivity of the infiltration media column when the suspended particle size was smaller. The operation periods were 48, 42, and 36 hr for suspended solids with...
particle diameters of 0.075–0.05 mm, 0.05–0.0385 mm, and < 0.0385 mm, respectively.

For the same infiltration media, surface clogging occurred in the recharge process with different particle diameters of suspended solids. The tendency of decline of the total hydraulic conductivity of the infiltration media column coincided with the surface clogging infiltration media layer. However, the delay time and decline rate were clearly influenced by the other layers.

### 2.2 Model parameters determination

When the recharge conditions were determined, such as aquifer recharge site and water source, the initial hydraulic conductivity ($K_i$), critical thickness ($M_{CT}$) and constant hydraulic conductivity ($K_{Con}$) of the clogging layer were dependent on the characteristics of the suspended solids. $K_i$ was calculated by Eq. (5), $K_{Con}$ was derived from constant data sets from each experiment, and $M_{CT}$ was the cumulative thickness of the clogging layer while $K_{Con}$ was reached. The values of $K_i$, $M_{CT}$ and $K_{Con}$ are presented in Table 3.

According to the data sets presented in Table 3, the quantitative relationship of $d_{17}$-$M_{CT}$ and $d_{17}$-$K_{Con}$ can be determined as follows:

$$M_{CT} = 3.0442d_{17} + 0.1042$$

$$R^2 = 0.956$$

(10)

$$K_{Con} = 0.0425d_{17} + 0.0026$$

$$R^2 = 0.951$$

(11)

$M_{CT}$ (0.00624 mm) and $n$ (0.56) of suspended solids in stormwater were measured. $K_i$ (0.074 m/day), $M_{CT}$ (0.123 cm) and $K_{Con}$ (0.0029 m/day) were calculated through Eq. (5), Eq. (10) and Eq. (11) respectively.

### 2.3 Modeling results analysis

Based on the experimental data, Eq. (7) was established to simulate the clogging process. The comparison between the observed and calculated hydraulic conductivity values of the infiltration media column (Fig. 4) indicated that the iteration equation performed well in simulating the clogging layer development process.

A case study of stormwater that infiltrated into the fine sand was used to verify the model validity. The hydraulic conductivity of the infiltrated media and clogging type had been analyzed previously. The results showed that the clogging depth of fine sand was mainly concentrated on the surface (Fig. 5).

Chemical clogging was mainly due to the mixing function between the recharge water and groundwater, as well as the water-rock interaction between recharge water and the aquifer matrix during the artificial recharge process. Chemical precipitation seems not to be the dominant process in the verification experiment because the effluent total dissolved solids (TDS) were higher than the influent (Fig. 6), indicating that dissolution was the dominant chemical process.

The growth of bacteria and polysaccharides, which implies the occurrence of biological clogging, always takes several days after the organisms come into a new environment (Rinck et al., 2000). Because the experiment ran for only two days, biological clogging was not considered in the present research. Consequently, the dominant type of clogging in the stormwater recharge experiment was surface physical clogging of suspended solids.

As shown in Fig. 7, the calculated results showed good agreement with the observed hydraulic conductivity of the total infiltration sand column. Therefore, the mathematical iteration model (Eq. (7)) can be adopted to depict the clogging process of infiltration media under artificial recharge conditions.

### 3 Conclusions

Nowadays, urban stormwater with large amounts of suspended solids is used to recharge into sand aquifers and clogging problems are very common. The results of this
study indicated that both clogging depth and rate depended on the particle sizes of the suspended solids. When the particle sizes of the suspended solids were small, they moved easily down the infiltration media, and the clogging rate of the infiltration media was fast.

A mathematical iteration model which depicted the hydraulic conductivity of the infiltration media under surface clogging conditions was built, and the regression equation of $M_{CT}$ and $K_{Con}$ was determined according to the experiments. Furthermore, the applicability of the model was verified by an artificial recharge experiment with urban stormwater. The fitting of observed and calculated data revealed that the model could describe the real laws of sand permeability change during infiltration.

However, the estimation regression relationship between $d_{17}-M_{CT}$ and $d_{17}-K_{Con}$, needs further study. The change laws of $K_{CLL}$ (Eq. (4)) also indicated that the suspended solids clogging process may not be solely a physical process.

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