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# Attachment–detachment dynamics of suspended particle in porous media: Experiment and modeling

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SUMMARY

Clogging problems occur frequently during the process of artificial recharge, and especially physical clogging, caused by suspended particles in the water, seriously affects the recharge efficiency. In our study, a mathematical model for simulating porous physical clogging were developed by coupling the model of particle transition–deposition in porous media and expressions correlating permeability coefficient, porosity and concentration of deposited particles, to provide a systematic description of the occurrence and development of physical clogging. In addition, the attachment and detachment coefficients in above model which used to be adopted as fixed values were found influenced by the Darcy velocity. And the experimental protocol to determine the particle attachment and detachment parameter was also proposed in the study. With a lower velocity, particles were attached to the surface of the grains, whereas when the velocity became higher, particles were gradually detached from the grain surface. When the deposited particles occupied the pore space, media clogging may occur. The modeling verification indicated that the calculated values displayed a good qualitative agreement with the measured values of the 1-D column test, therefore, the improved method for valuing attachment and detachment parameters can be used for the prediction of artificial recharge clogging.



## 1. Introduction

Artificial recharge of storm-water to groundwater aquifer, has been widely used for maintaining groundwater resources, reducing soil salinization, mitigating groundwater pollution, and remediating contaminated aquifers. The recharge is categorized as surface and subsurface recharge, respectively from surface sources, such as watersheds, ditches, river beds by hydraulic pressure gradient, and through wellbores. However, for each recharge mode, clogging problem in infiltration systems remains a key restricting factor in practice (Bouwer, 2002; Barrett and Taylor, 2004). The occurrence of clogging is related to the recharge water quality, aquifer properties and biological activities. Physical clogging is a kind of clogging caused by the retention of suspended particles, and it is the most common clogging form during well and surface recharge (De Vries, 1972; Vigneswaran and Suazo, 1987).

Up to now, researchers have made some important progress in the study of clogging mechanism by means of indoor simulation tests. As for physical clogging modeling of porous media, theoretical and empirical models have been developed in some cases. The empirical models are based on the temporal evolution of water pressure, infiltration rate and other parameters (particle concentrations in suspension and in deposition (Alfredo, 2001). These models are extremely limited by aquifer properties and recharge water quality (Alfredo, 2001). Bianchi et al. (1978) proposed a generalized equation to describe physical clogging, which is called exponentially-decay model, and the equation is similar to the form of the temporal evolution of soil infiltration capacity in rainy conditions.

Compared with empirical models, theoretical models are more applicable and complicated. Theoretical models relate the particle movement and the clogging process from the viewpoint of dynamics. Based on the deep bed filtration theory, the theoretical models build relationships between filtration rate and deposited particle concentration (Herzig et al., 1970; Bai and Tien, 2000; Gitis et al., 2010; Yuan and Shapiro, 2011; Bedrikovetsky et al., 2012; Boek et al., 2012). In terms of dynamics, the attachment and detachment activities of particles in the porous media is under the comprehensive influence of inertia force, gravity settling, electrostatic force and hydrodynamic shear stress (Zamani and Maini, 2009). In addition, many researchers have quantitatively examined the effect of each force on the micro level (Pfeffer and Happel, 1964; Yao et al., 1971; Tien and Ramarao, 2011; Bird et al., 2002). In general, it is the hydraulic performance and conditions of the percolation system that influence the particle attachment and detachment

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parameters, and some studies have figured out these kinetic parameters (Yoon et al., 2006; Santos and Bedrikovetsky, 2006; Siriwardene et al., 2007; Civan, 2010). Furthermore, the capillary model has also been considered as a useful numerical tool in which the pores of aquifer media are approximately taken as a bundle of straight capillaries with uniform radius, and then the particle deposition can be regard as the wall adsorption phenomenon under water flows (Reddi et al., 2000, 2005; Deo et al., 2010).

In summary, lots of studies were conducted to investigate the physical porous clogging phenomenon by means of different numerical methods. However, the key parameters of the clogging model,-the particle attachment and detachment parameters, were mostly assigned with the fitted or empirical values from previous studies. For example, the particle attachment coefficient was set within the range of $(1–50) \times 10^{-3}\ s^{-1}$, while the range of detachment parameter was $(1–60) \times 10^{-6}\ s^{-1}$ (Alfredo, 2001; Ying, 2009). However, these parameters are actually changing during the water injection process, rather than constant values.

In this study, a model of particle transition–deposition (TD Model) in porous media was built and the aquifer media physical clogging model (PC Model) was further developed by coupling the TD Model and the expressions correlating permeability coefficient, porosity and particle retention concentration. Besides, to obtain accurate attachment and detachment coefficient values for above model, given that surface infiltration can be considered as 1-D seepage, experiments were designed to quantitatively examine the correlation between velocity and particle attachment–detachment parameters. Finally, software of COMSOL Multiphysics® was employed as the PC Model and exhibited a good fitting effect with the experimental data from the clogging test.

## 2. Physical clogging model

In the porous aquifer, the Reynolds number is smaller than the critical value (2.0), and groundwater flows in laminar type (Happell and Brenner, 1965). Based on the model of particle transition–deposition (TD Model) in porous media, the mathematical correlations among the media permeability coefficient, porosity and deposited particle concentration were involved to develop a new mathematical model with which simulation of porous media physical clogging can be effectively carried out.

Under surface irrigation conditions, a small right angle hexahedron with three side lengths of $\Delta x$, $\Delta y$ and $\Delta z$ respectively was selected in the sand column, and water flowed in and out the volume along the $x$ direction following the Darcy's law. According to the law of mass conservation, the particle transition process can be described as Eq. (1):

$$\frac{\partial}{\partial t}(nC + C_S) + \frac{\partial}{\partial x}(C \cdot q) = 0 \tag{1}$$

where $n$ is the porosity of the sand media (dimensionless), $C$ is particle concentration in the bulk phase of suspension ($kg\ m^{-3}$), $C_s$ is deposited particle mass in unit pore space ($kg\ m^{-3}$), $q$ is the Darcy velocity ($m\ s^{-1}$).

Based on the particle attachment and detachment dynamics, the deposition process of suspended particles can be expressed in Eq. (2) (Herzig et al., 1970):

$$\frac{\partial C_S}{\partial t} = \alpha \cdot C - \beta \cdot C_S \tag{2}$$

where $\alpha$ is the particle attachment coefficient ($s^{-1}$) and $\beta$ is the particle detachment coefficient ($s^{-1}$).

During the recharge process, particles will easily be captured by the media sands and then deposit in the pores, causing a reduction of porosity, which can be written as Eq. (3):

$$n = n_0 - \gamma C_S \tag{3}$$

where $n_0$ is the initial porosity of aquifer media (dimensionless), $\gamma$ is a constant parameter ($m^3\ kg^{-1}$) which is in numeral equal to the pore volume occupied by unit mass particles.

The modification of Kozeny–Carmen equation used to express how the decrease of porosity $n$ affects the media permeability $K$ is expressed as follows (Xu and Yu, 2008):

$$K = \frac{n^3}{c(1-n)^2 S^2} \tag{4}$$

where $c$ and $S$ refers to Kozeny constant and specific surface area based on the solid volume, respectively. Because the values of $c$ and $S$ are constant, the following equation can be obtained

$$K_t = K_0 \cdot \frac{n^3}{(1-n)^2} \cdot \frac{(1-n_0)^2}{n_0^3} \tag{5}$$

where $K_t$ is the instantaneous saturated permeability coefficient during recharge (m/d) and $K_0$ is the initial saturated permeability coefficient before recharge (m/d).

To sum up, combining the initial and boundary conditions, the particle TD model can be expressed as Eq. (6):

$$\begin{cases} \frac{\partial}{\partial t}(nC + C_S) + \frac{\partial}{\partial x}(Cq) = 0 & 0 \leqslant x \leqslant L,\ t > 0 \\ \frac{\partial C_S}{\partial t} = \alpha C - \beta C_S & t > 0 \\ C|_{t=0} = 0.0 & 0 \leqslant x \leqslant L \\ C_S|_{t=0} = 0.0 & 0 \leqslant x \leqslant L \\ C|_{x=0} = C_0 & t > 0 \end{cases} \tag{6}$$

The porous media PC Model can be set up by coupling Eq. (3), (5) and (6) to quantitatively describe the occurrence and development of physical clogging.

The degree of clogging can be expressed as relative saturated permeability coefficient $k$ in Eq. (7):

$$k = K_t / K_0 \tag{7}$$

## 3. Measurement of the major parameters

As mentioned above, major parameters in the PC model include the particle attachment parameter ($\alpha$), the detachment parameter ($\beta$) and the pore volume occupied by unit mass deposited particles ($\gamma$). These parameters should be determined through a series of experiments.

### 3.1. Materials and setups

#### 3.1.1. Materials

(1) Sand sample the sand sample used in all laboratory experiments was collected from an unconfined aquifer near the Dagu River in Qingdao, China, with an average diameter of 0.497 mm. Sieving and densimeter method were taken to obtain the particle size distribution of the sand sample, and the result was shown in Fig. 1.
The mineral component of the sand sample was tested by D/max-rB Anode Rotary Diffractometer. The sample includes quartz (87.8%), feldspar (6.7%), dolomite (2.4%), hornblende (0.3%) and clay minerals (2.8%).

(2) Suspended particles suspended particles were collected by depositing, filtering and sieving the storm-water of the Dagu River sequentially. The eventually obtained particles were all less than 0.038 mm in diameter and their average diameter was 16.7 μm according to the measurement by MS2000 Laser Particle Analyzer.