

Round empty core infiltration and anti-filtration recharge wells and laboratory recharge tests

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Abstract Anti-filtration recharge wells are commonly installed in river channels and irrigation canals on the Shandong Peninsula, China, and can be used as an important recharge facility for underground reservoirs. However, during recharge, as the running time increases, the recharge capacity gradually decreases. This study was undertaken to develop a new recharge well and mitigate this deficiency. A round empty core infiltration and anti-filtration recharge well and laboratory recharge test equipment were developed. Subsequently, 1:25 models of the recharge pond, a round empty core recharge wellhead, and an artificial recharge well were prepared. Using equal recharge levels and ambient groundwater levels, laboratory steady-flow recharge tests on the existing anti-filtration recharge well, the new round empty core infiltration and anti-filtration recharge well, and an artificial recharge well were carried out. Experimental data on the measured groundwater table and single-well recharge quantity were also collected and analyzed. The results showed that compared with the existing anti-filtration recharge well, the new round empty core infiltration and anti-filtration recharge well had stronger anti-deposition and anti-scouring properties, and the single-well recharge quantity increased by 403%. With an increase in the number of recharge tests, the single-well recharge quantity gradually decreased and tended to stabilize as a whole.

Keywords recharge well, infiltration function, anti-filtration function, recharge quantity, recharge test

1 Introduction

Groundwater recharge is an effective means to increase the utilization rate of rain-flood resources and address water shortages. Groundwater recharge is generally divided into

deep recharge and shallow infiltration (Leach, 1982). For shallow infiltration, the water is accumulated in pits, ponds, and pools and then slowly penetrates to the aquifer. For deep recharge, the water is recharged to the aquifer through the recharge well, which includes the artificial recharge well and the anti-filtration recharge well.

Artificial recharge wells are often used as recharge facilities in many countries. In the USA, billions of cubic meters of purified surface water are recharged into aquifers by artificial recharge wells along the coastline of California every year, which prevents seawater intrusion (Eastwood and Stanfield, 2001; Mahesha, 2001; Händel et al., 2014). In the 1960s in Shanghai, China, the groundwater level was controlled by recharging reclaimed water to artificial recharge wells annually (Wu and Tang, 1998). When rainwater is used to recharge via artificial recharge wells, it must be filtered and purged to meet a certain water quality standard. However, this approach is expensive and can only be done on a small scale.

The existing anti-filtration recharge well is a unique recharge facility of underground reservoirs in Shandong, China (Li et al., 2006a; Li, 2009). The Shandong Peninsula is an area with serious water shortages. The annual rainfall distribution in northern China is extremely uneven and is concentrated in the flood season (July and August). Riverbeds are typically dry during the non-flood season. Additionally, the upper part of the aquifer is an impermeable or weakly permeable layer, so rain cannot easily infiltrate through the ground surface, leading to a large amount of rainwater during the flood season which passes into the sea. To better use rainwater resources, improve water resource utilization, and prevent water scarcity on the Shandong Peninsula, underground reservoirs, such as the Wanghe Underground Reservoir and Huangshui River Underground Reservoir, were constructed during the 1990s. Anti-filtration recharge wells have been put into use as efficient recharge facilities, generally on river channels or irrigation canals, to solve the rainwater recharge problem in areas where the upper part of the

aquifer consists of clay or loam with weak permeability and the lower layer is comprised of sand. Compared with artificial recharge wells, the existing anti-filtration recharge wells are equipped with a wellhead structure with infiltration and anti-filtration functions—a recharge pond, which has a certain water purification capacity and the ability to convert river water into groundwater. Rainwater can be recharged to the aquifer during the flood season and does not need to be filtered and purified. However, during the operation of the existing anti-filtration recharge wells, the recharge capacity gradually decreases as the running time increases.

Enhancement of recharge facility capacity is an important issue in the design of recharge projects. Presently, this issue is often studied from two directions. One is to reduce the clogging of the recharge facility, and the other is to increase the recharge quantity. The former is the more common focus of groundwater recharge research, whereas the latter is rarely studied.

Huang (2009) simulated the clogging process of the sand layer around the recharge well in his laboratory using a sand column and then analyzed the physical and biological clogging that could occur during the recharge process through changes in the permeability coefficient and water quality parameters. Phien-wej et al. (1998) analyzed the clogging caused by air and suspended particles of water and the chemical clogging caused by the recharge water and natural groundwater.

Rastogi and Pandey (1998) researched the effect of the recharge pond shape on the recharge quantity and then used the finite element method to analyze the recharge effect of different recharge pond shapes, i.e., rectangular and circular pools. He concluded that the recharge quantity of the rectangular recharge pond is the largest for a given infiltration area and recharge rate. Li et al. (2006b and 2013) studied the calculation method of the single-well

recharge quantity of the existing anti-filtration recharge wells and analyzed the existing problems, e.g., unreasonable structures of recharge ponds.

This paper describes the attempts to increase the recharge capacity of the existing anti-filtration recharge wells. A round empty core infiltration and anti-filtration recharge well (hereinafter referred to as the round empty core IAF recharge well) has been designed, laboratory recharge test equipment has been developed, and laboratory recharge tests have been conducted. Tests were also performed on an artificial recharge well and an existing anti-filtration recharge well for comparison. The objective of this paper is to improve the recharge capacity of the existing anti-filtration recharge wells, which has important practical significance.

2 Design of round empty core IAF recharge well

An existing anti-filtration recharge well has a certain purification capability, as shown in Fig. 1. The existing anti-filtration recharge well includes both a recharge pond and an artificial recharge well. The recharge pond is a trapezoid soil pit that is backfilled with sand-gravel anti-filter material and is often placed underground. The artificial recharge well is connected to the bottom of the center of the recharge pond. The top elevation of the recharge pond is basically the same as that of the riverbed. When the water flows over the anti-filtration recharge well into the river or channel, it vertically infiltrates into the recharge pond, falls into the artificial recharge well, and then goes into the aquifer after the particles and impurities of the water have been filtered out. For a medium-small valley with either no or slight pollution, some anti-filtration recharge wells are set on the riverbed. The rainwater can be

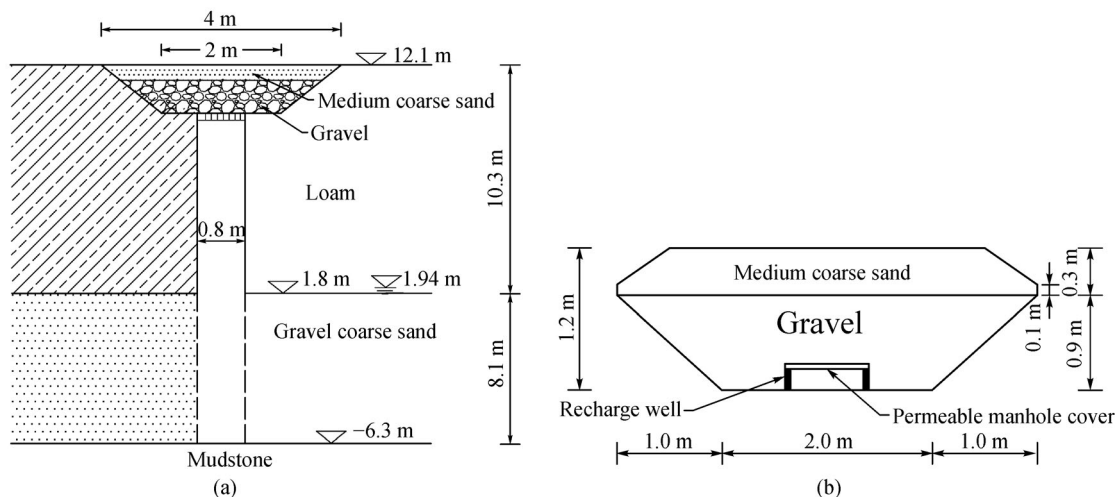


Fig. 1 Diagram of the existing anti-filtration recharge well. (a) Anti-filtration recharge well profile. (b) Recharge pond profile.

recharged directly to the aquifer during the flood season with no need of filtering or purification, resulting in reduced costs and large-scale rainwater recharging.

However, the existing anti-filtration recharge well has the following problems: 1) the recharge pond causes an excessively large water head loss, which greatly reduces the single-well recharge quantity, and the rainwater infiltration limited to one side. If the infiltration area is increased, the area of the recharge pond will also increase, more land will be occupied, and more filter material will be consumed; 2) when the water flow rate is relatively small, the top elevation of the recharge pond is basically the same as that of the riverbed, causing the silt in the river to enter the recharge pond and plug the pores, and thus resulting in a decrease in the recharge capacity; 3) when the water flow rate is relatively large, the recharge pond is a soil pit, and is easily destroyed by the water flow. The filter material can then easily be washed away, which disables the anti-filtration function of the recharge pond. The sediment particles can then enter the recharge well and clog the aquifers, disabling the function of the existing anti-filtration recharge well.

In view of the above shortcomings of the existing anti-filtration recharge well, the new design of the recharge well should work to improve the infiltration capacity and the

anti-deposition and anti-scouring properties of the recharge pond. Therefore, based on the above design requirements, a new round empty core IAF recharge well was developed, as shown in Fig. 2. The new round empty core IAF recharge well includes a round empty core recharge wellhead and an artificial recharge well. The recharge wellhead is placed on the ground and connected to the artificial recharge well. The bottom elevation of the recharge wellhead is basically the same as that of the riverbed. For the recharge wellhead, the permeable pores are set in the surface of the wellhead, which is used for river water infiltration. In addition, a layer of geotextile with filter functionality is covered over the wellhead outer surface. When the water flows over the round empty core IAF recharge well placed in the river or channel, it then flows through the wellhead and infiltrates the artificial recharge well after the particles and impurities of the water are filtered out.

In comparison with the existing anti-filtration recharge well, the new round empty core IAF recharge well has the following features:

1) It retains the artificial recharge well, however, the recharge pond is replaced with a recharge wellhead that can be placed aboveground, which can prevent the silt in the thin layer from clogging the recharge pond surface and

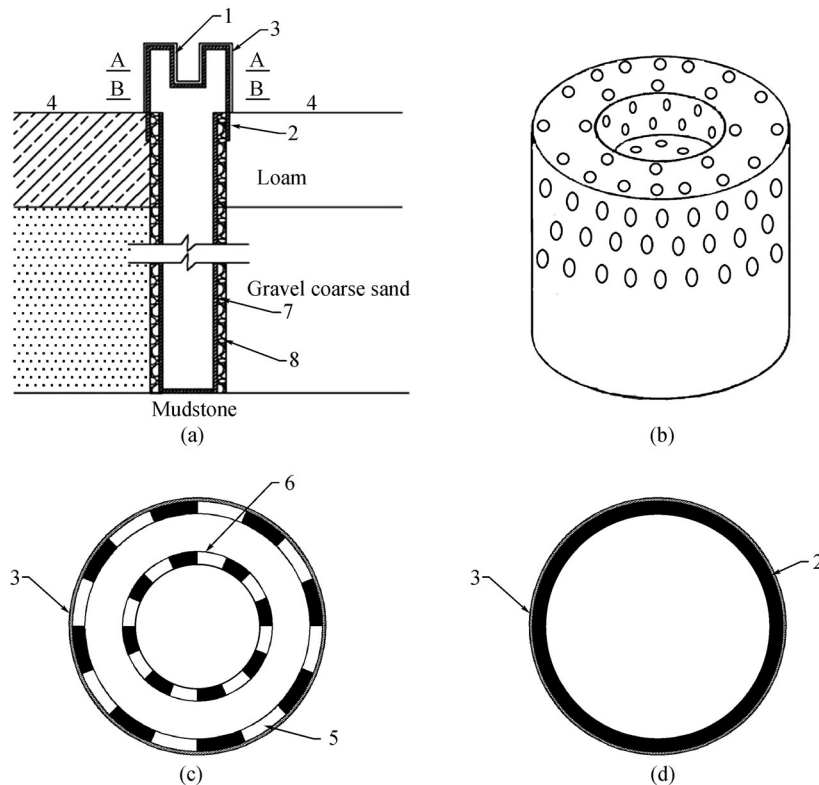


Fig. 2 Structural diagram of the round empty core IAF recharge well. (a) Schematic diagram of the vertical profile. (b) Round empty core wellhead. (c) A-A profile. (d) B-B profile Figure: 1-recharge wellhead; 2-sidewall; 3-geotextile; 4-ground surface; 5-lateral wall hole; 6-medial wall hole; 7-recharge well; 8-anti-filter material.

affecting the river water infiltration, greatly improving the anti-deposition capability. Compared to the recharge pond, the surface of the wellhead is permeable to the rainwater, and multi-surface infiltration occurs instead of one-side infiltration, which can increase the infiltration area and improve the infiltration capability.

2) The recharge wellhead uses hard materials, such as reinforced concrete to enhance the anti-scouring ability.

3) A layer of geotextile covers the surface of the recharge wellhead, which not only filters impurities from the recharge water, but also reduces the use of sand-gravel material. The geotextile is also easy to repair and replace.

4) The recharge wellhead is made of an impermeable body, within a certain range of the bottom, which can prevent wastewater from flowing into the well at the initial stage of rainfall.

5) A layer of an impervious geomembrane can be added to the outer layer of the geotextile to prevent the polluted river water from being recharged into the aquifer.

The applicable conditions of the round empty core IAF recharge well are as follows:

1) Seasonal rivers located in medium to small valleys are found to be either unpolluted or slightly polluted.

2) The upper part of the aquifer is an impermeable or weakly permeable layer (i.e., loam or clay), and the surface water can be recharged to the aquifer through the recharge well.

3) The aquifer is a sand and clay interbedded structure, and a hydraulic connection can be established between the several sand layers through the recharge well.

In actual recharge projects, the spacing of the recharge wells placed in the river channel is approximately 50 m. The recharge wells have little effect on surface water flow patterns and typically only affect the local flow pattern around the recharge wells, which has a certain scouring effect on the riverbed around the wellhead.

3 Laboratory recharge test of a round empty core IAF recharge well

The existing recharge wells are usually installed in a formation where the upper layer is clay and the lower layer is sand. When the groundwater level falls below the coping of the confined aquifer, the whole aquifer would translate into a confined-unconfined aquifer during the recharge progress. The aquifer close to the recharge well is a confined aquifer and the aquifer far from the recharge well is an unconfined aquifer. A laboratory recharge test was conducted on a fully penetrating recharge well in a confined-unconfined aquifer.

3.1 Test equipment and methods

The water dome formed in the aquifer is axisymmetric during the steady flow recharge process. Alternatively, the

sand tank, recharge well, and aquifer are all symmetric in structure. To facilitate the observation of the water dome changes in the aquifer, the model of the sand tank, the recharge well, wellhead, and the recharge flume were all divided into two equal part along vertical symmetric plane and a half-well, half-wellhead and half-sand tank modes were obtained, after which a half-well recharge test was performed.

The laboratory recharge test equipment consists of a cuboid made of plexiglass material measuring 1.8 m × 0.8 m × 1.3 m (length × width × height). It can simulate the steady flow recharge test of the fully or partially penetrating recharge well. The test equipment is shown in Fig. 3.

The laboratory recharge test equipment is divided into four systems: the recharge, measurement, water supply, and drainage.

The recharge system consists of a sand tank, a recharge flume, various wellheads, a recharge well, and two regulating tanks. The recharge flume is used to simulate the river channel or irrigation canal, the sand tank is used to place the clay and sand sample for simulation of a semicircular aquifer, and two regulating tanks are used to adjust the ambient groundwater level (the ambient groundwater level is equal to the water level of the regulating tank). A plexiglass pipe with a radius of 10 mm is divided into two equal part along its diameter and used to simulate half of the recharge well. The half pipe is closely bonded and fixed to the middle of the front wall of the sand tank, and the half pipe with small pores extends to the bottom of the sand tank. The recharge wellhead is made at the proportion of 1: 25 where half is used for the laboratory test. The diameter of the pore in the wellhead surface is 5 mm, and the opening ratio of the infiltration section is approximately 20%. The round empty core wellhead model with an outer diameter of 40 mm, an inner diameter of 20 mm, and a height of 60 mm is shown in Fig. 4(a). To facilitate the comparative analysis, the recharge pond model (see Fig. 4(b)) is also made at a ratio of 1:25, where half is used for the test. The top and bottom measurements are 40 mm × 80 mm and 20 mm × 40 mm, respectively.

The measurement system is composed of a flow and a water level measurement system. The flow measurement system is composed of both inflow and outflow measurements. The water level measurement system is composed of a water level scale attached to the sidewall of the sand tank, two water level scales that are attached to the sidewall of the regulating tanks, and 20 piezometric tubes that are arranged at the bottom of the sand tank. The piezometric tube arrangement is shown in Fig. 5.

The first and second layers of the sample consist of clay and sand, respectively. The sand sample uses natural river sand with an average particle size of 0.836 mm. The coefficient of uniformity is 3.20 and the coefficient of curvature is 1.18, which is classified as nonperforming coarse sand. The dry density of the sand is controlled

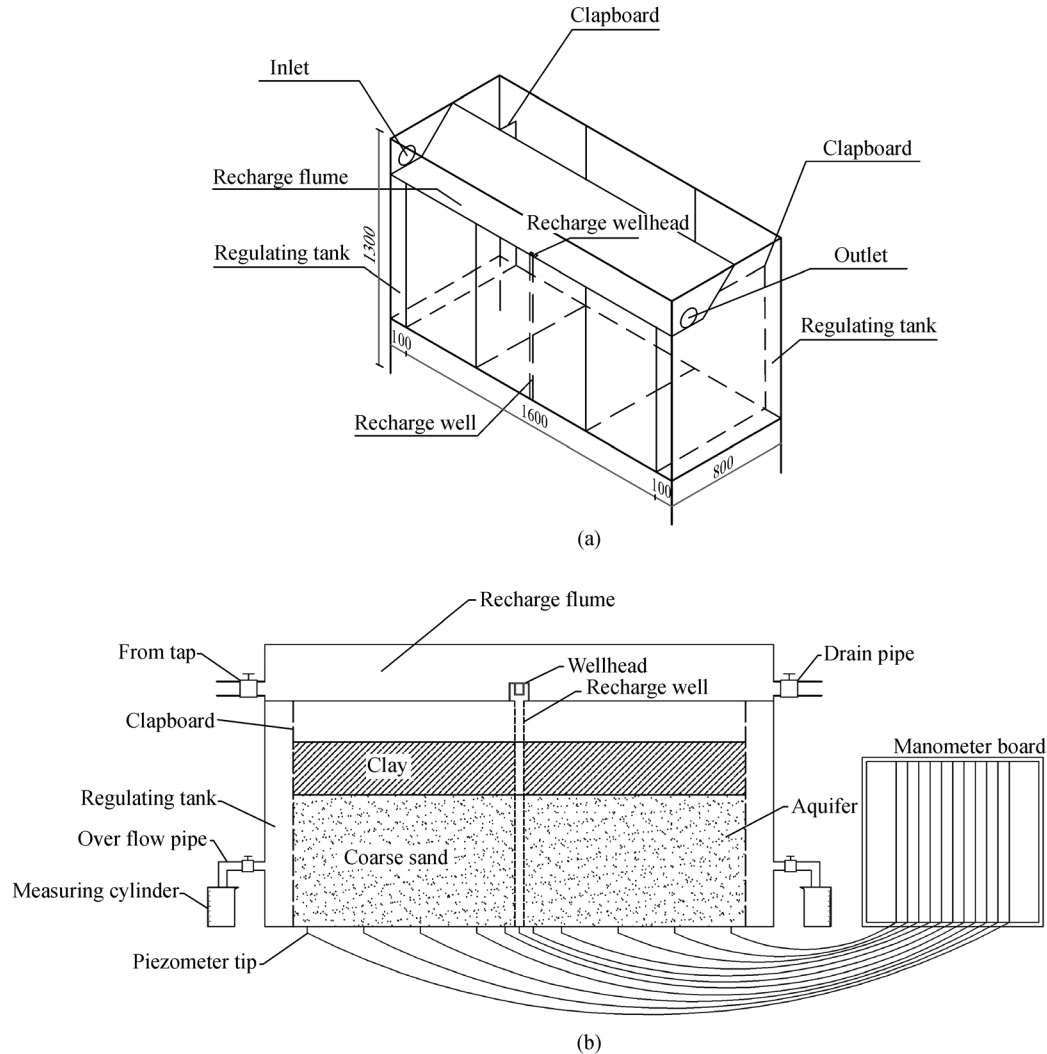


Fig. 3 Laboratory recharge test equipment. (a) Schematic diagram of test equipment. (b) Test equipment during recharge operation.

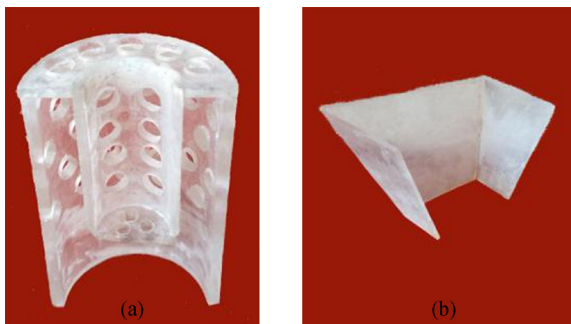


Fig. 4 Half-wellhead model of the recharge well during recharge test. (a) Round empty core wellhead. (b) Recharge pond.

within the range of $1.44\text{--}1.50\text{ g/cm}^3$, and the hydraulic conductivity at $3.0710 \times 10^{-4}\text{--}3.55 \times 10^{-4}\text{ m/s}$. The sand was put in the sand tank, consisting of two clapboards with small holes at both ends, allowing the water in the aquifer

to flow into the regulating tank through the holes. The filter layer of the recharge wellhead uses geotextiles. The composite hydraulic conductivity of the geotextiles and the wall of the recharge wellhead measure $6.2 \times 10^{-4}\text{ m/s}$.

Three types of recharge tests of the fully penetrating well in the confined-unconfined aquifer were intended for simulation: 1) the recharge test of the artificial recharge well without a recharge pond or recharge wellhead; 2) the recharge test of the existing anti-filtration recharge well; and 3) the recharge test of the round empty core IAF recharge well. In addition, during the laboratory recharge test, tap water is used as the recharge water resource.

To maintain the ambient groundwater level at a stable state, a gravel drainage belt was installed at the bottom of the sand tank sidewall opposite the recharge well and connected to the regulating tanks on both sides, so that the groundwater level was consistent with that of the regulating tank. The water inlet of the flume was connected to the water supply tank. The valve of the water inlet was

adjusted at the onset of the recharge test to maintain the recharge water level in the flume at 92 cm (taking the bottom of the sand tank as the 0 cm benchmark elevation). When the recharge water flowed into the recharge flume and flowed over the recharge well, a portion of the water would infiltrate into the recharge well through the wellhead or the recharge pond, and the remainder would flow out from the other end of the flume. The water in the recharge well would flow horizontally into the aquifer and then into the regulating tank. The regulating tank valves were adjusted to maintain the water level at 20 cm. When the recharge water level was kept at 92 cm and the water level of the regulating tanks was kept at 20 cm, the groundwater table in the piezometric tubes and the discharged water from the regulating tanks on both sides were collected. The amount time for discharge of water quantities from both sides of the regulating tanks and from the single recharge well was the same.

The final measurement value of the single-well recharge quantity was determined by finding the average after successfully measuring the recharge quantity three times.

3.2 Results and discussion

3.2.1 Groundwater level comparison with different well-heads

The groundwater level of the three recharge tests was measured by the piezometric tubes (Nos. 1–11) that were arranged along a horizontal line, as shown in Fig. 6.

The comparison of the measured groundwater levels among the different types of recharge wells is shown in Fig. 6. R refers to the distance from the piezometric tube to the half recharge well. Under the same conditions of the recharge water level, the aquifer structure, and the water level of the regulating tank, the groundwater level of the artificial recharge well was found to be the highest, followed by the round empty core IAF recharge well and the existing anti-filtration recharge well. These data show that the comprehensive water head loss of the existing recharge pond is the largest, that of the round empty core recharge wellhead is smaller, and that of the artificial recharge well as the smallest.

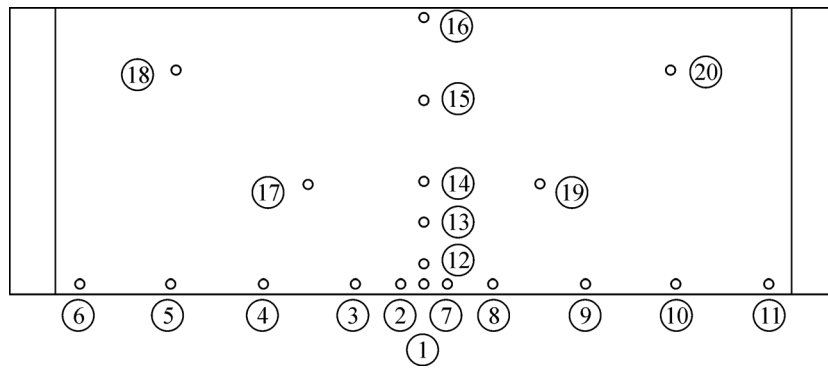


Fig. 5 Arrangement of piezometric tubes at the bottom of the sand tank.

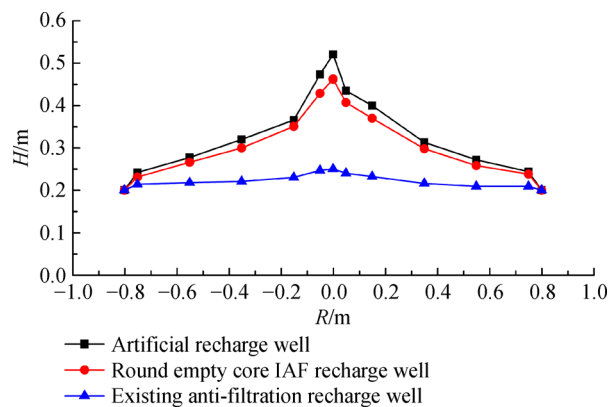


Fig. 6 Measured groundwater level.

3.2.2 Influence of wellhead type on single-well recharge quantity

Table 1 indicates the single-well recharge quantity of the fully penetrating well in the laboratory recharge test. The single-well recharge quantities of the existing anti-filtration recharge well and the round empty core IAF recharge well are 15.4% and 77.5% of the recharge quantity of the artificial recharge well, respectively.

The following observations were obtained through the analysis of the single-well recharge quantity and as shown in Table 1:

1) When compared with the artificial recharge well, the type of recharge wellhead or recharge pond is an important factor affecting the single-well recharge quantity of the recharge well. As seen from Table 1, the recharge quantity of the existing anti-filtration recharge well is the smallest. This result is because the recharge quantity of the existing anti-filtration recharge well is usually determined by the infiltration capacity of the recharge pond and the recharge capacity of the recharge well. The low infiltration capacity of the existing recharge pond affects and limits the recharge quantity of the existing anti-filtration recharge well, indicating that the infiltration capacity of the recharge pond does not match that of the recharge well, and the design is not reasonable. The round empty core IAF recharge well improves the infiltration capacity of the recharge wellhead, mitigates the incompatibility between the infiltration capacity of the recharge wellhead and the recharge capacity of the recharge well, and makes the structural design of the recharge wellhead and the recharge well more reasonable.

2) When compared with that of the existing anti-filtration recharge well, the single-well recharge quantity of the round empty core IAF recharge well increases by approximately four times. The occupied area of the round recharge wellhead is 0.39 times that of the recharge pond,

and the infiltration area is 1.37 times that of the recharge pond, illustrating that the round recharge wellhead has a small covered area and a large recharge quantity.

3.2.3 Influence of recharge test times on single-well recharge quantity

Taking the round empty core IAF recharge well as an example, under the same test conditions, a total of 12 groups of recharge tests were carried out. Each test involved recharging for 5 min, and a total of 12 sets of the single-well recharge quantity was measured. Figure 7 shows the curve between the single-well recharge quantity Q and the recharge test time N in a successive recharge test.

Figure 7 illustrates that the single-well recharge quantity of the first recharge test is the largest for a successive recharge test. With the increase in the number of tests, the single-well recharge quantity gradually decreased and stabilized as a whole. The stable quantity was approximately 60.2% of the initial quantity.

The test focuses on the effect of different types of recharge wellheads and physical clogging on the recharge quantity in successive recharge tests. The clogging caused by other factors will be evaluated in future research.

The main reasons for this phenomenon are as follows: before the recharge, both the recharge well and the sand layer contained gas, and the recharge flow drew some of the gas into the aquifer. Part of the gas formed a closed bubble which gradually accumulated. Meanwhile, the recharge water also mixed with air bubbles and impurities. These closed bubbles, impurities, and fine silt particles in the sand layer pore formed a blockage which also gradually accumulated, leading to a gradual reduction in the recharge quantity. As the recharge test continued, the unstable closed bubbles and impurities in the sand layer pore were removed by the groundwater and discharged through the outfall of the regulating tank. The relatively

Table 1 Results of the laboratory steady-state flow recharge test

Name of recharge well	Recharge quantity $/(L \cdot \text{min}^{-1})$	Infiltration area of wellhead/ cm^2
Artificial recharge well	3.96	1.57
Existing anti-filtration recharge well	0.61	32.00
Round empty core IAF recharge well	3.07	43.96

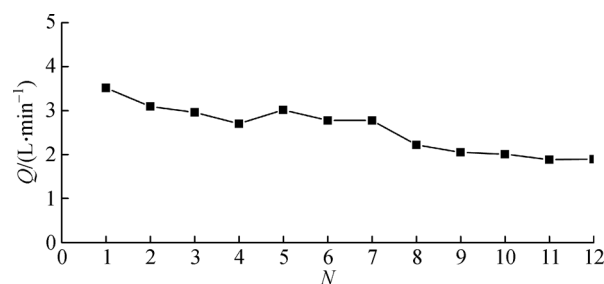


Fig. 7 Curve between the single-well recharge quantity Q and the recharge test time N .

stable closed bubbles and impurities in the sand layer pores formed a relatively stable blockage, and the single-well recharge quantity were relatively stable.

3.2.4 Influence of potential clogging on single-well recharge quantity

Empty core IAF recharge wells are usually placed in seasonal rivers or channels. When the river water contains impurities such as silt, the recharge water will cause potential clogging. Clogging of IAF recharge wells can be divided into two categories: clogging of the recharge wellhead and clogging of the aquifer.

Clogging of the recharge wellhead means that during the process of the river water infiltrating into the recharge well, the coarse particles in the river water will be filtered and intercepted by the geotextile covered on the outer surface of the recharge wellhead. At the same time, some fine particles and organic matter in river water will be adsorbed on the outer surface of the recharge wellhead due to electrostatic interaction, forming a physical blockage. With increasing recharge time, microorganisms such as bacteria will be produced on the outer surface of the recharge wellhead to form biological clogging.

Aquifer clogging refers to fine particles from the river water being carried into the aquifer through the filter layer of the wellhead. With an increasing flow cross section, the groundwater flow velocity decreases gradually, and the fine silt in the recharge water deposit within a certain range, produces a physical clogging. Moreover, since recharge is a discontinuous process, an alternate drying and wetting phenomenon occurs between the partial aquifer around the recharge well and the recharge well sidewall, which may produce microorganisms such as bacteria to produce biological clogging. In addition, chemical blockage clogging may occur due to differences in water quality between the recharge water and groundwater.

Through the process of groundwater recharge using river water, clogging could reduce the single-well recharge quantity. Serious clogging can cause the recharge function of the recharge well to be completely lost. Therefore, the geotextiles with filter functionality that cover the recharge wellhead must be replaced regularly. Additional effective measures for prevention of potential clogging must also be taken.

4 Conclusions

Based on the tests and analyses described in this paper, we can draw the following conclusions:

1) The existing anti-filtration recharge well is equipped with a recharge pond that is placed in a river channel or irrigation canal and has a certain water purification capacity and ability to automatically convert river water into groundwater. However, during the recharge, some

deficiencies in the infiltration and anti-deposition and anti-scouring capabilities have been observed.

2) When compared with the existing anti-filtration recharge well, the single-well recharge quantity of the round empty core IAF recharge well was 403% higher, and the anti-deposition and anti-scouring capabilities were effectively improved.

3) When compared with the existing anti-filtration recharge well, the design of the round empty core IAF recharge well is reasonable.

4) For successive recharge tests, the first recharge test of the round empty core IAF recharge well has the greatest single-well recharge quantity. With the increase in the number of recharge tests, the single-well recharge quantity gradually decreases and stability tends to increase.

Acknowledgements This work was financially supported by the Natural Science Foundation of Shandong Province (No. ZR2019MEE106), the Science and Technology Development Plans of Shandong Province (No. 2013GSF11606), and the Public Special Scientific Research of the Ministry of Water Resource (No. 201401024). All authors are very grateful to the editor and the three anonymous reviewers for their valuable comments, which have greatly improved the paper.

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