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REVIEW ARTICLE

Physical clogging experiment of sand gravel infiltration with Yellow River water in the Yufuhe River channel of Jinan, China

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Abstract To make sense of physical clogging during Yellow River water spreading in the strong leakage zone of the Yufuhe River, a laboratory sand column experiment was undertaken and the heterogeneous sand gravel with a uniformity coefficient of 25.2 from the Yufuhe River was used as an infiltration medium. Under either the condition of raw sand or washed sand, physical clogging tests were conducted with constant hydraulic heads of 10 cm and 30 cm and inflow suspension concentrations of 200 mg/L, 500 mg/L, and 1000 mg/L. The fine particles in the suspension and in the raw sand were considered exogenous and endogenous particles, respectively. Rapid clogging was observed in the porous medium when the inflow concentrations of the exogenous particles were high, and increased hydraulic head led to serious clogging. This result indicated that the Yufuhe River has a strong recharge capability with respect to clogging. The analysis of particle content shows that endogenous fine particles (diameter 1–10 μm and 50–74 μm) had less mobility and generally accumulated in the sand column, whereas particles with diameter 10–50 μm had greater mobility in the sand column. And the distribution of exogenous fine particles size after movement is relatively uniform in the sand column. Field observations indicated that the filtration effect of the aquifers have greatly improved the water quality of recharge water in the strong leakage zone of the Yufuhe River, and test data of turbidity also verified the results of the sand column experiments.

Keywords physical clogging, sand column experiment, exogenous particles, endogenous particles

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1 Introduction

To ensure the supply of urban water and spring water, a series of managed aquifer recharge (MAR) projects have been developed on the Yufuhe River in the west and south of Jinan City. MAR is the intentional recharge of water to an aquifer for subsequent recovery or environmental benefit (NRMMC-EPHC-NHMRC, 2009; Wang et al., 2009). Physical clogging occurs in the aquifer medium during the artificial recharge process, when surface water and rain-flood water are used as recharge water, which can have a severe impact on the efficacy of recharge. Problems of aquifer clogging in the groundwater artificial recharge system are inevitable (Barrett and Taylor, 2004; Pavelic et al., 2007). For example, in the United States, Maryland established 207 stormwater infiltration systems in 1986. However, 1/3 of them operated for less than 2 years before they were scrapped due to plugging. In 1990, this proportion was more than half (Lindsey et al., 1992). The phenomena reveal that aquifer clogging has an important influence on the operation of stormwater infiltration systems.

The physical clogging performance of a porous medium is influenced by several factors: the accumulation of suspended particles, the filling of gas and pressure, and the main clogging phenomenon caused by suspended particle clogging (Iwasaki et al., 1937; Rinck-Pffiffer et al., 2000; Siriwardene et al., 2007). The most typical physical clogging is caused by suspended particles. In 26 recharge cases surveyed by Dillon et al. (2001) clogging caused by suspended particles accounted for 50% of the total. Suspended particles are mainly from recharge water, and the clogging of solid suspension is related to the concentrations of suspended particles and to the size distribution, and to the porosity of infiltration medium (McDowell-Boyer et al., 1986; Huang et al., 2009). High concentrations of total suspended solids strongly affect water quality and the aquifer system, and the higher the suspension concentration is, the faster the clogging rate is

(Ha and Koike, 2011; Li et al., 2017a; Won et al., 2018). Zheng et al. (2013) found that the clogging of suspended solids will lead to the heterogeneity of the medium. The smaller the penetration distance is, the more serious the blockage is. It is recommended to control the concentration of recharge suspension within 25 mg/L. The particles that caused physical clogging were divided into two types (Pérezparicio, 2001), namely, exogenous particles, which were carried into the aquifer by the recharge water, and endogenous particles, which were present in the aquifer structure. Under hydrodynamics, endogenous particles can move and accumulate during the recharging process. As a result, clogging is caused by the rearrangement of the aquifer structure (McDowell Boyer et al., 1986). However, there are few studies on the source of particles in physical clogging. Yang et al. (2012) analyzed the transport and source of suspended particle in karst water under rainfall conditions, but the source of suspended particle is analyzed by tracer technology. Further study on the source and micro-movement of particles through laboratory simulation experiments is needed.

Yellow River water is pumped to release into the Yufuhe River channel through outlets and percolate through sand gravel to recharge the underlying limestone aquifer. The river bed and alluvial plain of the Yufuhe River mainly consists of quaternary sand gravels with an average thickness of 10 m, which can function as a buffer for the underlying karst aquifer during recharge (Li et al., 2017b; Rong et al., 2016). The study area is shown in Fig. 1. In MAR schemes, the injection of aerobic source water into anaerobic aquifers may result in anoxic conditions in the groundwater in the storage zone (Shareef et al., 2013). The redox reaction in MAR usually occurs when oxygen-containing source water enters the oxygen-starved aquifer or when organics enter the aquifer. If the concentration of organics is high in the source water, then the redox state becomes anoxic. The redox state of the Yufuhe River sediments is anoxic. This state can cause the accumulation of particles filtered from aquifer sediments or source water. A risk of blockage in the aquifer is also possible to some extent. Therefore, determination of the physical clogging mechanism is critical for sustainable MAR operations. Most previous studies were undertaken under the homogeneous medium, but in this paper, the physical clogging experiment occurs in a heterogeneous porous medium (uniformity coefficient of 25.2) in two different conditions of raw sand and washed sand. These two sand types were subjected to both saturated and steady-state flow regimes, at three different suspended particle concentrations. Meanwhile, in order to confirm the results of sand column experiment, water samples were collected from the Yufuhe River, the pore wells and karst wells at Dongkema village and Cuima village, and near riverbanks and river channels of the strong leakage zone of the Yufuhe River. Water quality was analyzed by comparing turbidity of source water, pore water, and karst water, and the quantity of particles in water samples were detected by particle counter to analyze the content change of pore water in the process of recharge.

2 Laboratory experiment

2.1 Materials

Two plexiglass columns with heights of 140 cm and an internal diameter of 14 cm were used in the experiment (Fig. 2). Overflow holes (1, 2) were designed in the locations of 10 and 30 cm, and they represent high hydraulic head and low hydraulic head, respectively. Between 40 and 130 cm is the sand filling area, and between 130 and 140 cm is the supporting layer. The sand filling area was divided into three parts from top to bottom, with an upper layer of 0–15 cm, middle layer of 15–45 cm and lower layer of 45–90 cm. The lower opening was

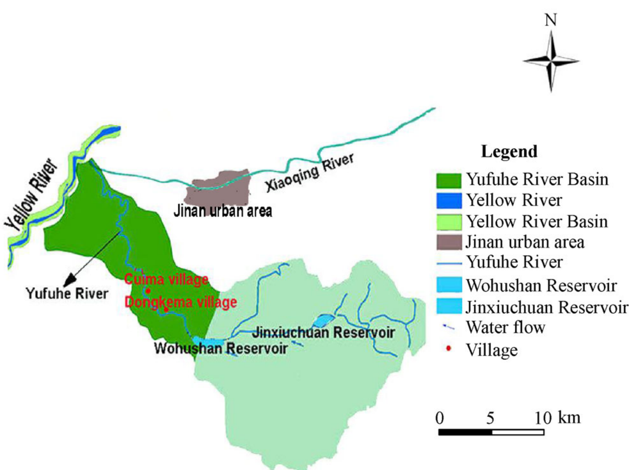

Fig. 1 Location of the study area.

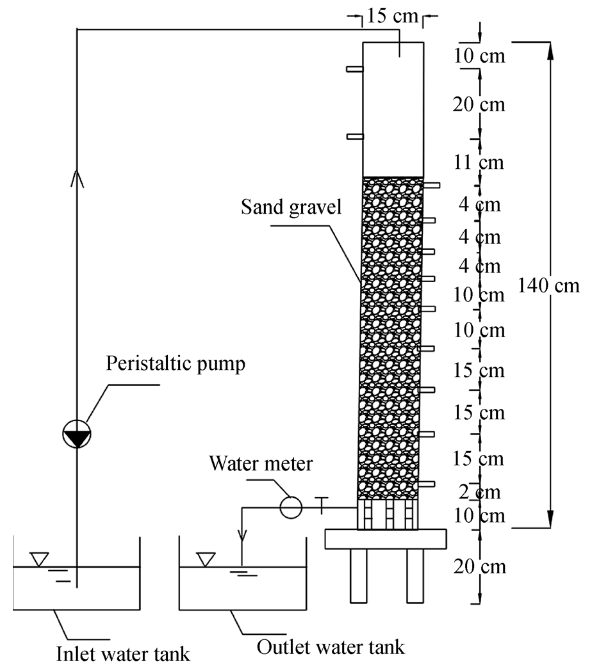

Fig. 2 Experimental device.

covered with a nylon mesh of 200 (74 μm) in diameter, and an outflow hole connected with a water meter was set in the buffer zone.

The porous media that filled the column during the experiments consisted of sand collected from within 10–100 cm of aeration in the strong leakage zone of the Yufuhe River. The grain-size distribution of the sieved sand had an effective granularity (d_{10}) of 2.6 mm, average granularity (d_{50}) of 25 mm, and uniformity coefficient (d_{60}/d_{10}) of 25.2 mm. The turbidity of recharge water was varied from 0.3 NTU to 0.5 NTU. To simulate the water characteristics of the Yufuhe River as much as possible, fine particles (74 μm) were injected into the column that had been collected from the bed of the Yufuhe River, and sorted with sediment sieving. Table 1 shows the relevant experimental conditions.

Table 1 Experimental conditions

L/cm	Internal diameter/cm	d_{10}/mm	d_{50}/mm	d_{60}/d_{10}
140	14	2.6	25	25.2

Experimental tools: one bucket (100 l), peristaltic pump, silicone tube, oven, iron box.

Experimental equipment: turbidity meter (Xinrui WGZ-1), laser particle size meter (Beckman Coulter LS 13 320), particle counter (IBR).

2.2 Methods

Using the methods for controlling variables, we conducted comparative tests to research the influence of exogenous particles concentration and hydraulic head on sand gravel clogging. The particles in the suspension were regarded as exogenous particles, and the particles in the raw sand were endogenous particles.

The test is divided into three parts.

1) The influence of particles concentration

The raw sand was packed into a plexiglass column, and the recharge water head was set to 30 cm. The comparative tests were conducted with constant suspension concentrations of 200, 500, and 1000 mg/L, respectively. In this investigation, the hydraulic conductivity (K) of each layer in the sand column during different periods of recharging was calculated using Darcy’s law. Meanwhile, the water samples were collected at the outlet from the column for the turbidity analysis with turbidity meter. The test was not stopped until the hydraulic conductivity (K) value was stable. The sand samples that were excavated from each layer of the sand column were dried, weighed, and then sieved. The fine particles of sieved sand samples were collected and the particle-size distribution of fine particles was acquired using a laser particle size meter.

2) Influence of hydraulic head

The raw sand was packed into a plexiglass column, and the suspension concentration was set to 200 mg/L. The aquifer clogging experiments were conducted with a hydraulic head of 10 cm and 30 cm, and the other test steps are the same as above.

3) Influence of endogenous particles and exogenous particles

A plexiglass column was used in the experiment. The raw sand was completely cleaned, meaning that particles with diameters less than 74 μm were completely removed, and the mass ratio of fine particles to total mass of unwashed sand reached 5%. As a result, the fine particles with sizes less than 74 μm were completely removed from the raw sand, and the mass ratio of fine particles reached 5% of the total mass of raw sand. The raw sand and washed sand tests were conducted with a hydraulic head of 30 cm and suspension concentration of 500 mg/L to study the influence of endogenous particles. Furthermore, the raw sand tests were also conducted when the tap water was used as recharge water. The three experiments were conducted to study the source of particles causing clogging in sand gravel, and the other test steps are the same as above.

3 Field observations

Water quality was monitored before and after each recharge for 13 months by the pore wells and karst wells at Dongkema village and Cuima village near riverbanks and river channels of the strong leakage zone of Yufuhe River, and the effect of recharge was analyzed by comparing turbidity of source water, pore water, and karst water. The quantity of particles in water samples were detected by a particle counter to analyze the content change of pore water in the process of recharge.

The test is divided into two parts.

1) Turbidity change in monitoring well

The water samples were collected from Yufuhe river and the pore wells and karst wells at Dongkema village and Cuima village, and the turbidity of water samples were detected to analyze the water quality.

2) The number of particles within a certain range of diameters

Water samples were collected from the Yufuhe River, and the pore wells from Dongkema and Cuima villages. To measure the effect of aquifers on the filtration or accumulation of particles, the number of particles in a certain size range were obtained by using a particle counter on the sample of well water.

4 Results

4.1 Influence of exogenous particle concentration

On the basis of experiment (1) and calculation of the relative hydraulic conductivity, variations in the relative hydraulic conductivity in the whole sand column were observed. Under the conditions of raw sand, the changing curve of the relative hydraulic conductivity with suspension concentration of 200, 500, and 1000 mg/L and hydraulic head of 30 cm are shown in Figs. 3(a)–3(c).

The relative hydraulic conductivity rapidly decreased initially at increased suspension concentrations, and the inflow concentration of the exogenous particles affected the movement and accumulation of the endogenous particles. The increase in exogenous particle concentration improved the movement and accumulation of the endogenous particles, thereby resulting in the aquifer clogging in the sand column. The exogenous particle concentration greatly influenced the final outflow turbidity, with higher exogenous particle concentration resulting in higher final turbidity.

4.2 Influence of hydraulic head

Experiment (2) and the calculation of relative hydraulic conductivity indicate the curve (Fig. 3(d)) of the relative hydraulic conductivity (K') in the entire column, and all the layers were tested under the condition of raw sand with 200 mg/L suspension and 10 cm hydraulic head.

Compared with the hydraulic conductivity in Fig. 3, the relative hydraulic conductivity under the low hydraulic head condition (10 cm) decreased faster and lasted longer at the early stage of recharge. Therefore, the movement and

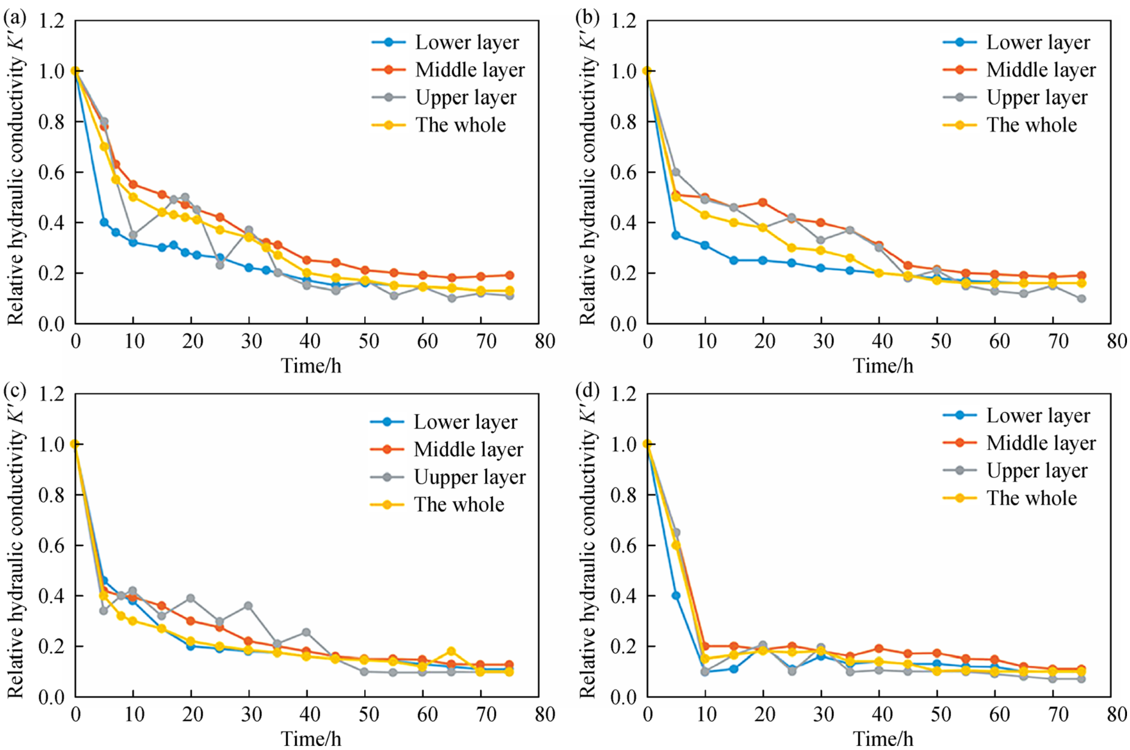

Fig. 3 Changing curves of the relative hydraulic conductivity ((a) the test with 200 mg/L suspension and 30 cm hydraulic head; (b) the test with 500 mg/L suspension and 30 cm hydraulic head; (c) the test with 1000 mg/L suspension and 30 cm hydraulic head; (d) the test with 200 mg/L suspension and 10 cm hydraulic head).

accumulation of endogenous particles had more influence on aquifer clogging than those of exogenous particles. That is, recharge under the condition of the low hydraulic head can exacerbate the aquifer clogging caused by endogenous particles. No relation between hydraulic head and final outflow turbidity was found.

4.3 Influence of endogenous particle

Following Experiment (3), the curve of outlet flow under the conditions of raw sand and washed sand are shown in Fig. 4.

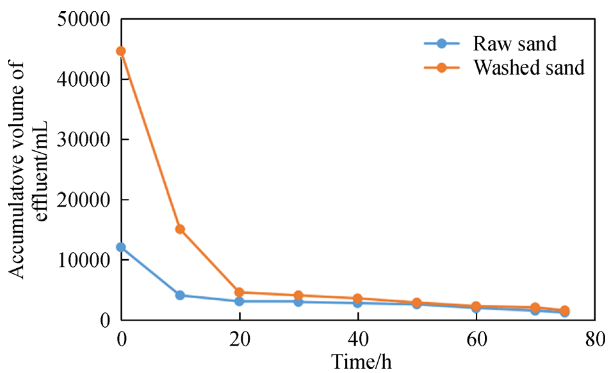

Fig. 4 Curve of outlet flow with 500 mg/L suspension and 30 cm hydraulic head under the condition of raw sand and washed sand.

Comparing the two curves, the initial flow was higher under the condition of washed sand, and the steady flow under washed sand conditions was higher than the steady flow under the raw sand conditions. This result indicates the particles in the raw sand greatly affects the recharge flow of the sand column. That is, endogenous particles have a great effect on sand clogging. The exogenous particles can fill the gaps produced by the removal of endogenous particles and cause sand clogging. However, the degree of clogging was less than that of clogging caused by endogenous particles.

4.4 Source of fine particles that caused the clogging

According to experiment (3), sand samples were collected from the upper, middle, and lower layers of the sand column. The sand samples were dried and sieved. We compared the mass of the particles (74 µm) in this test with the mass of the particles (74 µm) in the raw sand. The relative content histogram of the particles was then drawn (Fig. 5).

For the sand column experiment with 500 mg/L suspension and 30 cm hydraulic head under the conditions of raw sand, the mass ratio of the fine particles in the upper layer of the sand column was 7.2% of that of the raw sand. This result indicates that the upper layer of the sand column received a large amount of particles in the suspension. The mass ratio of the fine particles in the middle layer was 5.3%; the mass ratio of fine particles in the lower layer of the sand column was 6.1%, which is 1.2 times of the fine particles (5%) in the original sand. This result shows that the lower layer of sand column received a large amount of fine particles.

For the sand column experiment with tap water and 30 cm hydraulic head under the raw sand conditions, few particles were present in the tap water; thus, no exogenous particles were present. The mass ratio of the fine particles in the upper layer of the sand column was 3.9% of the original sand, which is 0.8 times of the fine particles (5%) in the original sand. Overall, the decreased number of particles was due to the downward movement of the endogenous particles. The mass ratio of fine particles in the middle layer was 4.8%, and the mass of the fine particles in this layer maintained a certain equilibrium. The mass ratio of fine particles in the lower layer of the sand column was

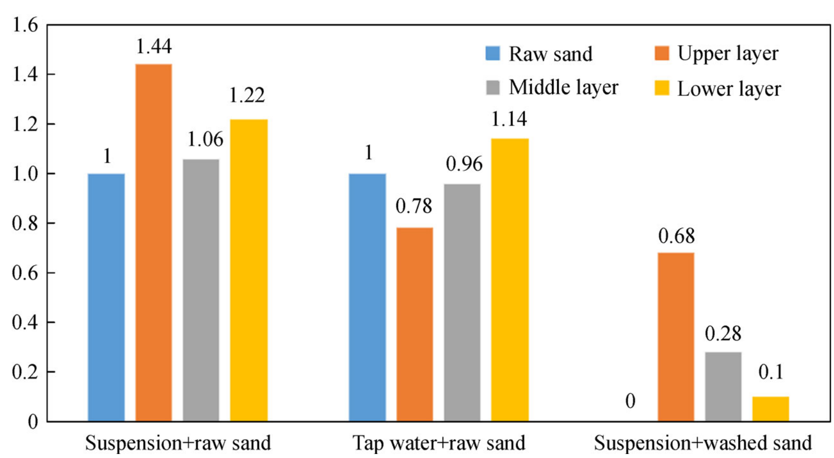

Fig. 5 Relative content histogram of particles (The values of Y is the ratio of fine particles in sand samples after the experiment and fine particles in raw sand).

5.7% of that of the original sand. That is, 1.1 times that of the raw sand. The increase in fine particles in the sand column was ascribed to the vertical migration and accumulation inside the sand column.

For the sand column experiment with 500 mg/L suspension and 30 cm hydraulic head under the washed sand conditions, the mass ratio of fine particles on the upper and lower layers of the sand column reached 3.4%, 1.4%, and 0.5% of the initial value. The mass of exogenous particles received from the top portion to the bottom portion of the sand column decreased in turn, thereby indicating that the accumulation of exogenous particles in the sand column continued to decrease from top to bottom in the absence of fine particles inside the sand column.

In the experiment on suspension recharge with washed sand, the final mass of the particles (3.4%) did not achieve that of particles (5%) in raw sand. This result indicates that the steady-state of flow at this time was temporary. In the experiment of suspension recharge raw sand, after completely clogging, the mass ratio of fine particles in the upper layer was 7.2%, and the mass ratio of fine particles in raw sand was 5%. The raw sand had a strong ability to receive particles. Therefore, the material was pushed into the strong leakage zone of Yufuhe River in the field. From the perspective of containing fine particles, this result indicates great potential for recharge in the strong leakage zone of Yufuhe River.

4.5 Microscopic movement of the fine particles

Experiment (4) was divided into three parts: the test with 500 mg/L suspension and 30 cm hydraulic head under raw sand, the test with tap water and 30 cm hydraulic head under raw sand, and the test with 500 mg/L suspension and 30 cm hydraulic head under washed sand. After the experiments, sand samples were collected from the upper, middle, and lower layers in the sand column. The sand samples were tested by laser particle size meter. The cumulative volumes of the particles were drawn (Figs. 6 (a)–6(c)). The slope of the particle curves represents the volume ratio of the particle mass.

Comprehensive analysis of Figs. 6(a)–6(c) indicates that under three experimental conditions, the fine particles with diameters of 1–10 μm and 50–74 μm have weak mobility. Overall, the particles were retained in the sand column. The 10–50 μm fine particles were highly mobile. The particles were discharged with the outflow of recharge water. However, when the plexiglass column was packed with washed sand, particle mobility was not obvious under recharge conditions. Given the difference in experimental conditions, the endogenous fine particles were considered the main reason for this difference. That is, the endogenous fine particles with the size of 1–10 μm and 50–74 μm had weak mobility. They accumulated in the sand column. By contrast, the fine particles with the size of 50–74 μm had strong mobility. They were discharged with water flow.

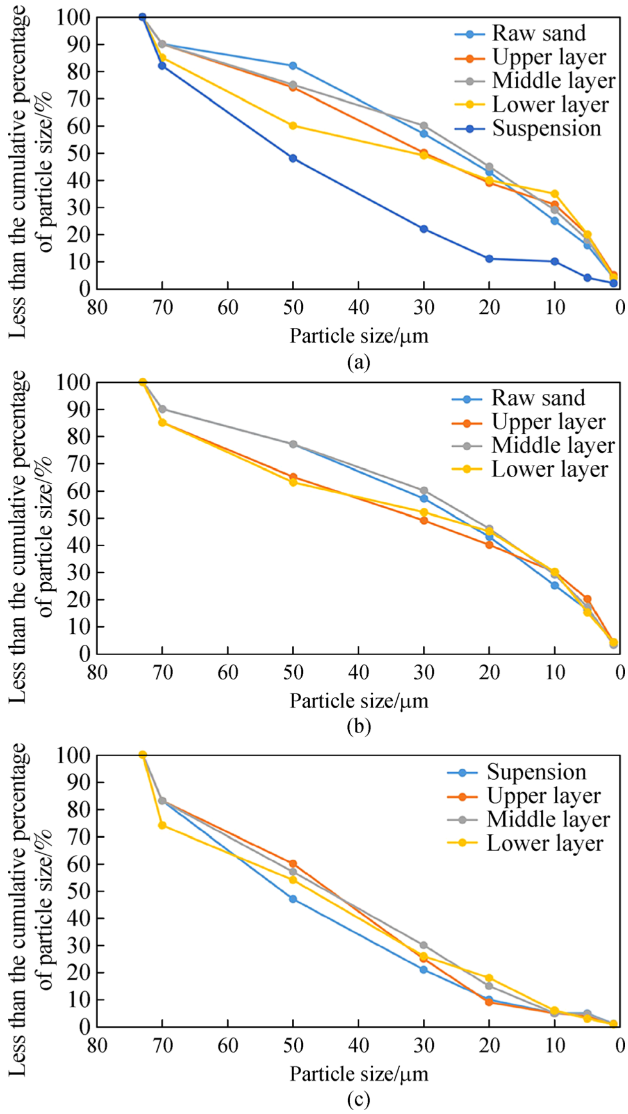

Fig. 6 Gradation curve of fine particles ((a) the test with 500 mg/L suspension and 30 cm hydraulic head under raw sand; (b) the test with tap water and 30 cm hydraulic head under raw sand; (c) the test with 500 mg/L suspension and 30 cm hydraulic head under washed sand).

Although having the same mode of movement and accumulation, exogenous particles have lower performance than endogenous particles. Thus, the movement and accumulation of exogenous particles with different size is uniform.

Only an aquifer containing endogenous particles was present in the strong leakage zone of the Yufuhe River. Thus, the vertical movement of fine particles within the range of 1–50 μm in the recharge process was the strongest. That is, this part of the particles easily entered the groundwater. The fine particles with sizes of 1–10 μm and 50–74 μm had weak mobility, and they easily accumulated and induced clogging.

4.6 Turbidity change in monitoring wells

The turbidity detection of the Yufuhe River and the shallow observation wells in Dongkema village and Cuima village indicate that the turbidity of the observation wells in Cuima is obviously less than the water turbidity of the observation wells in Dongkema. On one hand, Cuima is downstream of Dongkema; thus, the turbidity is partially reduced. On the other hand, the groundwater level in the Cuima observation well is approximately 20 m lower than the observation well in the Dongkema. The vertical distance of the recharge water through the aquifer increased by 20 m. As a result, this phenomenon improved the water quality by the filtering of fine particles in the aquifer.

By the turbidity detection of the deeper observation wells in Dongkema and Cuima villages, the turbidity of the observation wells at Cuima village is obviously less than the water turbidity of the observation wells at Dongkema village, and the turbidity is less than the shallow observation wells overall (shown in Table 2). This result indicates that the water quality of karst water has improved because the suspended particles can adsorb trace organics, and sand gravel has limited retention of fine particles. For the environment and public health, turbidity remains a residual risk item.

Table 2 Average turbidity of source water, shallow and deep well at locations during recharge events

Site	Turbidity/NTU		
	Maximum	Minimum	Average
Yufuhe River	11	6.5	8.66
Pore well at Dongkema village	10.2	3.2	6.36
Karst well at Dongkema village	5.2	1.2	3.4
Pore well at Cuima village	2.3	0.9	1.26
Karst well at Cuima village	1.5	0.2	0.47

4.7 The number of particles within a certain range of diameters

Water samples were collected from the Yufuhe River, and the pore wells from Dongkema and Cuima Villages, and a particle counter was used to plot the accumulation of particles in the three types of water (Fig. 7).

To measure the effect of aquifers on the filtration or accumulation of particles, the number of particles in a certain size range of well water was expressed relative to the rate of change of particles (α) in the corresponding interval of river water (Eq. (1)). If α is positive, then the aquifer exhibits a total filtration effect on the particles in this particle size range and vice versa.

$$\alpha = \frac{\Delta A - \Delta A'}{\Delta A}, \quad (1)$$

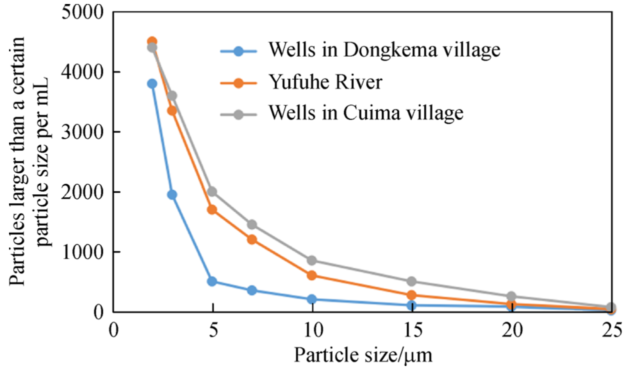

Fig. 7 Relationship diagram of particle content in observation wells and Yufuhe River.

where ΔA is the number of particles with a certain size interval in river water; $\Delta A'$ is the number of particles with the corresponding interval in well water, and α is the rate of change of particles

Detecting the number of particles in water samples (Fig. 7) indicated that the total number of particles was reduced compared with Yufuhe River water and the observation well water in Dongkema village. The aquifer at this well affects the interception and filtration of particles overall. This process is of great help to the improvement of water quality during groundwater recharge. A comparison of the observation wells at Cuima and Yufuhe River water indicates that the number of particles at Cuima was slightly low. Thus, the aquifer at this well maintains a certain balance of particle reception and discharge. The 2–3 μm particles showed a small decrease, indicating that they were trapped by the aquifer. The number of particles in the other sizes increased. Moreover, the increased degree of particles with sizes of > 10 μm is the largest, thereby indicating the aquifer discharged most of the particles (> 10 μm). This result also confirms the conclusion that the mobility of particle size in the range of 10–50 μm is high and that a particle is discharged from the sand column as a whole.

5 Discussion

A water sample of the Yufuhe River is collected and measured, the value of TOC (Total organic carbon) is less than 10 mg/L, so bioclogging is not considered; the concentration of diadic iron ion is low, less than 11.2 mg/L. And chemical clogging is a long-term accumulation process. The release to the Yufuhe river channel from the Yellow river is intermittent, lasting 7 days to one month per each time during spring period of extraction groundwater for agriculture water use. The chemical reaction on iron is neglected because the concentration of dyadic iron is low and water spends less time in the sand column . The silt concentration of the Yellow river is higher and organic matter is very low so that the physical clogging is the main concern in this study.

According to the sand column experiment, rapid clogging was observed in the porous medium when the inflow concentrations of the exogenous particles were high, and increased hydraulic head led to serious clogging. So in the process of recharge, the concentration of exogenous particles should be controlled to prevent aquifer clogging. Higher hydraulic head is more likely to cause blockage, but have a certain impact on the shallow layer, while lower hydraulic head is more likely to cause shallow clogging, and have less impact on the deep layer. On the whole, the higher hydraulic head is, the more serious clogging is.

In the experiment of suspension recharge with washed sand, when the outflow rate is stable, the mass of fine particles had not reached the mass of fine particles in raw sand, and there is still a great difference. The result showed the outflow rate is temporarily stable, but after changing the experimental conditions, the outflow rate will change. In the experiment of suspension recharge with raw sand, after completely clogging, the mass of fine particles increased, which indicated that the raw sand had a strong ability to receive particles. The mass ratio of fine particles in the upper layer was 7.2%, which is the largest content of fine particles under clogging condition. Therefore, the material was pushed into the strong leakage zone of Yufuhe River in the field. From the perspective of containing fine particles, this result indicates great potential for recharge on the strong leakage zone of Yufuhe River.

The analysis of particle content shows that the endogenous fine particles with the size of 1–10 μm and 50–74 μm have weaker mobility. They are generally accumulated in the sand column. The fine particles with the size of 10–50 μm have stronger mobility. There are only endogenous particles in the aquifer of the Yufuhe River strong leakage zone, therefore, it is considered that the fine particles with the size of 10–50 μm have stronger mobility in vertical direction,that is, it is easy to enter groundwater; the fine particles with the size of 1–10 μm and 10–50 μm accumulate easily and cause clogging. So, the particles of the two particle size ranges in the recharge water should be particularly noticeable in the recharge process. And field observation data also verified the results of the sand column experiment. The results of the sand column experiment can be applied to the strong leakage zone of the Yufuhe River.

The physical clogging in the vertical direction has been studied through sand column experiments. However, sand tank experiments will be conducted to model vertical and horizontal movement of water. The change of turbidity, suspended particles concentration, and the hydraulic conductivity in vertical and horizontal directions will be measured. Meanwhile, a mathematical model with two-dimensional saturated and unsaturated flow will be established to simulate the migration and clogging of suspended particles in sand tank by the coupling of HYDRUS-2D and Kozeny-Carmen.

6 Conclusions

This paper studied the the problem of aquifer clogging in quaternary sedimentary strata by using the heterogeneous Yufuhe River sand gravel alluvium as an infiltration medium in laboratory testing of sand columns. Under the conditions of raw sand and washed sand, physical clogging tests were conducted with two hydraulic heads and three inflow suspension concentrations. Meanwhile, in order to confirm the results of sand column experiment, water samples were collected from the Yufuhe River, the pore wells and karst wells at Dongkema village, and Cuima village near riverbanks and river channels of the strong leakage zone of the Yufuhe River. Water quality was analyzed by comparing turbidity of source water, pore water, and karst water, and the quantity of particles in water samples were detected by particle counter to analyze the content change of pore water in the process of recharge.

1) The sand column comparison tests indicate that the higher the inflow concentrations of exogenous particles, the faster the clogging of the sand column. The increase in exogenous particles concentration promoted the movement and accumulation of the endogenous particles. The aquifer clogging caused the endogenous particles to easily occur under the conditions of low hydraulic head. However, the particles were present in the deep layer of the sand column, causing the clogging there. In general, the higher the head of the recharge water, the greater the degree of sand column clogging.

2) Experimental analysis indicates that the mass ratio of fine particles in the upper layer is 7.2%. The mass ratio of fine particles in raw sand is 5%. From the perspective of containing fine particles, this indicates great potential for recharge on the strong leakage zone of Yufuhe River.

3) The analysis of particle content shows that the endogenous fine particles with the size of 1–10 μm and 50–74 μm have weaker mobility. They are generally accumulated in the sand column. The fine particles with the size of 10–50 μm have stronger mobility. They are discharged with water flow. The movement of exogenous fine particles is relatively uniform in the sand column.

4) Field observations indicate that the filtration effect of the strong leakage zone in the Yufuhe River has greatly improved the water quality of the recharged water. At the same time, the test data also verified the results of the sand column experiment. The results of the sand column experiment can be applied to the strong leakage zone of the Yufuhe River.

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