Effects of Colloid Transport on Permeability of Water-bearing Media in Subsurface Environment

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Abstract A sets of sand column experiments were conducted to investigate the transport and deposition of colloids in water-saturated porous media, and the mechanism of the permeability reduced by transport and deposition of colloids are discussed. The research results show that the breakthrough curves of colloid transport in water-bearing media presented as three stages: “not-yet-breakthrough”, “breakthrough in process”, “stable-breakthrough”, however, there were no completely breakthrough. The concentration of colloid had great influence on the permeability of water-bearing media, and the effect of low concentration was relatively smaller. The deposition of colloids was the main reason for the permeability loss of the porous media.

Key Words Colloid; transport and deposition; water-bearing media; permeability

1 Introduction

Natural colloids, which are ubiquitous in groundwater systems, are composed of inorganic and organic molecular constituents or microorganisms [1]. Colloidal particles can transport long distances with the groundwater. Grolimund (1998) reported the primary mechanisms controlling the transport of colloidal particles in subsurface porous media are particle advection, dispersion, and deposition (filtration) [2]. These are influenced by the surface chemical characteristics of the natural porous media and colloids, size and morphology of colloidal particles and granular porous media, solution chemistry, and the fluid flow field. Moreover, some of these mechanisms are closely interrelated. For instance, particle deposition is influenced by particle advection, whereas particle dispersion in porous media is directly related to fluid velocity and particle advection [3]. The transport of colloids through porous media strongly depends on the kinetics of colloid deposition and release [4].

Tianjin is situated in the northeast of the North China plain, south of the Yanshan mountain chain and west of Bohai Bay. The porous media of the Tianjin coastal plain are characterized by high salinity and colloid content. In this paper, the colloid migration and deposition in water-saturated porous media were studied by a sets of packed sand columns. Based on the experimental results and quantitative analyses of colloids transport in porous media, the key permeability change mechanism governing the transport of natural colloidal particles in sand are discussed.

2 Materials and methods

2.1 Materials
2.1.1 Porous Medium
Representative fine sand sampled from the strand plain of Tianjin. Before the experiment the sample was air-dried, passed through 30~50-mesh screen. To remove colloidal particles, the sand sample was added into Erlenmeyer flasks with distilled water and oscillated several times until the conductivity and turbidity of supernatant were close to the distilled water’s, air-dried, and stored at 4 °C. The particle density, bulk density and porosity of the sample were 2.3 g/cm³, 1.6 g/cm³ and 0.314 respectively.
2.1.2 Preconditioning of colloids
100g of natural clay, passed through a 60-mesh screen, was put into 500ml beaker with 200ml deionized water. The mixture was stirred to homogenize and form a disperse system. After dispersed by ultrasonic and settled for 24h, the supernatant was removed by siphoning and filtered through 0.8µm cellulose acetate film to gain the colloidal solution. Measured by gravimetric method, the average
concentration of colloid was 631mg/L. It was diluted to different concentrations for experiment.

2.1.3 Determination of colloid content
The contents of colloids in the aqueous phase can be calculated by turbidity through the calibration curves which contents of colloids as horizontal ordinate and correspondent turbidity as vertical ordinate are obtained.

2.2 Column experiment
2.2.1 Experimental setup
The column setup used for the colloid particle transport mainly includes a water-supply bottle, constant head setup, plexiglass column and effluent measuring system. The column is the main body of conducting the experiment. The bottle supplies water to column through constant head setup. The upper overflow orifice of the constant head setup can retain constant water level, the one outlet can supply water to the column.

Column dimension for the various concentrations of colloids particle transport experiments was 3 cm in diameter and 10 cm in length. Two ends of the sand were packed with 3~4mm glass bead used to cushion. Nylon net was used to separate the sand and cushion. The glass bead was thoroughly cleaned prior to use. The cleaning procedure consisted of ultrasonication for 30 min in deionized water, followed by immersion in dilute nitric acid (1:10) for 24 h to remove surficial compounds. The columns were “wet-packed” during the subsequent experiment, and placed horizontally to minimize gravitational movement of colloid along the column.

2.2.2 Experimental methods
As columns were packed well, they were connected to fixed head buffering column by flexible hose, then leached with different colloid concentration of 70 mg/L, 160 mg/L and 265 mg/L. Colloid concentrations in the column effluent were monitored when flow flux was 15mL instantly, and recording the head difference, sampling time, effluent volume at the same time. The experiment stopped when the colloid concentration of effluent was stable. Room temperature was maintained during experimentation (about 25 °C). Solution pH of influent and effluent showed little during the experiments, remaining between 8.5 and 8.9. Under the condition of constant head, the permeability can be measured according to the Darcy’s law and quantitatively expressed in hydraulic conductivity.

3 Results and Discussion

3.1 Transport of colloid in porous medium
Fig.1 shows the breakthrough curve of colloids in different influent concentrations through porous medium. The results showed that the breakthrough curves experienced three stages–“not-yet-breakthrough”, “breakthrough in process” and “stable-breakthrough”, yet not thorough breakthrough. The relative concentration of colloid in each curve was close to 0 before 3 pore volumes, which showed colloid breakthrough did not occur yet. Relative concentration of colloids increased rapidly at 3~5 pore volumes, the colloids began to penetrate and inflexion point appeared at around fifth pore volumes. The pore volumes of inflexion point appeared in colloid breakthrough curve of 70mg/L, 160mg/L and 265mg/L were 5.53, 5.19 and 4.72 respectively, and corresponding maximum relative concentrations of colloid were 0.22, 0.57 and 0.38. After inflexion point, relative concentrations of 160mg/L and 265mg/L decreased from 0.57 and 0.38 to 0.39 and 0.31 respectively, while the colloid concentration of 70mg/L showed steady tendency.
3.2 Colloid deposition in porous medium

Fig.1 showed concentrations of colloid didn’t penetrate completely in porous medium. That was to say, deposition of colloid occurred in the process of transport. In order to analyze the deposition characteristics of colloid, the accumulative amount and total deposition ratio of colloid particles in effluent were measured. The accumulative amount and total deposition ratio for colloid can then be expressed as

\[
\text{The accumulative amount}(S) = \sum_{i=1}^{n} (C_0 - C_i) V_i \quad (1)
\]

\[
\text{Total deposition ratio}(R) = \left(\frac{\sum_{i=1}^{n} C_0 V_i - \sum_{i=1}^{n} C_i V_i}{\sum_{i=1}^{n} C_0 V_i}\right) \times 100\% \quad (2)
\]

Where \(C_0\) is the colloid concentration of the influent, \(C_i\) is the colloid concentration of the effluent corresponding to the pore volume \(i\), \(V_i\) is the effluent volume of the pore volume \(i\).

The result showed that the total accumulative amount of colloid deposition were 9.35mg, 29 mg and 65mg corresponding to the influent colloid content was 70mg/L, 160mg/L and 265mg/L, and the total deposition ratio was 83.7 %, 63.6 % and 68.5 %, respectively. It is found that the total accumulative amount of colloid deposition increases with increasing the influent colloid content, however, the total deposition ratio is contrary.

3.3 Dynamic of the permeability of porous media

In order to investigate the effects of colloid transport on the porous media permeability, hydraulic conductivity \(K\) was determined after the flow rate of the column remained stable with the Darcy’ law

\[
K = \frac{QL}{A\Delta h} \quad (3)
\]

Where \(Q\) is volumetric flow rate in cm\(^3\)/s, \(A\) is flow area perpendicular to \(L\) in cm\(^2\), \(L\) is flow path length in cm, \(h\) is hydraulic head in cm, \(\Delta\) denotes the change in \(h\) over the path \(L\).

Relative permeability coefficient \((K / K_0)\) is used to describe the dynamic of the porous media permeability, and \(K_0\) is the natural hydraulic conductivity when leaching distilled water. Fig.2 showed that \(K / K_0\) of porous media decreased continuously from 1.0 to 0.63 during the first 17 pore volumes when the influent colloid content was 70mg/L, and hydraulic conductivity \((K)\) in the column decreased from 1.89×10\(^{-2}\) cm/s to 1.23×10\(^{-2}\) cm/s, and the permeability decreased by 37%.

![Figure 2  Relation curves of relative permeability coefficient with pore volumes](image)

When the column influent colloid content was 160mg/L, \(K / K_0\) decreased from 1.0 to 0.56 before the 18 pore volumes, and permeability coefficient \((K)\) decreased from 1.42×10\(^{-2}\) cm/s to 0.89×10\(^{-2}\) cm/s, and the permeability decreased by 44%. Moreover, \(K / K_0\) decreased continuously from 1.0 to 0.9 before the 19 pore volumes when influent colloid content was 265 mg/L, and permeability coefficient \((K)\)
decreased from $1.62 \times 10^{-2}$ cm/s to $0.43 \times 10^{-2}$ cm/s, and the permeability decreased by 71%. It is obviously that colloid transport effected on the permeability of porous media, especially for high concentration of colloid particles. The higher concentration of influent colloid increased, the larger the reduction degree of permeability was.

Fig1 showed that colloids were not thorough breakthrough, this is mainly because that some pore of the porous media limited the colloid transport, and increasing the collision frequency between colloids and pore wall, so that colloids deposit on the surface of the porous media. With colloids particle depositing continuously, the pore space of porous media was becoming narrow, leading to the loss of porous media permeability.

4 Conclusion

(1) The breakthrough curves of colloids transport showed three stages-“not-yet-breakthrough”, “breakthrough in process” and “stable-breakthrough”, yet not thorough breakthrough.

(2) The deposition can occur in the process of colloids transport. The total accumulative amount of colloid deposition increases with increasing the influent colloid content, however, the total deposition ratio is contrary.

(3) The deposition of colloids particle leads to the loss of porous media permeability. The higher concentration of influent colloid increased, the larger the reduction degree of permeability was.

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