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Study on artificial recharge and well loss in confined aquifers using theoretical and back-analysis calculations of hydrogeological parameters from recharge and pumping tests

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Abstract

The main components of the confined aquifer in Tianjin are silt and silty sand. In addition, when the recharge of a shallow confined aquifer is used in deep excavation engineering to control the subsidence caused by pressure relief, the recharge cone and well loss require attention. Pressure recharge is often used to improve the efficiency of recharging. However, in the process of pressure recharge, the phenomena of recharge failure and water burst easily appear. In this study, single-well pumping, natural recharge, and pressure recharge tests were conducted at a green field site. Pressure recharge can further improve the recharge efficiency and reduce the number of recharge wells and the cost of recharge. Compared with clay sealing of the well wall's outer hole, grouting sealing with slurry cement can significantly improve the recharge pressure and efficiency. The water level rise is close to the water level drawdown in the aquifer farther than 5 m from the recharge/ pumping well based on the monitoring results. However, close to the recharge/pumping well in the aquifer, the water level rise in recharge is higher than the drawdown in pumping. In particular, the well loss in the recharge test is much greater than that in the pumping test because aquifer clogging occurs in recharge at the same flow rate. Based on the field test results, an equation to predict the well loss in recharge of the third confined aquifer in the Tianjin area is proposed.

Keywords Confined aquifer · Water level · Recharge test · Pumping test · Well loss

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Introduction

Artificial groundwater recharge is a common technique to raise the head of a confined aquifer and is usually used to solve the long-term surface subsidence caused by groundwater exploitation in deep confined aquifers. At present, artificial recharge has been widely applied for groundwater recharge and storage in many areas (Bhusari et al. 2016; Shi et al. 2016; Sarma and Xu 2017; Simmers 1988; Lerner 1990). Scanlon et al. (2002) studied the methods for quantifying groundwater recharge. Many researchers have studied the effects of artificial recharge on deep confined aquifers through field experiments and numerical simulations (Bouri and Dhia 2010; Sayana et al. 2010; Kuroda et al. 2017). Based on field artificial recharge test results, Dong et al. (2011) studied the changes in hydrogeological parameters with the empirical analysis method. Healy and Cook (2002) proposed a method to estimate the recharge rate based on data of the groundwater level changes with time in a field recharge test.

In general, a confined aquifer is cut off by a diaphragm wall or waterproof curtain to control the water level drawdown outside the excavation during dewatering inside the excavation (Yuan et al. 2018). However, when the excavation

is too deep or the confined aquifer is too thick, it is usually very difficult or expensive to cut off the confined aquifer using a waterproof curtain. If the waterproof curtain cannot completely cut off the groundwater connection inside and outside the excavation, pressure relief of the confined aquifer will cause subsidence of the surrounding ground and engineering infrastructures (Kim et al. 2018; Kim and Moon 2020).

Artificial recharge can be used to offset the drawdown in the confined aquifer and to control the surrounding subsidence caused by pressure relief inside the excavation when the confined aquifer cannot be cut off by a waterproof curtain. Based on the study of an excavation project in Britain, recharge outside the excavation was proven to be effective in controlling ground subsidence caused by excessive drawdown (Powrie and Roberts 1995). Because shallow and deep confined aquifers have different hydraulic conditions, Zhang et al. (2017) improved artificial recharge technique and conducted recharge tests in shallow confined aquifers to analyze the recharge effect in Shanghai.

At present, research has mainly focused on the deformation mechanism of shallow confined aquifers caused by engineering practices (Budhu and Adiyaman 2010; Moon and Fernadez. 2010). Research on the artificial recharge of shallow confined aquifers in deep excavation engineering is relatively rare and is outpaced by engineering practice (Wang et al. 2012; Wu et al. 2017). Therefore, it is still necessary to conduct further studies on the artificial recharge of shallow confined aquifers in deep excavation engineering.

Tianjin city is located on the coast of the Bohai Sea in China. The main components of the shallow confined aquifer in Tianjin are mainly silt and silty sand, and its permeability is relatively low compared with that of sand and gravel. Scholars and engineers have long doubted the feasibility of recharge in these confined aquifers in Tianjin.

In addition, clogging is one of the main factors limiting recharge efficiency (Liu and Zhu 2009). Well clogging mainly includes physical, biological, and chemical types, among which physical clogging plays a major role. When the water quality of recharge deteriorates, clogging easily occurs (Ye et al. 2011). Henry et al. (2012) studied the microstructure of clogging when physical clogging occurs under natural recharge through laboratory tests. Page et al. (2011) established the local evaluation index of the recharge water quality, which was used to evaluate plugging treatment schemes.

Because of clogging and other unknown problems in recharge, the well loss in recharge is much larger than that in dewatering. For natural recharge, the well loss in recharge is a very important factor influencing the recharge efficiency. If the well loss is large, the water level inside the recharge well will readily reach the wellhead, and the recharge rate and the water level rise in the confined aquifer surrounding the well will be low. Therefore, well-loss prediction is important for the design of the recharge scheme. However, research related to the well loss in recharge is very limited.

To investigate the abovementioned problems of artificial recharge in deep excavation engineering, in this study, a series of single-well pumping and recharge comparison tests with similar flow rates and pressure recharge contrast tests of different well structures were conducted at a site in Tianjin. The feasibility and effectiveness of recharge in Tianjin's silt and silty sand confined aquifers were studied and discussed. In addition, the single-well recharge and well-loss phenomena and the test results of different well structures were analyzed.

Study site conditions

The test site is located in an open space inside a company, Dongli District, Tianjin, China, as shown in Fig. 1. A cross-sectional view of the hydrogeological setting at this site is shown in Fig. 2. This site is chosen as the test site mainly because it is far away from the urban area, with few underground buildings and pipelines nearby, and it has enough scale to carry out the test without affecting the surrounding environment and structures. Second, this site is in line with the typical stratigraphic characteristics of Tianjin, and the hydraulic connection between different layers is relatively small, which can exclude the influence of overflow on the recharge cone and dewatering funnel.

According to the survey data provided by the geological survey, there are four aquifers within a depth of 60.00 m, i.e., an upper phreatic aquifer and three confined aquifers (labeled as CA1, CA2, and CA3, from top to bottom, respectively). These confined aquifers are located in the $\circledS_2$ silt layer, the $\circledn_2$ silt layer, and the $\circledii_2$ silty sand layer and are all stratified. The excavation depth of Tianjin metro stations is generally within 40 m, and the depth of pumping and recharging groundwater in practical projects is generally within 70 m, while the stratum depth of most of the excavation pumping and recharging is within 50 m. In this site, the soil layer within this depth range is CA2 and CA3, but the CA2 in this site is thin, and the recharge rate and recharge efficiency were relatively poor. Therefore, the thick soil layer CA3 within the depth of 40 m is finally selected. All the overground structures around the site adopt shallow foundations, and their influence on groundwater flow in the third confined aquifer buried 40–50 m below the surface can be ignored. The stratigraphic relationships between $\circledS_2$, $\circledn_2$, and $\circledii_2$ are shown in the stratigraphic section of Fig. 4. The physical and mechanical parameters of the different soil layers are also shown in Fig. 2.

Fig. 1 Location and satellite map of the test site
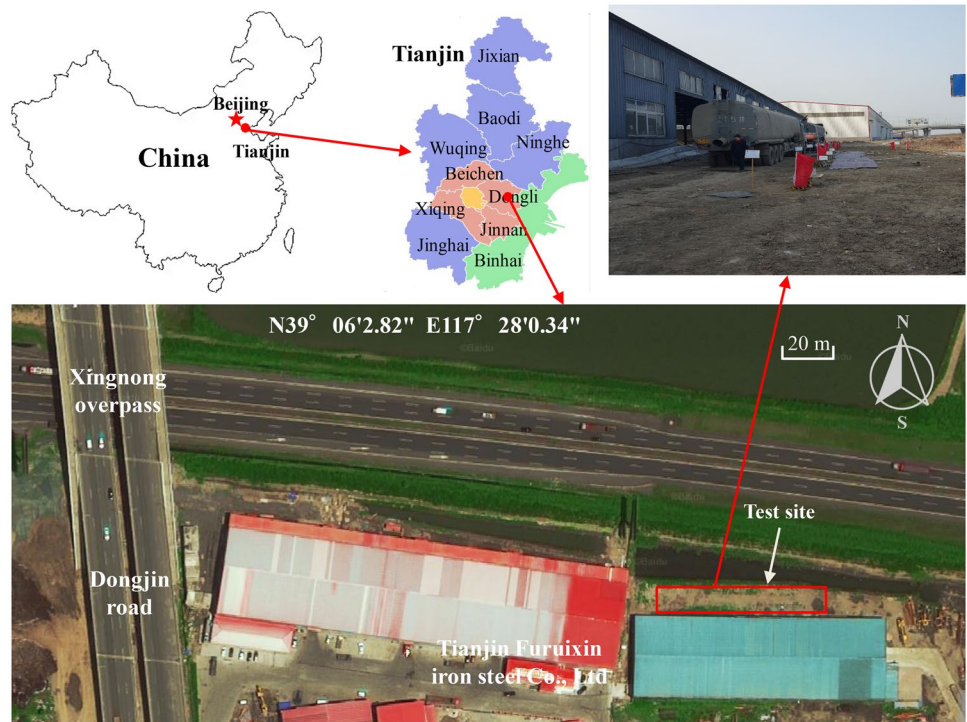
Materials and methods

Introduction of materials

The well at this site is made of steel pipe with a thickness of 6 mm. The gap between the well wall and the borehole is filled with fillers. The filter material in the aquifer is made of gravel to filter the groundwater, and the filter material in the aquitard is made of clay balls to block hydraulic connection. Close to the surface, the gap between the hole wall and the wall of well H11-1 was sealed with slurry cement no. 425, which has a compressive strength of 32.5 MPa after 28 days of induration, and gaps of remaining wells were sealed with clay to study the difference between filling materials. Each

MF=Miscellaneous fill, MC=Muddy clay, SC=Silty clay, CA=Confined aquifer; n=Porosity, ω_L=Liquid limit, ω_p=Plastic limit, γ=Unit weight, c=Cohesion, φ=Internal friction angle, Cc=Coefficient of compressibility, q_c=Probe resistance, f_s=Frictional resistance.
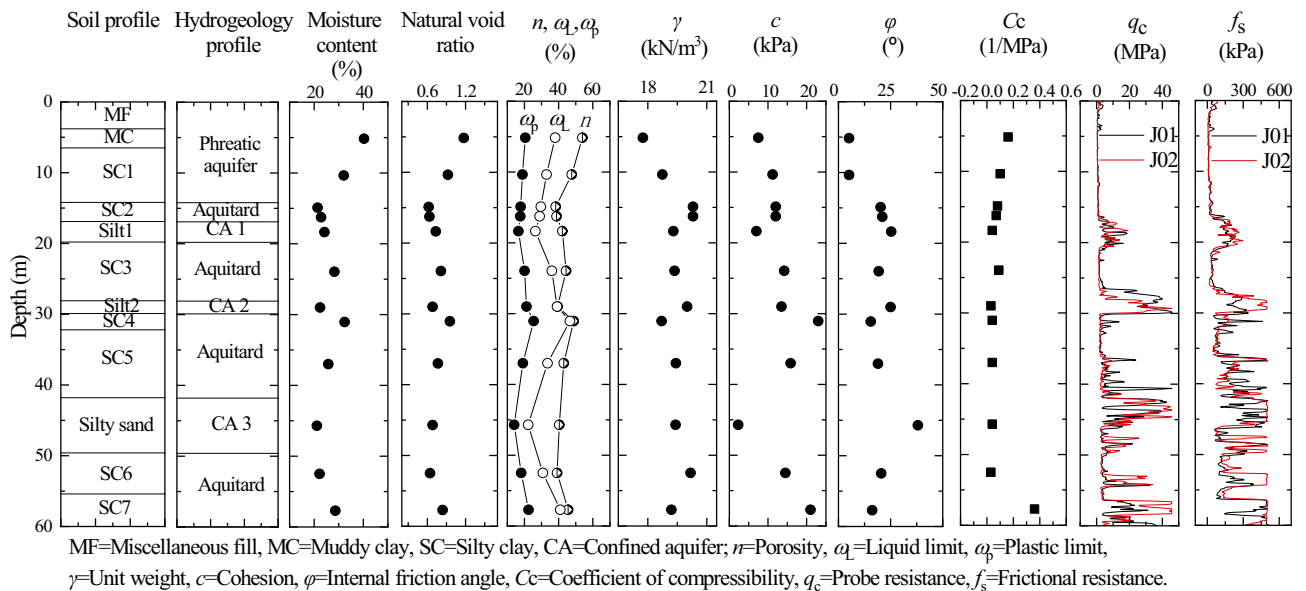
Fig. 2 Typical soil profile and geophysical and mechanical soil parameters at the test site

Table 1 Experimental scheme

Testing phases		Date	Pumping well/ recharge well	Recharge rate or pumping rate (m³/h)	Recharge pressure (MPa)	Test duration (h)	Recovery duration (h)
Natural	Pressured						
P1		2016.1.19	H11-1	0.890	-	12.68	16.85
P2		2016.1.17	H11-1	2.110	-	24.53	21.17
P3		2016.1.10	H11-1	2.960	-	25.00	23.58
P4		2016.1.15	H11-1	3.540	-	24.20	24.70
R1		2016.1.8	H11-1	0.924	-	10.00	12.85
R2		2016.1.9	H11-1	2.130	-	10.18	13.32
R3		2016.1.1	H11-1	3.000	-	24.00	24.22
R4		2016.1.12	H11-1	3.700	-	10.00	14.02
R5		2016.5.15–2016.5.16	H11-1	4.200	-	13.50	20.00
	PR1	2016.5.30–2016.5.31	H11-1	6.000	0.24		
	PR2	2016.5.29	H11-2	4.000	0.24		

well uses an automated water level monitoring system, where sensors are placed at the bottom of the well and transmitted through data cables to a computer to automatically monitor changes in the water level. The soil parameters, such as the water moisture content ω, unit weight g, natural void ratio e, cohesion c, internal friction angle φ, plasticity limit ω_p, liquidity limit ω_L, and coefficient of compressibility Cc, were determined based on a series of laboratory tests (e.g., oven-drying method, direct measurement with a sharp cutting ring, water pycnometry, consolidated undrained direct shear (CUDS) test, fall-cone method, and plastic limit rolling procedure (hand rolling) and oedometer test). The probe resistance q_c and frictional resistance f_s were determined by a static cone penetration test.

Experimental scheme

In this study, 12 tests were conducted, including 4 pumping-recovery tests (referred to as P1–P4) with different pumping rates and 8 recharge-recovery tests with different recharge rates (6 natural recharge tests, i.e., R1–R6, and 2 pressure recharge tests, i.e., PR1 and PR2). The experimental schemes are listed in Table 1. The plan layout of the test site is shown in Fig. 3. During the layout of observation wells, due to the limitations of the site surface (there are buildings on the surface), the layout of observation wells is affected. Most wells can only be deployed east–west; however, to reflect the 2D characteristics of the site, observation well G11-2 of CA3 was arranged as far as possible from south to north. According to the test results,
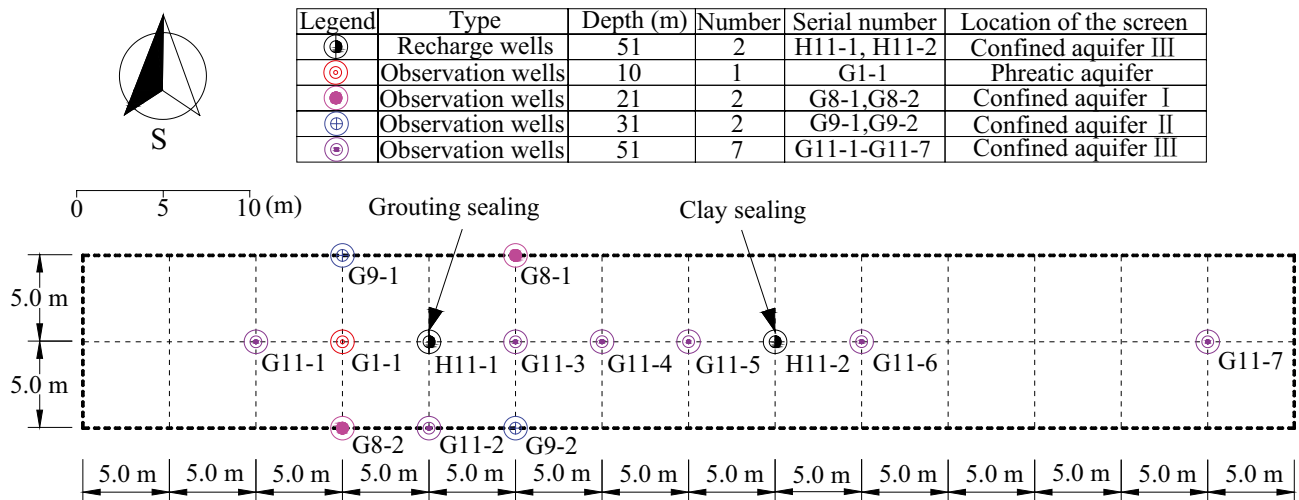

Fig. 3 Plan layout of the test site

as shown in Fig. 8, the results of G11-2 and G11-3 are very close, indicating that the site is relatively uniform in both directions. Under such circumstances, for well H11-1, when the site is relatively uniform, the model is axisymmetric, and the layout on a straight line does not affect the test results. There was a total of 14 wells, including 2 recharge wells (H11-1 and H11-2) and 7 observation wells (G11-1 to G11-7) for CA3 at a depth of 51 m, 2 observation wells (G9-1 and G9-2) for CA2 at a depth of 31 m, 2 observation wells (G8-1 and G8-2) for CA1 at a depth of 21 m, and 1 observation well (G1-1) for the phreatic aquifer at a depth of 10 m. The observation wells were arranged at different distances from the recharge well. The structures of the different test wells are shown in Fig. 4. Most tests (P1–P4, R1–R5, and PR1) were conducted using well H11-1. In test PR1, the wellhead was sealed and connected to a pressure pump. The recharge pressure was controlled by the power of the pump, and the pressure in the wellhead was monitored by a piezometer. The pressured recharge equipment is shown in Fig. 12a. The pressure gradually increased during the test, and the water levels in the observation wells and the pressure in the recharge well were recorded.

During the pumping or recharge tests, the head changes in the different aquifers near the central well (H11-1 or H11-2) were monitored by observation wells. When the heads in the observation wells reached relatively stable levels, pumping or recharge was stopped, and the heads began to recover until the initial levels were reached. Then, the

next cycle of pumping or recharge started. The responses of CA3 to the recharge-recovery and pumping-recovery processes were investigated through the water level changes in observation wells G11-1–G11-7.

Calculation method

To obtain the hydrogeological parameters through back analysis of the tests and to further investigate the relationship between the drawdown and water-level rise cone, numerical simulations of the pumping and recharge tests were conducted using the 3D finite difference method. Based on the site investigation during the construction of wells, the horizontal distribution of the strata in this site is relatively homogeneous. The test results also confirmed the homogeneity of the site. Hence, the geologic layers are modeled as a continuum of material with no lateral changes. The mesh and dimensions of the numerical model are shown in Fig. 5. The hydraulic boundary of the model was a constant-head boundary, and the simulation used transient-state analysis. In the numerical model, the hydrological parameters are adjusted until the calculated drawdown of the groundwater level was in great agreement with the measured value.

In 1935, Theis proposed the well function to calculate the unsteady well flow of groundwater. Cooper and Jacob found that when the parameter u of Theis well function
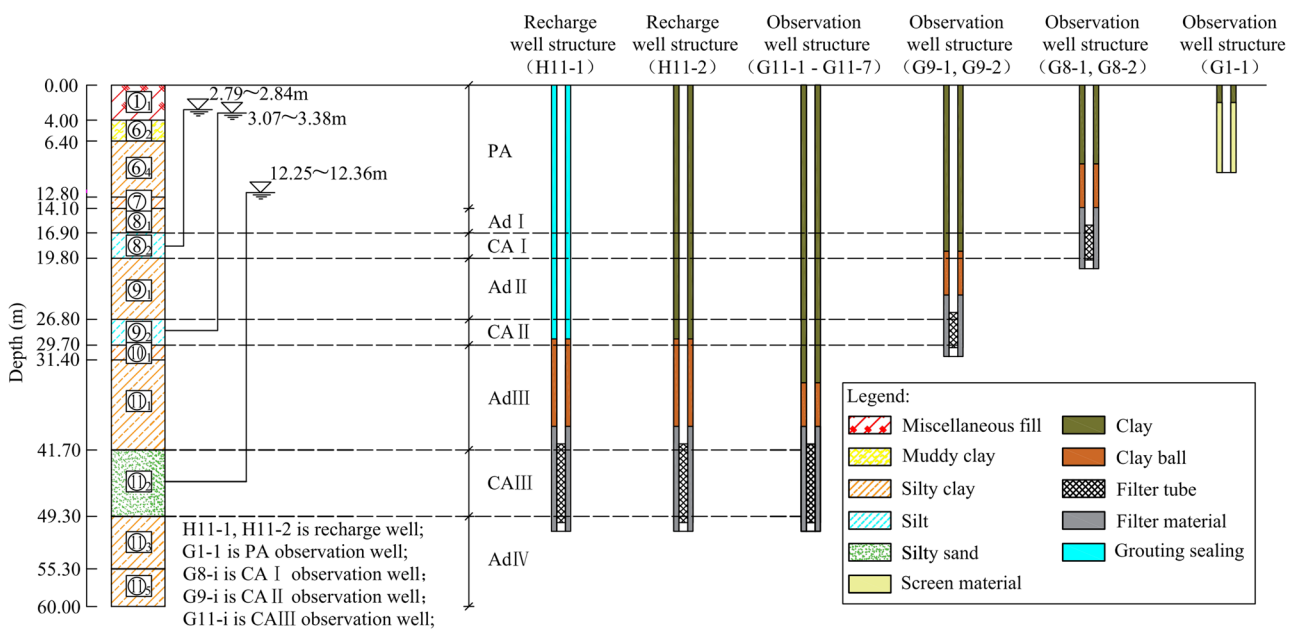

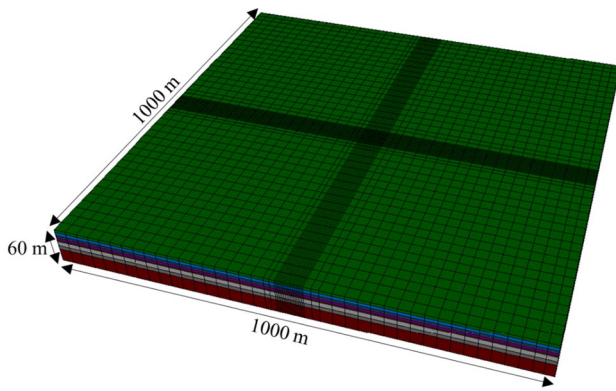**Fig. 4** Schematic diagram of the test well structures

Fig. 5 Model and mesh of the numerical simulations

is small, the second-order and higher-order terms of this well function can be neglected (Cooper and Jacob 1946). The permeability coefficient, k, can be derived through the slope of the linear section of Theis's curve (1935) using the straight-line approximation proposed by Cooper and Jacob (1946):

$$k = \frac{2.30Q}{4\pi b i_s} \tag{1}$$

and the storage coefficient, S_s, is obtained by using the horizontal intercept, t_0, of an extension of the late-time drawdown asymptote resulting from a typical drawdown curve:

$$S_s = \frac{5.515Q t_0}{4\pi i_s r^2} \tag{2}$$

where r is the distance between the observation well and pumping well and b is the thickness of the confined aquifer. When the values of t_0, r, and b are known, k and S_s can be calculated by using Eqs. (1) and (2), respectively.
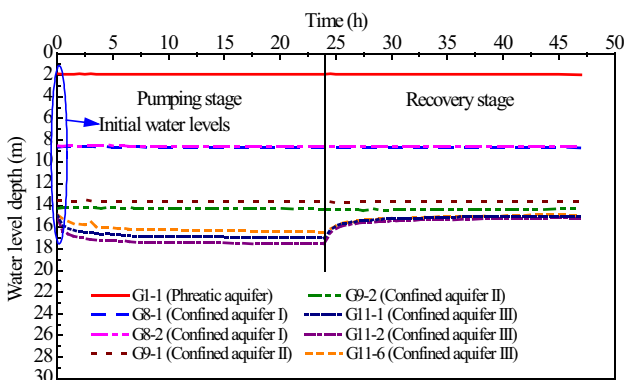
Fig. 6 The water head change in the different aquifers when the third confined aquifer was pumped

Fig. 7 Water level variation curves for the field pumping and recharge ▶ tests and corresponding numerical back-analysis results: **a** pumping rate of 0.89 m³/h, **b** recharge rate of 0.924 m³/h, **c** pumping rate of 2.11 m³/h, **d** recharge rate of 2.13 m³/h, **e** pumping rate of 2.96 m³/h, **f** recharge rate of 3.00 m³/h, **g** pumping rate of 3.54 m³/h, and **h** recharge rate of 3.70 m³/h

Results and discussions

Recharge and pumping test results

Single-well pumping and natural recharge test results

The initial water levels of the observation wells in each aquifer are shown in Fig. 6. When the water level drawdown was more than 2.5 m in pumping well H11-1, the water levels in the other aquifers almost did not change, which indicated that the third confined aquifer was not hydraulically connected with the first and second confined aquifers.

Figure 7 shows the variation in groundwater level caused by the single-well pumping test (Fig. 7a, c, e, and g) and the single-well natural recharge test (Fig. 7b, d, f, and h) under different flow rates. The test procedures for single-well natural recharge tests R1–R4 performed without artificial recharge pressure at different recharge rates within the grouting-sealed well display the same absolute fluctuation values of the pumping tests. The groundwater level drawdown or rise in the observation wells was synchronous with that in the pumping or recharge well. As the distance to the observation well increased, the water level change in the observation well decreased. Additionally, the magnitudes of the water level variations in the pumping/recharge and observation wells were proportional to the flow rate.

When the water levels in the observation wells (G11-3–G11-5 and G11-7) had nearly stabilized, the water level in the recharge well (H11-1) was still increasing, and the increase rate was higher in the test at a higher pumping rate. This phenomenon is apparently different from that in the pumping tests (H11-1), in which the water level in the pumping well (H11-1) also stabilized when the water levels in the observation wells were stable. This result was mainly caused by clogging of the recharge well (Barrett and Taylor 2004). In the process of recharge, clogging of the recharge well will directly affect the recharge efficiency and service life of the recharge well. To prevent clogging in the recharge wells and ensure the recharge efficiency of the recharge well under long-term operating conditions, the recharge well needs to be periodically pumped. According to a test on the interval and duration of pumping needed for a recharge well in Tianjin, the cumulative number pumping for the recharge well basically increased linearly with the recharge duration. The average pumping frequency is 9 times per month under the specific conditions where the

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)
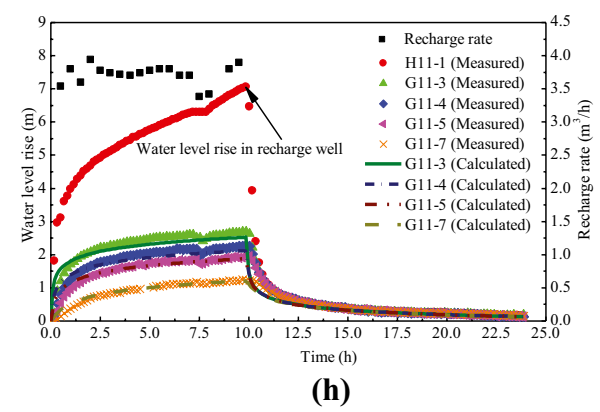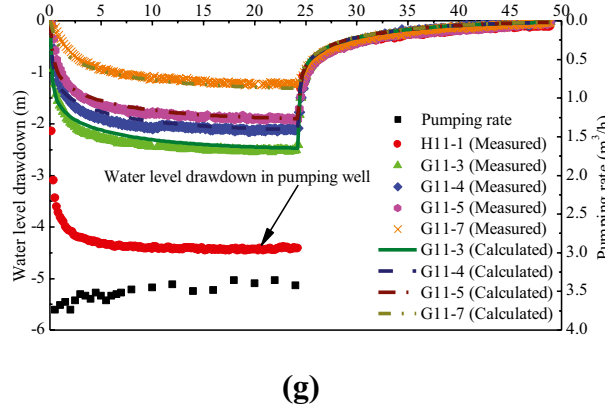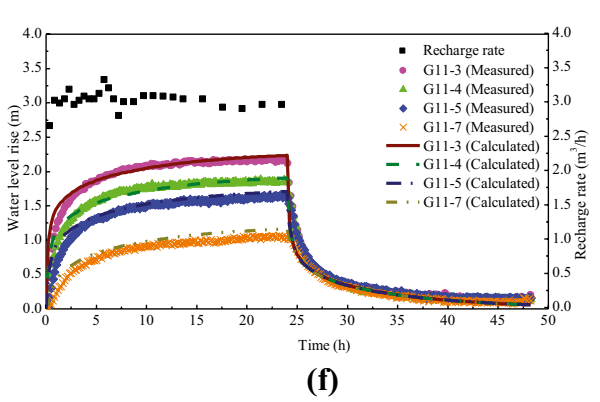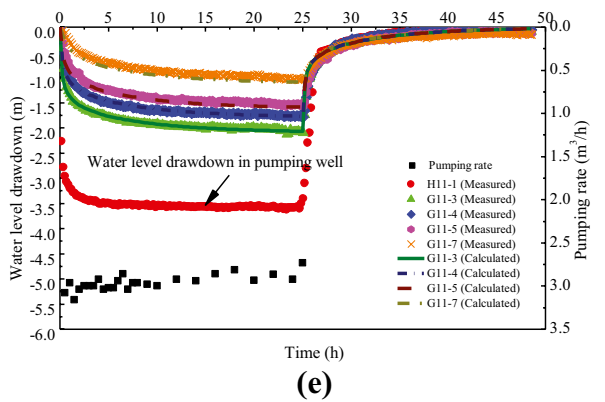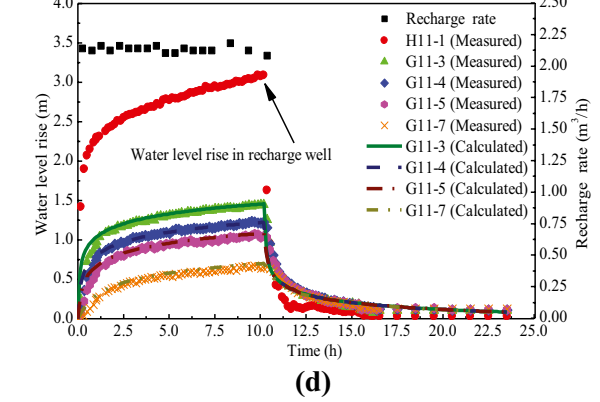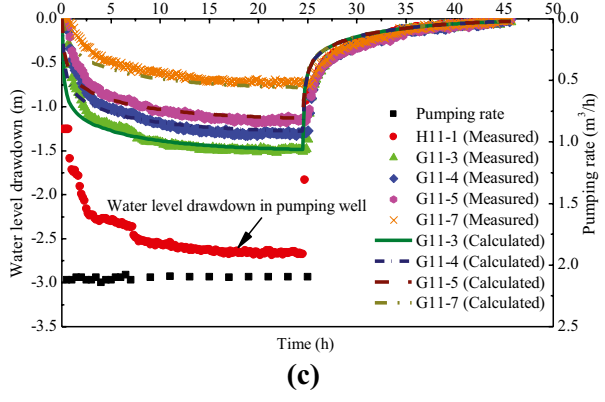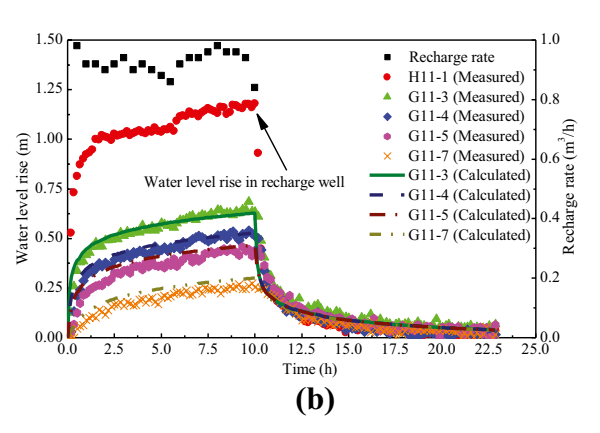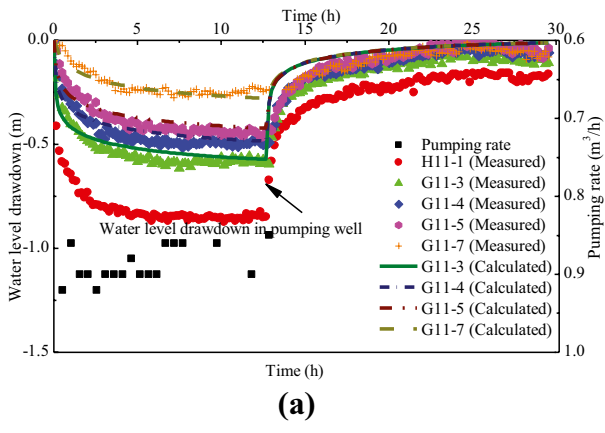
recharge well is located (Zeng 2014), but for different sites, the frequency of pumping required may vary.

The pumping tests and recharge tests have also been simulated using the model in Fig. 5. The numerical simulation curves of the water level changes in the wells (G11-3–G11-5 and G11-7) are shown in Fig. 7. The CA3 hydrogeological parameters in the pumping tests, i.e., the permeability coefficient (k) and unit storage coefficient (Ss), were assigned to be 2.765 m/day and 1.8×10^{-5}/m, respectively. In recharge tests, they were set as 2.55 m/day and 2.2×10^{-5}/m, respectively, which are close to the parameters used in the simulations of the pumping tests. Additionally, the k value obtained from the pumping tests is slightly larger than that from the recharge tests, which may be attributed to the fact that the recharge process could have caused a certain degree of clogging in the confined aquifer around the well. As shown in Fig. 7, the measured and calculated pumping rates correlate well. This means that the numerical model is close to the real site, and the values of the hydrogeological parameters used in the numerical simulations are hydrogeologically accurate.

The recharge test R5 the of H11-1 well sealed by grouting was performed to obtain the maximum recharge rate under natural recharge conditions. In this test, the water level reached the wellhead, indicating a water level rise of 14.55 m half an hour after the start of recharge. Then, flow control using a pump was carried out so that the water level in the recharge well was maintained at the wellhead. The monitoring results of the surrounding observation wells (G11-1–G11-7) are shown in Fig. 8. During this test, the average recharge rate was approximately 4.2 m³/h.

Groundwater water table fluctuation analysis

The comparison of the water levels obtained from the pumping and recharge tests is shown in Fig. 9. The shapes of the drawdown cone and the recharge cone are almost identical when the distance from the well is larger than 5 m, which is close to the results obtained at another site (Zheng et al. 2018). The contrast test of single-well pumping and recharge is conducted at another site in Tianjin. The comparison between the recharge cone curves (*h-r* curve) at different recharge rates obtained by the numerical simulation with the measured data are shown in Fig. 10, where the numerical simulations of the single-well recharge tests were carried out using the hydrogeological parameters obtained from the single-well pumping tests.

At a similar flow rate, several possible reasons could explain the differences between the pumping curves and the recharge curves within a certain distance of the center well. First, turbulence may occur near the recharge well. Second, the recharge process could have caused a certain degree of clogging in the confined aquifer around the well, which could have decreased the permeability coefficient of the confined aquifer around the well (Nie et al. 2011). The third possible reason was attributed to the bridge-filter structure of the recharge well screen, as different flow directions led to different well-loss values during the pumping and recharge tests (Longe 2011).

The above analysis suggests that the hydrogeological parameters obtained from the measured drawdown data from pumping tests can be used to predict the water level rise during recharge tests. However, the predicted results underestimated the water level rise near the recharge well (within 7 m) in the actual project. In practical engineering, when only the hydrogeological parameters obtained from a pumping test are available, these parameters can be used to design the recharge scheme. However, the water level rise near the recharge well should be adjusted. One possible method is to choose a correction factor to calibrate the permeability coefficient within 7 m from the recharge well. The choice of correction coefficient needs further study.

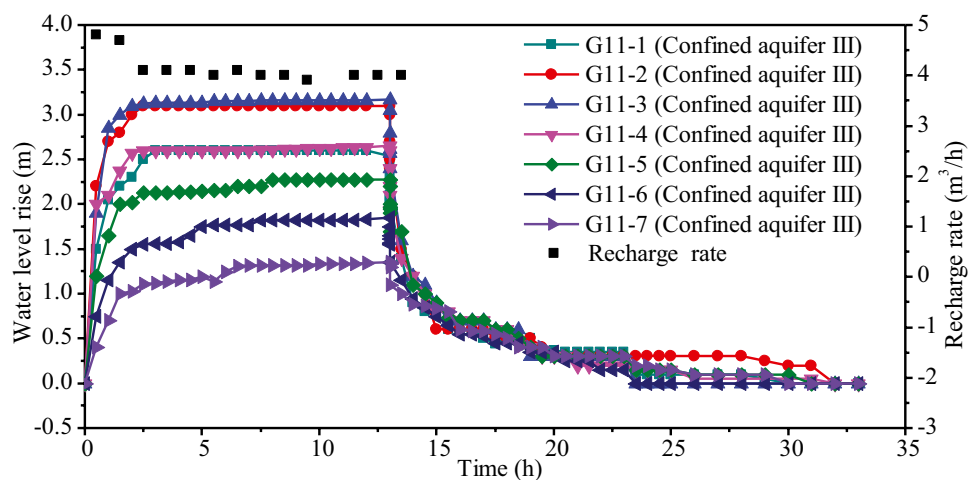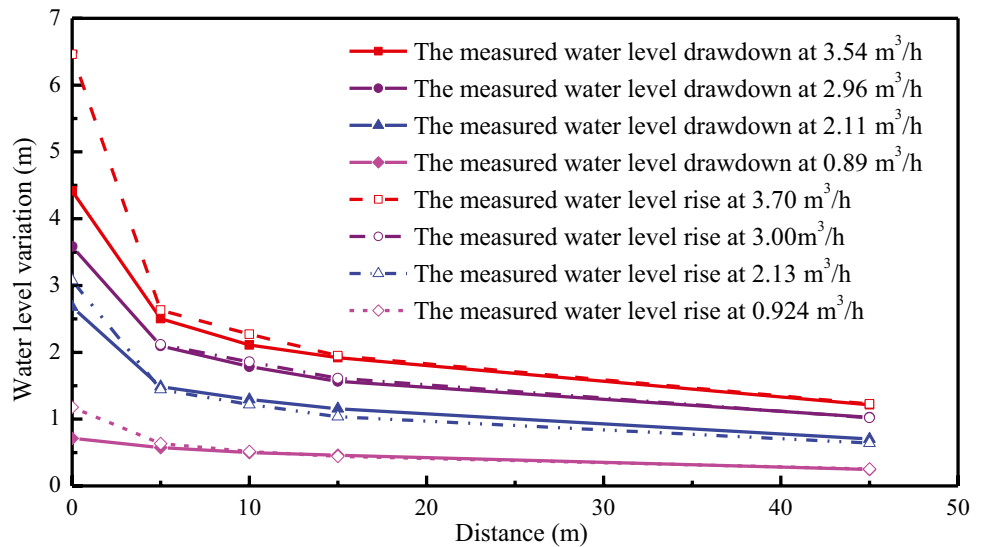**Fig. 8** Water level curves of the natural recharge test in well H11-1

Fig. 9 Comparison of the water levels obtained from the pumping and recharge tests


## Comparative analysis of measured and calculated hydrogeological parameters

In the sections "Single-well pumping and natural recharge test results" and "Groundwater water table fluctuation analysis" the hydrogeological parameters are derived by back analysis of the results of the pumping and recharge tests. In actual engineering, the hydrogeological parameters are measured by laboratory tests. However, they are often inaccurate due to disturbance. Therefore, pumping test are often performed on site to obtain accurate hydrologic parameters. In addition to numerical inversion, Cooper and Jacob methods are also used to obtain hydrological parameters based on pumping test results. In this section, the hydrogeological parameters obtained by laboratory tests, numerical method, and Cooper and Jacob method are compared and analyzed.

Based on the survey report of excavation engineering with similar geological conditions, the permeability coefficients of the CA3 confined layer are 2.2 m/day, 5 m/day, and 0.5 m/day (Zheng et al. 2014, 2019, Shen et al. 2015) through laboratory tests. It can be seen that the permeability coefficient of the same layer obtained by the laboratory test is quite discrete and different from the parameters obtained by the numerical simulation. Therefore, it is suggested that the pumping test should be carried out before the design of dewatering to obtain an accurate permeability coefficient.

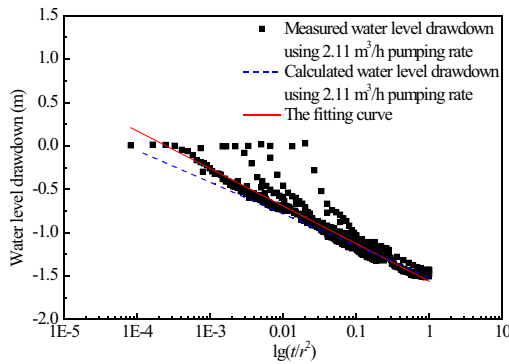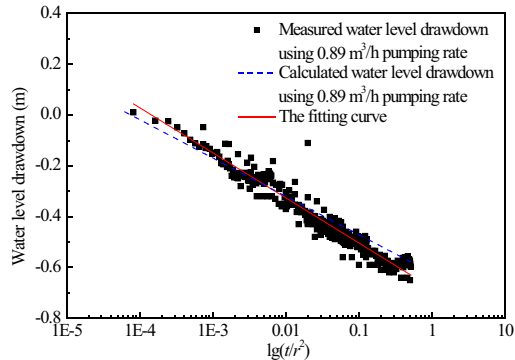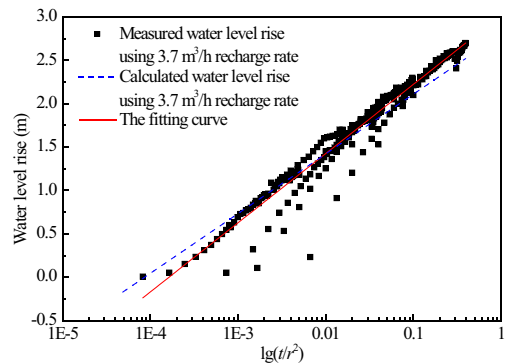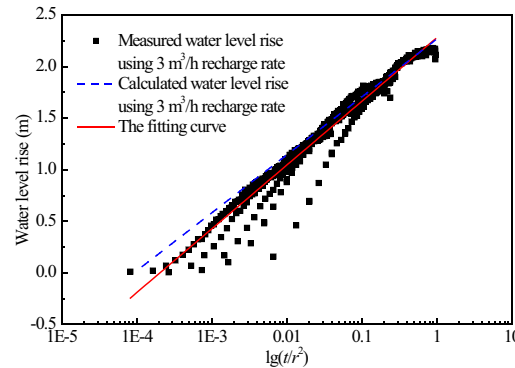**Fig. 10** The *h-r* curves of single-well multistage recharge
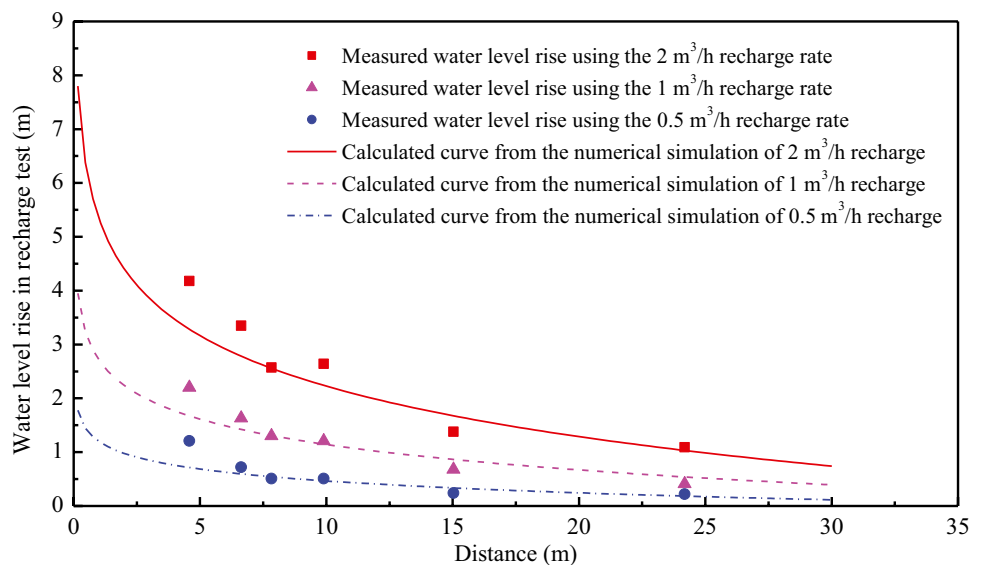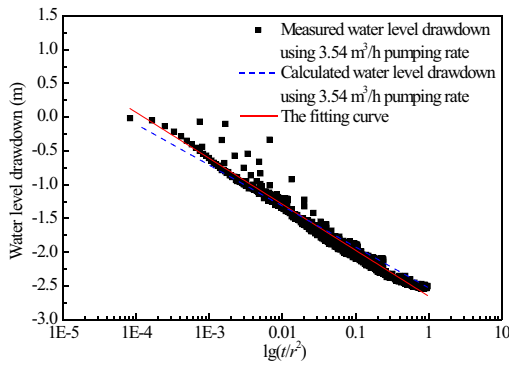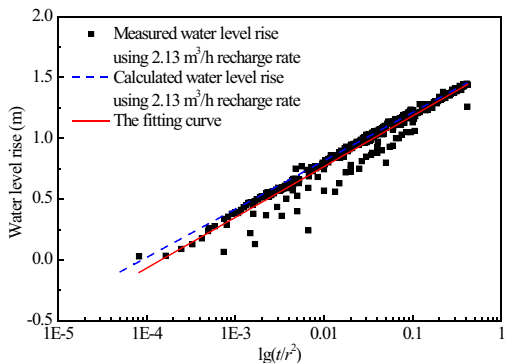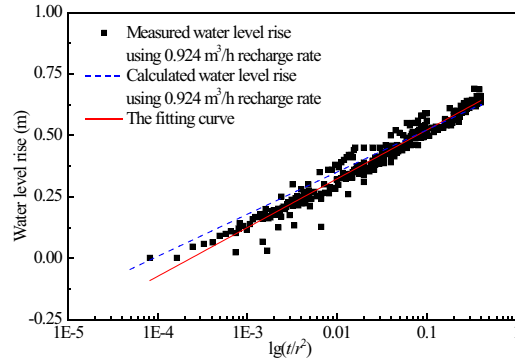
(a)
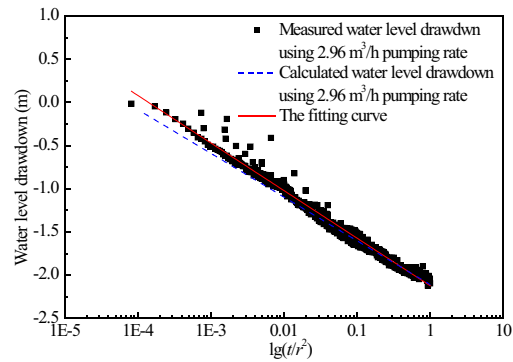
(b)

(c)

(d)

(e)

(f)

(g)

(h)

◄**Fig. 11** The s-log(t/r^2) curves for the single-well pumping and recharge tests: **a** pumping rate of 3.54 m^3/h, **b** pumping rate of 2.96 m^3/h, **c** pumping rate of 2.11 m^3/h, **d** pumping rate of 0.89 m^3/h, **e** recharge rate of 3.70 m^3/h, **f** recharge rate of 3.00 m^3/h, **g** recharge rate of 2.13 m^3/h, and **h** recharge rate of 0.924 m^3/h

For Cooper-Jacob method, Fig. 11 shows the s-log(t/r^2) curves for the single-well pumping (P1–P4) and recharge tests (R1–R4). The permeability coefficient (k) and unit storage coefficient (Ss) can be calculated, as listed in Table 2. The results obtained from the pumping tests using the Cooper-Jacob method are close to those obtained from the recharge tests, and the k value obtained from the pumping test is also slightly larger than that obtained from the recharge test, which is consistent with the results in the "Single-well pumping and natural recharge test results" section.

Compared with numerical back analysis, the k and Ss values obtained by the Cooper-Jacob method are larger. The difference between the k values from these two methods is relatively small, while the difference between the Ss values is considerably larger. The reason can be explained as follows. In Fig. 11, the s-log(t/r^2) curves derived from the back-analysis numerical simulation in the "Groundwater water table fluctuation analysis" section are also depicted. The slope of the calculated water level curve is slightly smaller than that of the linear regression curve based on the measured points. This is because the variation in the water level was smaller than the theoretical value due to the effect of wellbore storage at earlier times (Hegeman et al. 1993). This made the slope of the linear regression curve slightly smaller, resulting in smaller k values. The Ss values were determined based on the intercepts of the regression lines with the X-axis. Because the abscissa is in logarithmic form, a slight change in the regression lines resulted in a significant change in the intercept, which caused a very large error of the Ss value. Therefore, due to the influence of the well storage effect (Preene 2012), the accuracy of the unit water storage coefficient (Ss) obtained by the Cooper-Jacob method is poor. Therefore, the hydrological parameters identified by numerical back analysis were more accurate than those identified by the Cooper-Jacob method.

Pressured recharge test result analysis

To investigate the technique to improve the recharge efficiency in confined aquifers, two pressured recharge tests (PR1 and PR2) were carried out after the single-well natural recharge tests (R1–R5) using well H11-1. Based on the pressured recharge test results, the ultimate recharge pressures and recharge rates in the grouting-sealed well (H11-1) and clay-sealed well (H11-2) were compared.
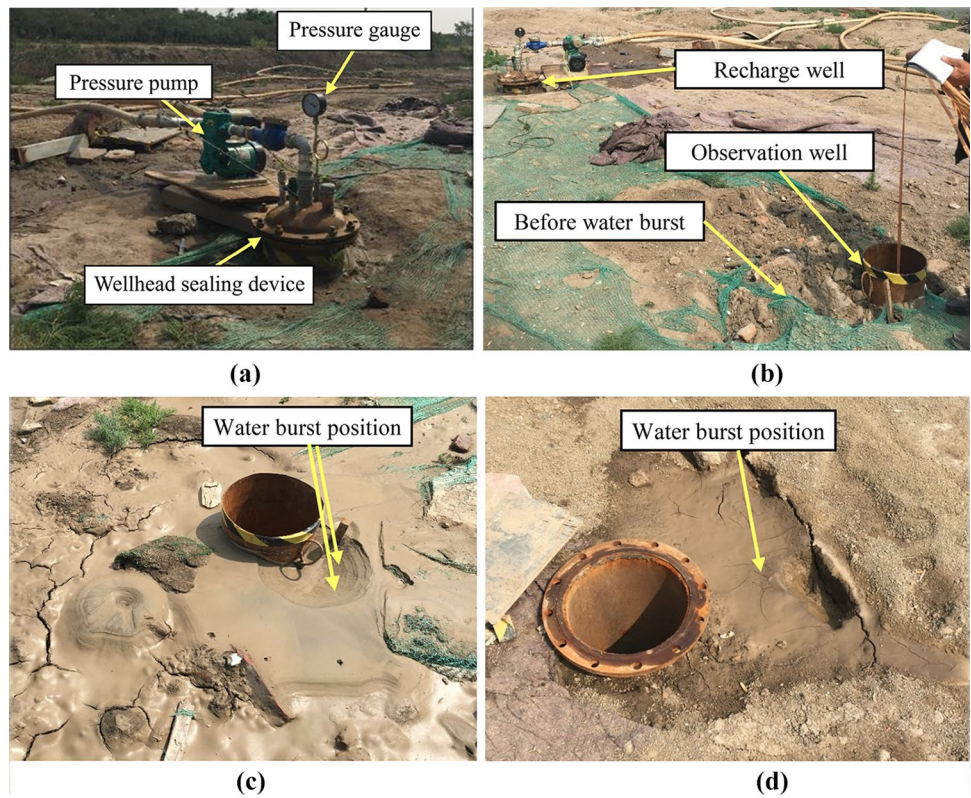
Pressured recharge test using the grouting-sealed recharge well (H11-1)

The pressure recharge test data are shown in Fig. 13. After applying pressure for approximately 20 h, when the recharge pressure reached a maximum value of 0.24 MPa, water began to flow out of the shaft lining of observation well G11-3, which was 5 m from the recharge well. The water burst position is shown in Fig. 12b and c. As shown in Fig. 13, when a water burst occurred outside the G11-3 well, the recharge pressure began to decrease and remained stable at 0.20 MPa. The recharge rate before water burst mainly remained stable at 6 m^3/h, which is approximately 43% higher than the maximum natural recharge rate, i.e., 4.2 m^3/h. After water burst, the recharge rate was reduced to 5 m^3/h. Pressured recharge can increase the efficiency of recharge, which will reduce the number of recharge wells and the recharge cost.

During the pressured process, there was no water burst around the outer wall of the recharge well (H11-1) because the grouting sealing was relatively tight. However, well G11-3 was sealed with clay. In Tianjin, clay sealing is a traditional method to seal the gap between the borehole and the well wall of all types of wells, such as pumping, observation, and recharge wells.

In this test, it can be deduced that as the water pressure in the confined aquifer increased, hydraulic fractures occurred and gradually developed along the weak surface outside the well wall of well G11-3. Water flowed along the hydraulic fracture surface, and when the hydraulic fractures extended to the ground surface, water burst occurred.

Table 2 Hydrogeological parameters of the pumping and recharge tests derived by the Cooper-Jacob method

Property	Pumping rate (m^3/h)				Average	Recharge rate (m^3/h)				Average
	3.54	2.96	2.11	0.89		3.7	3	2.13	0.924	
Permeability (m/d)	2.93	3.02	2.74	2.82	2.88	2.61	2.73	2.88	2.62	2.71
Unit storage (10^{-5}/m)	3.66	4.07	7.20	4.20	4.78	4.73	5.90	4.18	6.82	5.41

Fig. 12 The scenarios of the test site: **a** schematic diagram of the pressured equipment, **b** before water burst of G11-3, **c** after water burst of G11-3, and **d** the water burst position of H11-2


(a)

(b)

(c)

(d)

Pressured recharge test using clay-sealed recharge well (H11-2)

The pressured recharge test, PR2, was carried out in clay-sealed well H11-2. When the well was pressured from 0 to 0.24 MPa, water began to flow out of recharge well H11-2 itself, as shown in Fig. 12d.

Water burst occurred in both pressured recharge tests with different sealing methods at a pressure of approximately 0.24 MPa. However, at an artificial recharge pressure of 0.24 MPa, the borehole of the recharge well sealed by grouting (H11-1) was safe, but the recharge well sealed by clay (H11-2) failed. It can be concluded from this test that grouting sealing was more effective in

Fig. 13 The time-history curve of the pressured recharge test of H11-1
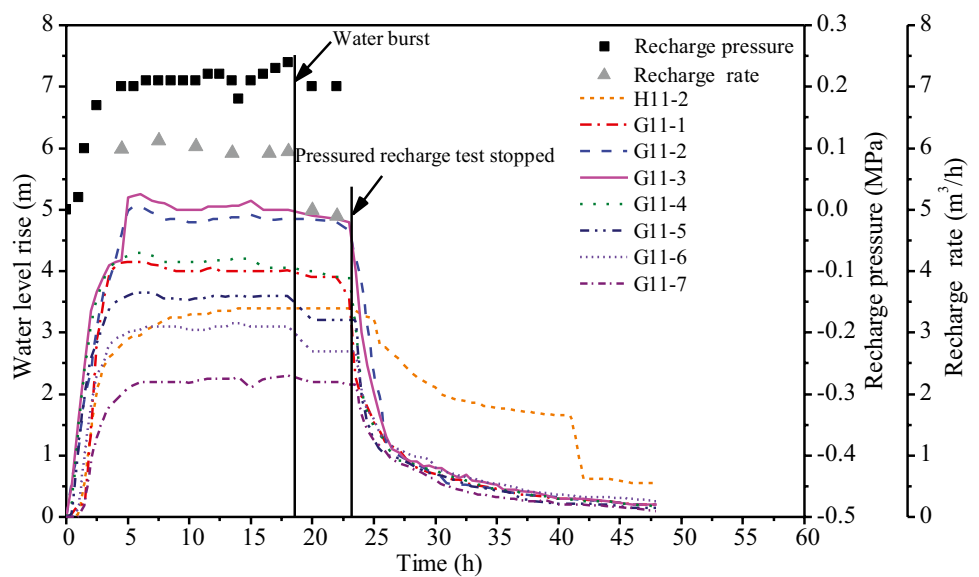
preventing hydraulic fractures than clay sealing. Additionally, the recharge pressures at the wellhead of the recharge wells in the two tests were both 0.24 MPa. Therefore, the water pressure outside the screen of well G11-3 in test PR1 should be much lower than that outside the screen of recharge well H11-2 in test PR2. However, both G11-3 and H11-2 failed, indicating that the sealing quality of clay was not uniform and could not be guaranteed.

Based on the above two tests, it can be concluded that pressured recharge can improve the recharge efficiency compared with natural recharge, but the recharge well and the observation wells around the recharge well within a certain distance should be sealed by effective sealing methods, such as grouting, to obtain a higher recharge pressure and recharge rate and avoid failure of the wells. In addition, when pressured recharge is needed, the recharge well and adjacent observation wells should all be sealed by grouting to avoid failure of the wells.

Well-loss analysis

Theoretical calculation of well loss

The total drawdown in a pumped well is composed of aquifer and well losses. Quantification of the well loss is important to assess the efficiency condition of a well. Driscoll (1986) considered aquifer loss to be a laminar term and well loss a turbulent term s_w. The laminar term is assumed to be proportional to the pumping rate or equal to BQ, in which Q is the pumping rate, and B is the aquifer loss or formation loss coefficient. The turbulent term is assumed to be proportional to the power of the pumping rate or equal to CQ^n, where C is a constant called the well-loss coefficient and n is a constant greater than 1, which can be called the well-loss power. Therefore, the total drawdown $s_{t,w}$ in the pumping well can be expressed as:

Fig. 14 The $s_{t,w}$-Q curves

$$s_{t,w} = s_w + CQ^n = BQ + CQ^n \tag{3}$$

In the graphical method presented by Todd (1980), the well loss was assumed to be equal to CQ^2. Rorabaugh (1953) observed that well losses were proportional to the pumping rate to a power of 2.4–2.8. Singh (2002) showed that the exponent of the pumping rate could be identified as approximately 2 using a better optimization that made use of all observed drawdowns.

Figure 14 shows the drawdowns at the different pumping rates in the pumping tests (P1–P4), and the water level rises after 10 h of recharge at the different recharge rates. By fitting the data in Fig. 14 based on Eq. (3), the undetermined coefficients B and C can be obtained. The $s_{t,w}$-Q curves in Fig. 14 are parabolic, and the values of the determined coefficients B and C corresponding to the pumping (P1–P4) and recharge tests (R1–R4) are $B = 0.946$, $C = 0.088$, and $n = 2$ and $B = 0.927$, $C = 0.264$, and $n = 2$, respectively. The B values for the pumping and recharge tests are close. However, the C value for recharge is much larger than that of pumping, which indicates that the well loss in recharge is much larger than that in pumping.

$$s_{t,w} = 0.946Q + 0.088Q^2 \tag{4}$$

$$s_{t,w} = 0.927Q + 0.264Q^2 \tag{5}$$

Numerical back-analysis calculation of well loss

Figure 15 shows the data points of the measured water level changes in the pumping or recharge well, H11-1, and the observation wells in the different tests. The solid line and the dotted line represent the water level change curves calculated based on the numerical back-analysis parameters and the Cooper-Jacob parameters in Table 2, respectively. The water level change curve based on the numerical back-analysis parameters is closer to the measured water level change data. This indicates that the permeability coefficient (k) and unit water storage coefficient (Ss) calculated by the numerical back-analysis method are more accurate than those calculated based on the Cooper-Jacob method. Due to the influence of the well loss, the water levels at the shaft lining are lower than the water levels in the H11-1 well, and the higher the flow rate is, the larger the difference. According to the difference between the measured water level in well H11-1 and the water level at the shaft lining obtained via numerical simulation (Fig. 15), the well-loss values at the different flow rates can be obtained, which are listed in Table 3 and shown in Fig. 16.
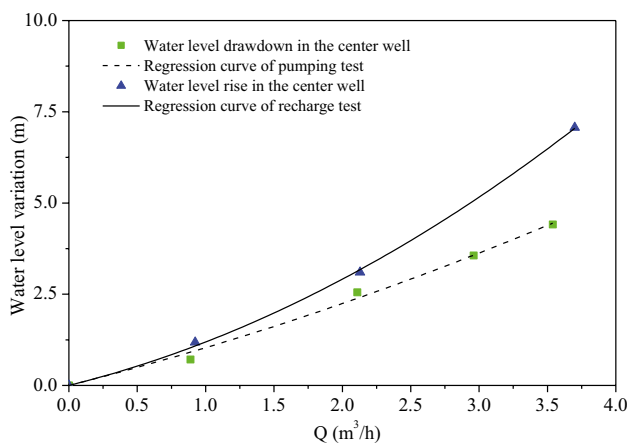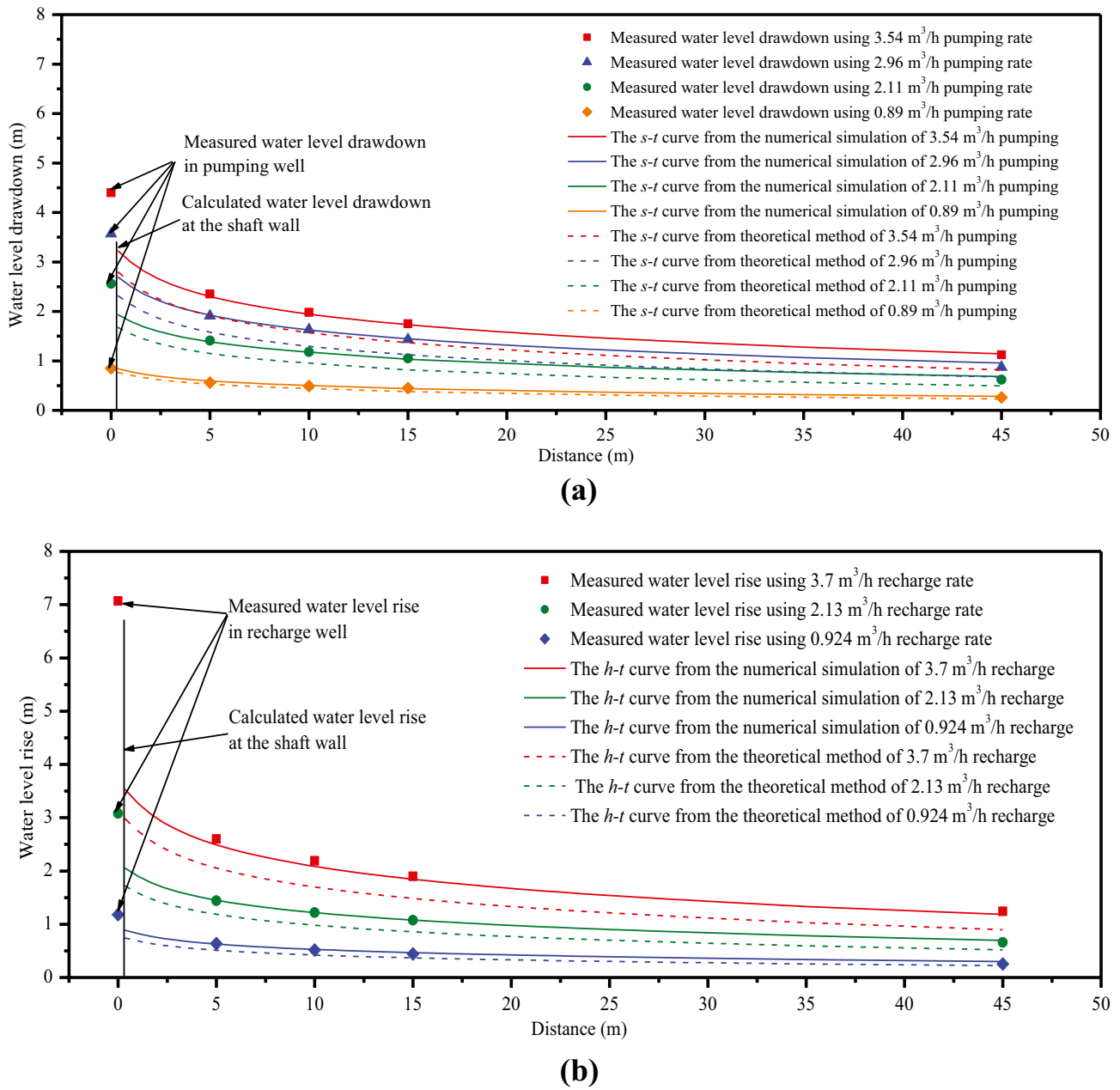
(a)

(b)

Fig. 15 Measured data points and calculated curves of the water level changes in the pumping or recharge well, i.e., H11-1, and the observation wells in the different tests: **a** pumping tests, **b** recharge tests

As shown in Fig. 16 and Table 3, the well losses calculated based on Fig. 15 are close to those calculated using Eqs. (4) and (5), which indicates that Eqs. (4) and (5) are relatively reasonable for the calculation of the well losses in pumping and recharge for the confined aquifer CA3 in the Tianjin area. In addition, as the flow rate increases, the well loss in pumping and recharge increases, but the growth rate of the well-loss value of H11-1 in recharge is higher than that of H11-1 in pumping. For the same flow rate, the well loss in the recharge test is much greater than that in the pumping test, which can be explained by clogging and other unknown problems (such as different clogging effects when water flows through the screen in the pumping and recharge tests) that occurred in recharge.

Table 3 Well-loss values based on the different methods

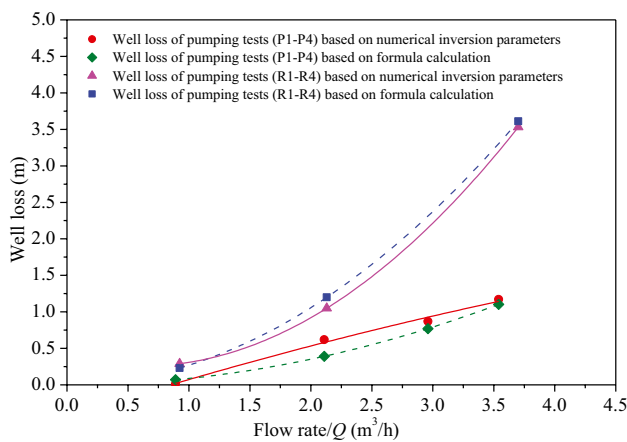| Test number	Flow rate/Q (m³/h)	Numerical back calculation (based on the numerical back-analysis parameters)		Theoretical calculation based on Eq. (2) or (3)	
				BQ	CQ^2
		Water level change at the shaft lining	Well loss	Water level change at the shaft lining	Well loss
P4	3.540	3.23	1.17	3.35	1.10
P3	2.960	2.70	0.87	2.80	0.77
P2	2.110	1.94	0.62	2.00	0.39
P1	0.890	0.84	0.01	0.84	0.07
R4	3.700	3.54	3.53	3.43	3.61
R2	2.130	2.05	1.05	1.97	1.20
R1	0.924	0.89	0.29	0.86	0.23

Fig. 16 Well losses at the different flow rates calculated by the two methods

Conclusions and recommendations

A series of pumping and recharge field tests were conducted for the silt and silty sand confined aquifer in Tianjin to verify the feasibility and effectiveness of recharge in the confined aquifer. The relationships between the single-well recharge and pumping methods, the determination of the hydrogeological parameters, the pressure recharge, and the well loss in recharge were analyzed. The conclusions can be summarized as follows:

- It is feasible to recharge the confined aquifer in Tianjin. The natural recharge rate of the third confined aquifer at this site in Tianjin was approximately 4.2 m³/h. Pressure recharge can effectively improve the recharge efficiency, which is at least 6 m³/h, and can reduce the number of recharge wells and recharge costs. When pressure recharge is needed, both the recharge well and the adjacent observation wells should adopt the method of grouting to seal the gap between the shaft lining and the borehole to obtain a higher recharge pressure and recharge rate and prevent failure of the well.

- For same pumping/recharge rate, the shapes of the depression cone and the recharge cone are almost identical when the distance from the well is larger than 5 m. When the distance from the well is within 5 m, the cone value of the recharge water level rise is slightly larger than that of the depression cone curve, which may be caused by a certain degree of clogging in the confined aquifer around the well in the recharge process. In practical engineering, the hydrogeological parameters obtained from measured drawdown data using pumping tests can be used to predict the water level rise during recharge tests.

- The clogging effect easily occurs in the recharge process, and it directly influences the recharge efficiency and service life of the recharge well. To prevent clogging and ensure the recharge efficiency of the recharge well in long-term operation, the recharge well needs to be pumped back regularly.

- Based on the results of the single-well pumping and recharge tests, the permeability coefficient (k) and unit water storage coefficient (Ss) obtained by the numerical back-analysis method are more accurate than those obtained using the Cooper-Jacob method. For both methods, the permeability coefficient (k) obtained from the single-well pumping test is slightly larger than that obtained from the single-well recharge test, which is probably due to the clogging effect during recharge. In addition, because of the well storage effect, the permeability coefficient (k) obtained by the Cooper-Jacob method is slightly larger than that derived by the numerical back-analysis method, and the unit water storage coefficient (Ss) obtained by the Cooper-Jacob method is much larger than that derived by the numerical back-analysis method.

- Based on the results of the single-well pumping and recharge tests under natural conditions, well-loss values can be calculated by the theoretical and numerical methods, and the well losses derived from the two methods are similar. As the flow increases, the well-loss value in pumping and recharge increases, but the growth rate of the well-loss value in recharge is higher than that in pumping. At the same flow rate, the well loss in the recharge test is much greater than that in the pumping test, which can be explained by the clogging effect and other problems that occurred in recharge. In addition, Eqs. (4) and (5) can be used to calculate of the well losses in pumping and recharge for the third confined aquifer in the Tianjin area.

Declarations

Conflict of interest The authors declare no competing interests.

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