Influence of artificial recharge in a phreatic aquifer on deep excavation dewatering: a case study of Dongguantou Nan Station in Beijing, China

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Abstract

Dewatering in deep excavation projects induces groundwater-level drops and the loss of groundwater resources. A series of multi-well pumping-recharge tests were carried out in a phreatic aquifer in Beijing (China) to study the feasibility and effectiveness of artificial recharge applied to dewatering projects and to understand the influence of artificial recharge on deep excavation dewatering especially. During the tests, the abstraction and recharge quantity were almost equal. The abstraction was positively correlated with the injection. Under the conditions of significant groundwater-level difference and excellent hydraulic conductivity in the gravel strata, the injected water mainly seeped towards the excavation sites and quickly induced an increase in abstraction quantity. For example, to maintain the groundwater level in the excavation pits at 15 m above mean sea level, the water abstraction rate from the pits increased by 21,702 m^3/day (i.e., increased rate of about 32%) compared with the corresponding case without recharge. The results show that it is feasible to conduct artificial recharge to infiltrate all the pumped water into the pumped aquifer and simultaneously maintain the excavation pits in dry workable conditions; artificial recharge has the advantage of mitigating groundwater overexploitation and helping the goal of sustainable use of water resources. To ensure the successful operation of the pumping-recharge system, an analytical method was proposed to predict the discharge rate (or quantity) under the combination of pumping and recharge based on steady-state and Dupuit assumptions. The usefulness of this method was demonstrated with data from field tests.

Introduction

In the past few decades, groundwater resources have been overexploited to meet municipal, industrial, and agricultural usage (Chaudhuri and Roy 2018; Mays 2013). Long-term groundwater overdraft has induced groundwater level drops, seawater intrusion (Bakker 2010; Jasechko et al. 2020; Sherif et al. 2012), land subsidence (Galloway and Burbey 2011; Xu et al. 2017), and a series of environmental and geological disasters. Beijing, China, is suffering from groundwater overexploitation (Feng et al. 2013; Sun et al. 2014; Wei et al. 2018; Zhou et al. 2013), in which dewatering measures

during deep excavations have caused a large quantity of groundwater to be drawn from aquifers and lost (Xu et al. 2019; Zhang et al. 2015). Therefore, during deep excavation, recovering the pumped water and replenishing the aquifers are of great significance to mitigate groundwater overexploitation in Beijing.

Artificial recharge technology was initially proposed for aquifer storage and recovery (Bouwer 2002; Dillon 2005; Forghani and Peralta 2018; Muppidi et al. 2020). It is considered to be an efficient method to minimize groundwater level decline and mitigate dewatering-induced settlement in deep excavation engineering (Wu et al. 2018; Zeng et al. 2019a; Zhang et al. 2017a). In the artificial recharge technology, pumped groundwater is injected into the same aquifer using recharge wells around the protected structures to compensate for groundwater drawdown and relieve or even eliminate dewatering-induced soil compression (You et al. 2018; Zhang et al. 2017b; Zheng et al. 2018). Powrie and Roberts (1995), Phien-Wej et al. (1998), Zeng et al. (2019b),

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and Zheng et al. (2019) carried out field tests to investigate groundwater behaviour and the response of soils during artificial recharge in confined aquifers; they proved that artificial recharge could effectively restrict dewatering-induced drawdown and ground settlement. To improve its feasibility and effectiveness in deep excavations, pumping-recharge system technology was proposed and developed in practice (Lopik et al. 2020; Song et al. 2020; Wang et al. 2012a, b; Zhang et al. 2017a).

The current research on artificial recharge applied in deep excavations mainly focuses on controlling land subsidence for environmental protection (Wang et al. 2012a, b). Such artificial recharge is mostly performed in confined aquifers, and the recharge wells are arranged around the protected facilities to increase the confined aquifer's water level to control the ground settlement (Gambolati and Teatini 2015; Shi et al. 2016; Zhang et al. 2017a, b). However, there have been few studies on artificial recharge in which the recovered pumped water from deep excavation dewatering was used to mitigate groundwater overdraft and improve groundwater storage in cities (Gao et al. 2019; Zhong et al. 2019).

The application of this type of recharge aims to recover all the groundwater abstracted during excavation dewatering and return it to its original aquifer and simultaneously maintain excavation pits in dry workable conditions (the groundwater level must be controlled below the bottom of the excavation pit throughout the excavation process). In some water-rich sand or gravel aquifers, the water inflow into the foundation pits can be enormous, so it is challenging to simultaneously inject all the abstraction water into the pumped aquifer. Additionally, the arrangement of the recharge wells is generally restricted by construction conditions and they are always located within the influence radius of pumping wells, which affects the dewatering effect of excavation pits. Due to having different purposes, the current research on recharge used to control land subsidence cannot guide the design and construction of recharge used to increase aquifer storage. Hence, to recover the pumped groundwater during excavation dewatering without endangering construction and alleviate urban groundwater over-exploitation, the feasibility and effectiveness of this type of recharge need to be further investigated.

Part of the Fengtai District, Beijing, is located on the alluvial-fan plain of the Yongding River. The Quaternary sediments are mainly composed of thick sand and gravels layers, which have good hydraulic conductivity. In some projects, such as the deep excavation projects conducted at metro station sites in the Fengtai District, Beijing, reported by Shi et al. (2015) and Wang et al. (2013), there is only a phreatic aquifer within the depth of excavation. In a phreatic aquifer, groundwater movement is driven by the transformation of gravitational potential energy into kinetic energy and groundwater flows from a high level to a low level, which

conforms to the conservation of energy law (Chen et al. 2011; Dupuit 1863). If pumping and recharge are carried out in a phreatic aquifer while the recharge wells are placed within the influence radius of pumping wells, part of the injected water will flow back to the excavation pit area under the groundwater level difference, which is a complicated situation that needs to be considered. To ensure that all the pumped water is injected into the pumped aquifer successfully and avoid adverse impacts on excavation dewatering, it is necessary to analyze the influence of artificial recharge on deep excavation dewatering when designing a pumping-recharge system, in which accurately predicting the water inflow into the pits (the water amount needs to be abstracted) is critical.

This report presents field tests of pumping and recharge in a phreatic gravel aquifer of the Dongguantou Nan Station of the Beijing Metro Railway. The feasibility of artificial recharge used to recover pumped water during dewatering and increase aquifer storage in a phreatic gravel aquifer was studied. Meanwhile, the groundwater behaviour during the field tests was measured to analyze the relationship between pumping and recharge, and evaluate the influence of artificial recharge on excavation dewatering. Furthermore, under the combination of pumping and recharge, an analytical method for calculating the discharge rate (or quantity) is discussed, based on test parameters and Dupuit assumptions. The results obtained from the tests provide a reference and guidance for designing similar pumping-recharge systems.

Site characterization

Project description

The investigated project is the Dongguantou Nan Station, a transfer station of Line 16 and Fangshan Line, located at the intersection of the Beijing-Shanghai Railway and the West Third Ring Road, Fengtai District, Beijing, China, as shown in Fig. 1. It is a three-story underground island platform station with a maximum excavation depth of 27.4 m below the ground surface (bgs). An air shaft is installed at the north side of the station. The air shaft is a three-story double-span underground structure, and its maximum excavation depth was 27.8 m bgs. Both the station and the air shaft adopted an excavation pit support scheme of "steel support + retaining piles". The environmental conditions of the project site are presented in Fig. 1. The excavation station is surrounded by roads and is adjacent to the planned Fengcao River. There are residential buildings to the south and east of the site, and construction is planned to the northwest of the site. A large green space is located northeast of the site, and it is the preferred recharge site.
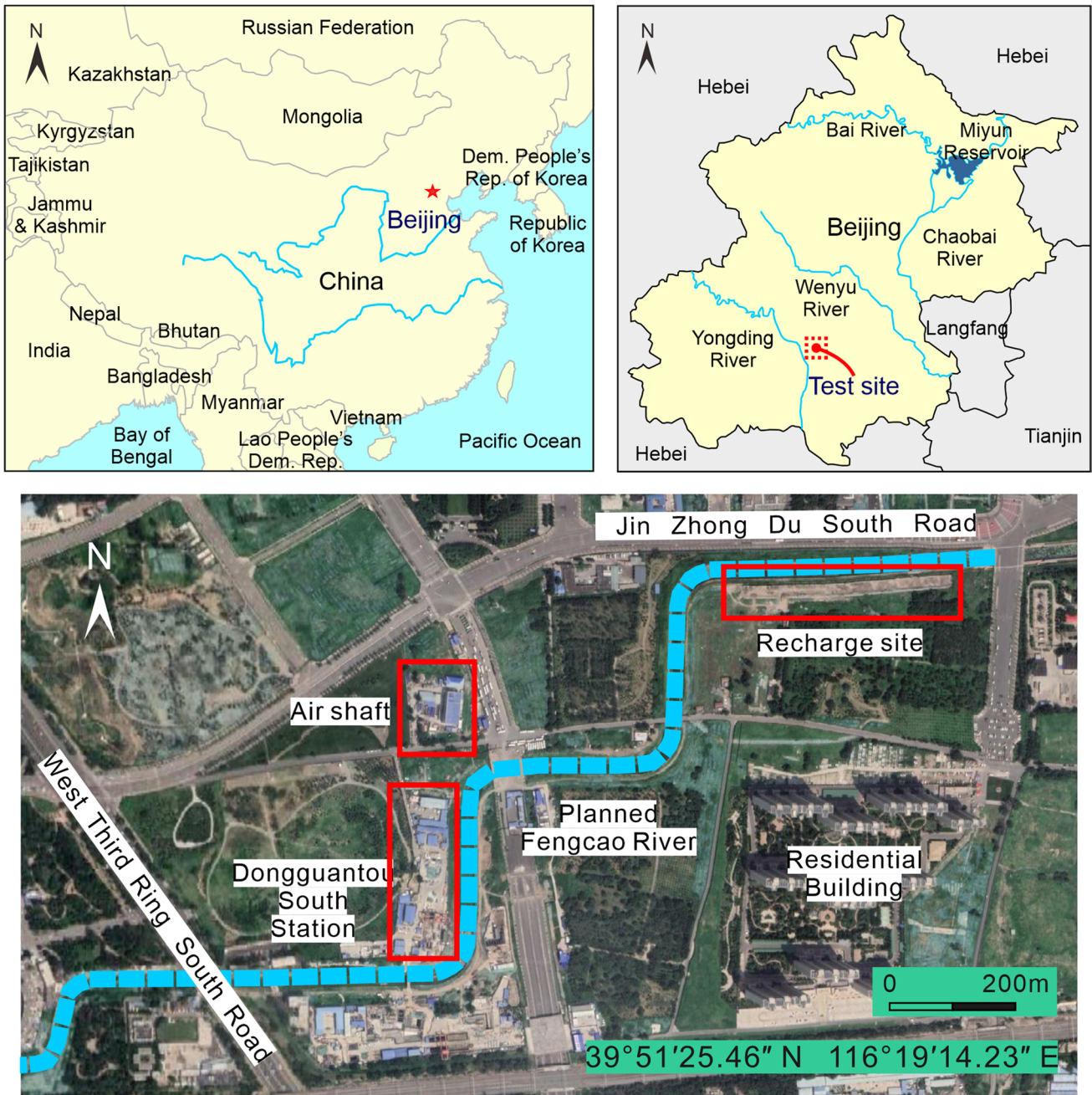
Fig. 1 **a** Location and **b** satellite maps of the test site

Geological and hydrogeological conditions

Figure 2 portrays a typical geological section of the test site. According to the geotechnical investigation report, the Quaternary sediments at this site are stratified. The first layer is an accumulation layer in the upper 3.5 m below the ground surface, including plan fill and miscellaneous fill. The next layer is silty clay extending to a depth of 4.5 m bgs, while beneath this silty clay layer, there is a sand layer to a depth of 6.5 m bgs. Under the sand layer, two gravel layers are

present at the site, to a depth of 39 m bgs. Below these gravel layers, there is a conglomerate layer to a depth of 45 m bgs. The parameters of each layer are listed in Table 1. The unit weight γ was obtained by laboratory tests. The cohesion (c) and friction angle (φ) were determined from the triaxial tests. The hydraulic conductivity, K, of soils was obtained by field pumping tests in fully penetrating wells, including steady and unsteady flow pumping. The assumptions and methods of Dupuit (1863), Neuman (1975), and Thesis (1935) were applied in the inference of hydraulic conductivity.
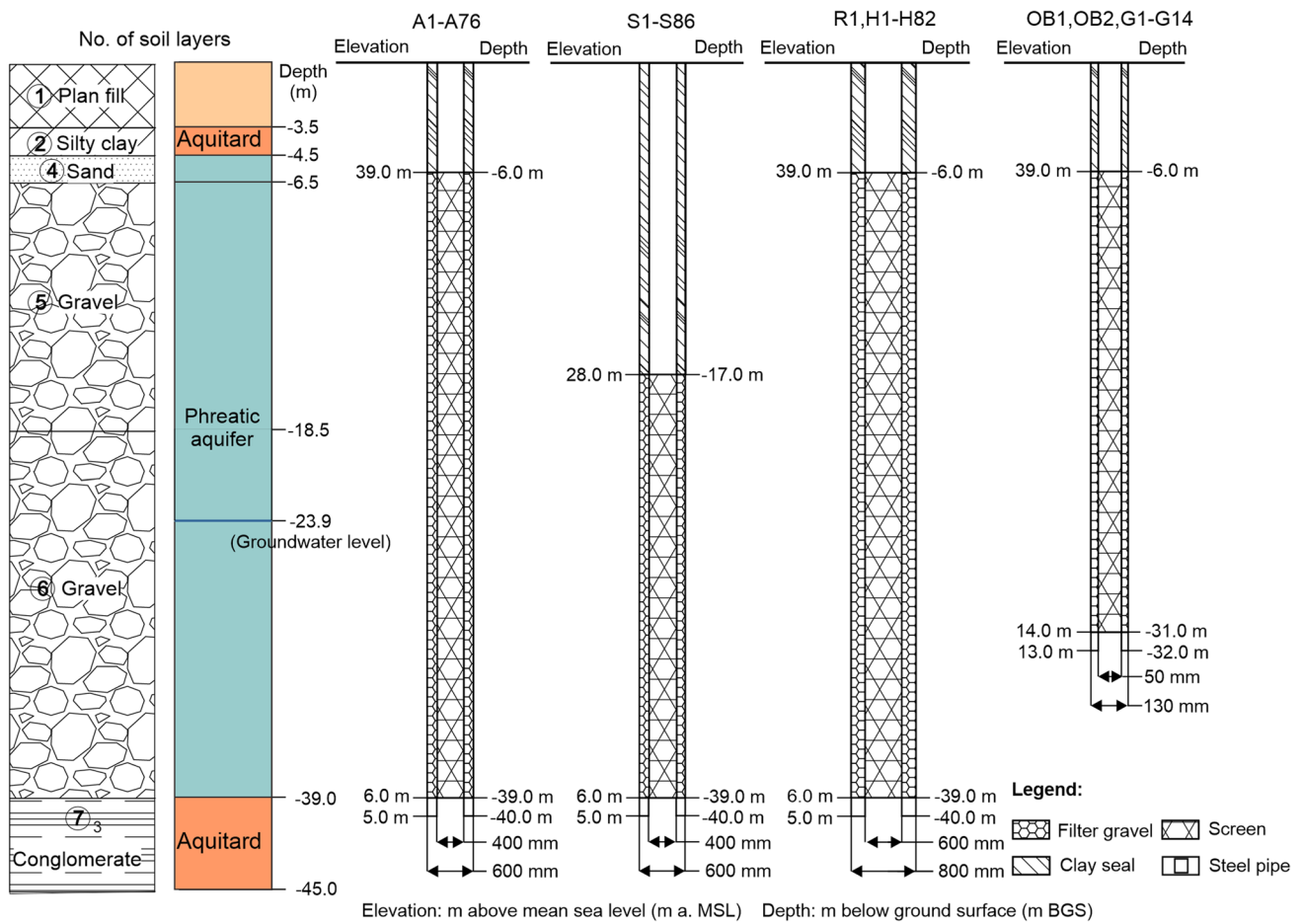
Fig. 2 Typical geological profile and structure of the test wells

As shown in Fig. 2, there is only one phreatic aquifer at this site. The phreatic aquifer mainly consists of gravels (layers 5 and 6) within a 40–80 mm grain size (the coarsest grain size is approximately 150 mm) and has a thickness of 14.45–16.10 m. The water level of the phreatic aquifer ranges from 19.45 to 21.10 m above mean sea level (amsl), which changes with precipitation and seasons. The groundwater runoff direction is from west to east, with a hydraulic gradient of 1.5–2.0‰.

Field tests

Background introduction and single-well recharge test

Based on excavation dewatering, a series of multi-well pumping-recharge tests were carried out to evaluate the effectiveness of artificial recharge during pumping in a phreatic gravel aquifer and to study the influence

Table 1 Soil layers and parameters on the test site

Layer	Elevation of bottom (m amsl)	Thickness (m)	Unit weight γ (kN/m³)	Cohesion c (kPa)	Friction angle φ (°)	Hydraulic conductivity K (m/day)
1 Plan fill	41.10	0.1~3.6	19.5	8.0	10.0	-
2 Silty clay	39.08	0.3~2.6	19.55	20.5	34.5	0.00432
4 Sand	36.46	0.1~3.3	20.5	0	35	80
5 Gravel	25.76	10.3~11.8	21.0	0	40	420
6 Gravel	6.16	17.2~19.4	22.5	0	45	420

of artificial recharge on excavation dewatering. Before the multi-well tests, a single-well test was conducted to investigate the maximum recharge rate with gravity in the phreatic gravel aquifer (without artificial recharge pressure) and verify the feasibility of artificial recharge in the stratums.

In the single-well recharge test, one recharge well (labelled R1) and two observation wells (labeled OB1 and OB2) were installed. R1, OB1, and OB2 were arranged in a straight line, and the distances from OB1 and OB2 to R1 were 5 and 15 m, respectively. The single-well recharge test lasted for 6 h. The recharge test on R1 was initiated with a recharge rate of 60 m^3/h without an artificial recharge pressure, and the recharge rate increased by 5 m^3 every half hour.

Multi-well pumping-recharge test

Arrangement of multi-well test

Figure 3 presents the arrangement of the test wells. The field tests were based on the excavation dewatering projects of Dongguantou Nan Station and the air shaft. Eighty-six pumping wells (labeled S1–S86) were installed around the station, and 44 pumping wells (labeled S20–S64) were utilized in the test. Meanwhile, the 76 pumping wells that were arranged around the air shaft (labeled A1–A76) were utilized in the tests. The spacing of neighboring pumping wells was 7 m. According to the dewatering schemes, the maximum abstraction quantities of the station and the airshaft were estimated to be 160,000 m^3/day. The maximum recharge rate of the single recharge well obtained from field tests with gravity was approximately 2,400 m^3/day (section 'Feasibility and maximum recharge rate with gravity'). Based on previous studies (Gao et al. 2019; Weber and Chapuis 2013), well interference and uncertainty were considered; the design's single-well recharge rate was reduced by 20%; thus, 84 recharge wells were needed. Because the width of the recharge site was 14 m and the length was 350 m, the recharge wells were divided into two rows 10 m apart with 41 wells in each row. Referring to the artificial recharge tests carried out in deep excavation projects by Zeng et al.(2019a) and Zheng et al. (2018) and the design standards, the spacing of neighboring recharge wells was determined to be 8 m.

In addition, according to construction conditions, 14 observation wells were placed in the test site to monitor the groundwater level changes. Observation wells G1, G2, and G3 were located in a straight line towards the southwest.
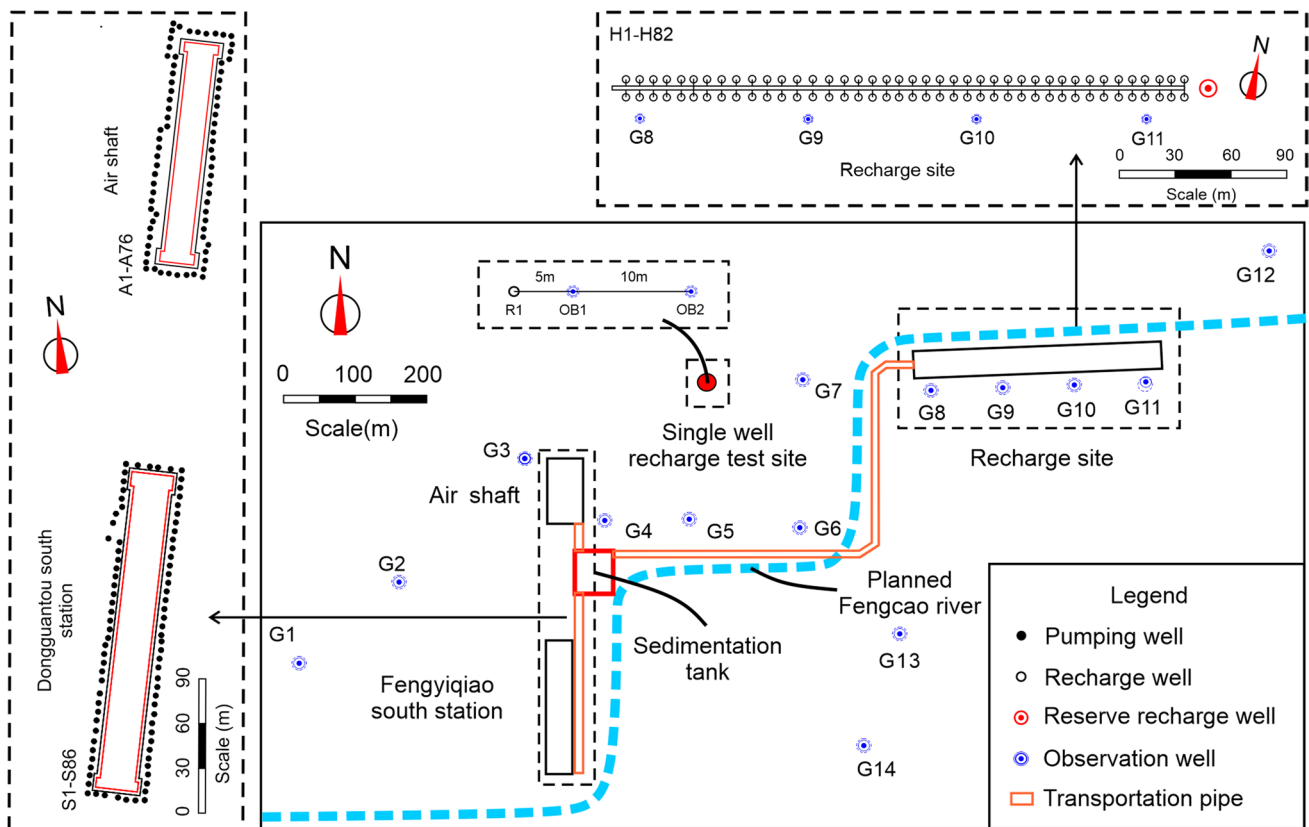

Fig. 3 Arrangement of the test wells

Between the excavation sites and the recharge site, wells G4, G5, G6, and G7 were arranged along the Fengcao River to monitor the groundwater level changes affected by the coupling influence of pumping and recharge. Wells G8, G9, G10, and G11 were arranged in a straight line from west to the east near the recharge wells. In addition, well G12 was established in the northeast corner of the test site. Wells G13 and G14 were installed on the south side. An ultrasonic flow meter was installed on the pumping collection pipe, and the recharge quantity was also monitored. Groundwater levels and abstraction and recharge quantities were observed once a day.

Test procedure

Figure 4 shows the vertical sketch of the pumping–recharge system at the test site. Specifically, the groundwater extracted from the station and the air shaft was collected (Figs. 4 and 5a) and transported to the recharge site after sedimentation treatment (Figs. 4 and 5b) through closed pipelines (Figs. 4 and 5c). Subsequently, the pumped water entered the recharge collection pipe in the recharge site (Figs. 4 and 5d), where it flowed into the branch pipes with gravity (no artificial pressure) from west to the east (Figs. 4 and 5e). Each branch pipe was connected to a recharge well, in which the pumped

water was infiltrated into the aquifer through well screens (Figs. 4 and 5f).

The tests, which lasted for 40 days, consisted of four stages, as detailed in Table 2. According to the excavation program, the pumping wells of the station and the air shaft had already extracted groundwater for a period; therefore, the groundwater level in excavation pits had reached a stable state of 15 m amsl before the test. In stage 1, pumping wells A1–A60 were operated with a discharge rate of 50 m³/h per well, and S20–S64 were operated with a discharge rate of 63 m³/h per well. The abstraction water from pumping wells A1–A60 were infiltrated into the phreatic aquifer through recharge wells H1–H82; note that wells H1–H82 operated throughout the tests. Pumping wells A1–A60 and S20–S64 worked during stage 2. All the abstractions from the pumping wells were injected into the phreatic aquifer in stage 2 and this remained the same in the following stages. In stage 3, the number of pumping wells surrounding the station was increased, A1–A76 were activated, and the discharge rate was increased to 63 m³/h per well. Wells S20–S64 remained the same as in stages 1 and 2. In stage 4, the number of wells and the rates of pumping were generally reduced. Wells A1–A60 were operated, and their discharge rates were reduced to 50 m³/h per well. The operation of the pumping wells
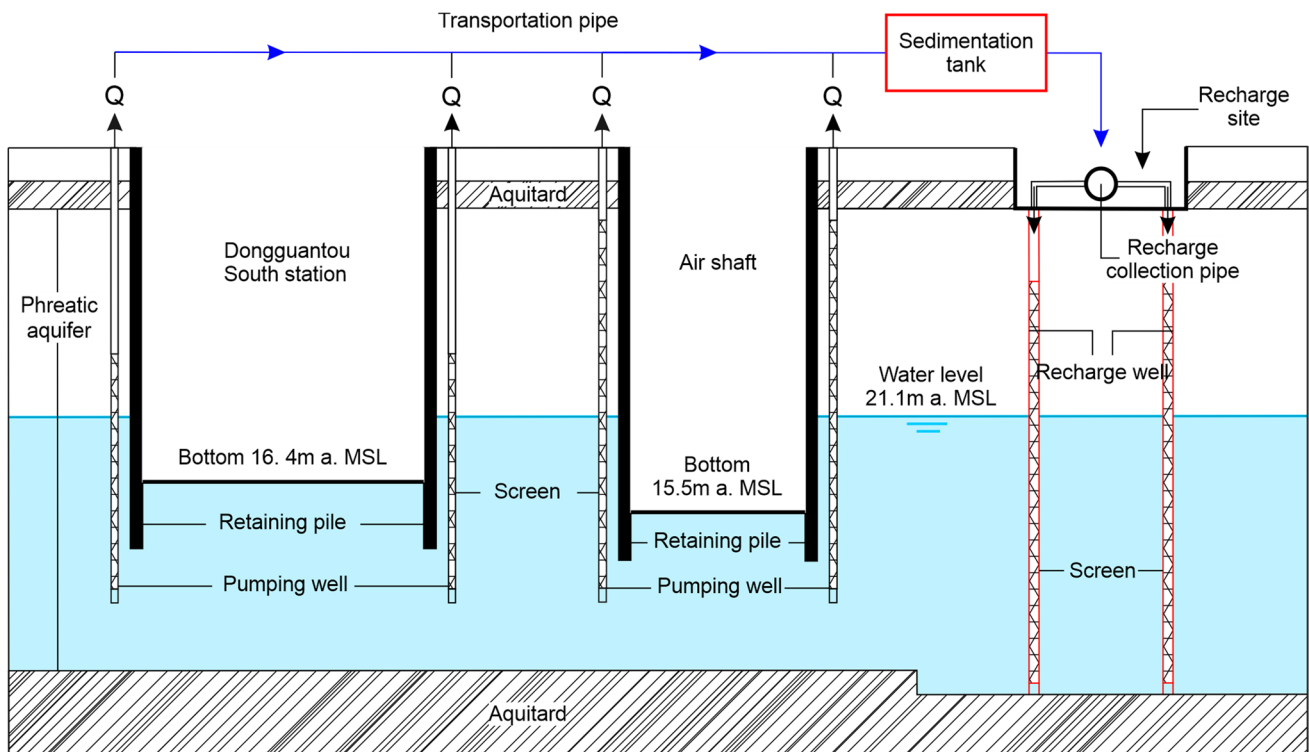

Fig. 4 Vertical sketch of the pumping–recharge system

Fig. 5 Test equipment for the multi-well pumping-recharge tests: **a** abstraction collection tank; **b** sedimentation tank; **c** transportation pipe; **d** recharge site; **e** recharge collection pipe; **f** recharge well

around the air shaft were reduced, only wells S30–S53 were operated, and their discharge rates were also reduced to 50 m³/h per well.

Well structures

Table 3 lists the details of the test wells, and the different types of well structures are shown in Fig. 2. The depths of all the pumping and recharge wells were 45 m bgs, and they were inserted into the impenetrable conglomerate layer. To ensure the maximum recharge rate, the screen length of recharge wells was 33 m, roughly covering gravel layer 5 and gravel layer 6. Moreover, pumping wells A1–A76 had screen lengths of 33 m, and pumping wells S1–S86 had screen lengths of 22 m. In addition, there were 14 observation wells, the depths of the observation wells were 32 m bgs, and they had screen lengths of 25 m. The screens of all the test wells were located in the phreatic aquifer.

Table 2 Four stages of the multi-well pumping-recharge test

Stage	Pumping wells	Number of wells pumping	Discharge rate per pumping well (m³/h)	Recharge situation	Recharge wells	Observation wells	Duration (days)
1	A1–A60	60	50	Recharge	H1–H82	G1–G14	10
	S20–S64	44	63	No recharge			
2	A1–A60	60	50	Recharge	H1–H82		5
	S20–S64	44	63				
3	A1–A76	76	63	Recharge	H1–H82		3
	S20–S64	44	63				
4	A1–A60	60	50	Recharge	H1–H82		22
	S30–S53	24	50				

Table 3 Test wells information

| Item	Type	Depth (m bgs)	Screen location	Screen top elevation (m amsl)	Screen bottom elevation (m amsl)	Screen length (m)	Casing radius (mm)	Borehole radius (mm)	No. of wells	Wells
Single well recharge test	Recharge well	40	Phreatic aquifer	39	6	33	529	800	1	R1
	Observation well	32		39	14	25	50	130	2	OB1–OB2
Multi-well pumping-recharge test	Recharge well	40		39	6	33	529	800	82	H1–H82
	Pumping well	40		28	6	22	400	600	162	S1–S86
				39	6	33				A1–A76
	Observation well	32		39	14	25	50	130	14	G1–G14

Results and discussion

Feasibility and maximum recharge rate with gravity

Figure 6 presents the variation of the groundwater level rise measured in well R1 during the single-well recharge test. The groundwater level rise in the recharge well increased rapidly in the first 1–2 h, gradually slowed down, and finally stabilized. When the groundwater level rise stabilized at approximately 14.5 m, the recharge rate of the single well was 100 m³/h (2,400 m³/day). The recharge capacity in the recharge well is strong; moreover, the final increase of groundwater level in well R1 was 14.5 m, and the groundwater levels in observation wells OB1 and OB2 rose by 0.50 and 0.15 m, respectively, proving that the phreatic aquifer has good hydraulic conductivity. As stated previously, it can be inferred that the phreatic aquifer can accept a large quantity of injection, and it is suitable for artificial recharge.

Abstraction and recharge quantities

The daily quantities of abstraction and recharge during the multi-well pumping tests (section 'Multi-well pumping-recharge test') are shown in Fig. 7, in which the abstraction quantity (the total discharged water) is negative, and the recharge quantity (the total injected water) is positive. Before the test, the abstraction water was 66,943.7 m³/day without artificial recharge. In stage 1, water abstracted from pumping wells A1–A60 was infiltrated into the phreatic aquifer through recharge wells H1–H82, and the abstraction quantities of the pits increased gradually. In stage 2, not only the water abstracted from pumping wells A1–A60 but also wells S20–S24 was injected into the phreatic aquifer, and the abstraction water of the pits continuously increased. To prevent groundwater flow into the excavation pits, in stage 3, the number of pumping wells and their discharge rates were increased. Simultaneously, as all of the pumped water was transported to the recharge site, the injection into the aquifer also increased. Therefore, the abstraction of the pits was significantly increased to a maximum of 186,314 m³/day, and the recharge quantity reached a maximum of 185,983 m³/day at the same time. In stage 4, as the number of pumping wells and their discharge rates were generally decreased, the abstraction and recharge quantities decreased together to a stable state. The abstractions of the pits were stabilized at approximately 88,646.1 m³/day. During the tests, when the water inflow into the pits trended to increase, the pumping wells in operation were added immediately so that dry workable conditions for the excavation pits could be maintained. Hence, groundwater levels around the pits did not apparently rise, and excavation work was not affected as a result. Moreover, the correlation between abstraction and recharge

Fig. 6 Variation of the water-level rise measured in test wells during the single-well recharge test
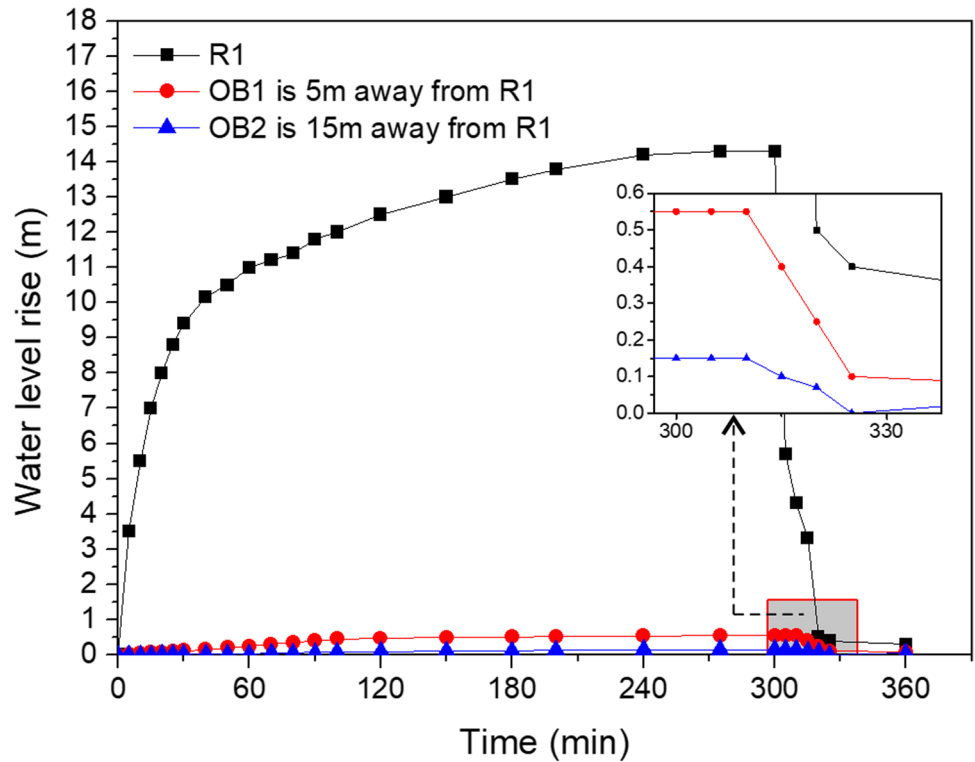
quantities was determined; the abstractions from the pits were positively correlated with the recharge quantities. If the injected water increases, the abstraction of groundwater will increase.

In Fig. 7, the quantity difference is given by subtracting the daily recharge quantity from the daily abstraction

quantity, which is referred to as the water loss in the transportation process, and it ranged from 200 to 636 m³/day. The ratio of the loss quantity to abstraction quantity varied from 0.26 to 0.65%, as shown in Fig. 8, and the ratio of the recharge quantity to the abstraction quantity was between 99.34 and 99.73%. Almost all the abstraction water was

Fig. 7 Time-history curves of abstraction and recharge quantities during the multi-well tests
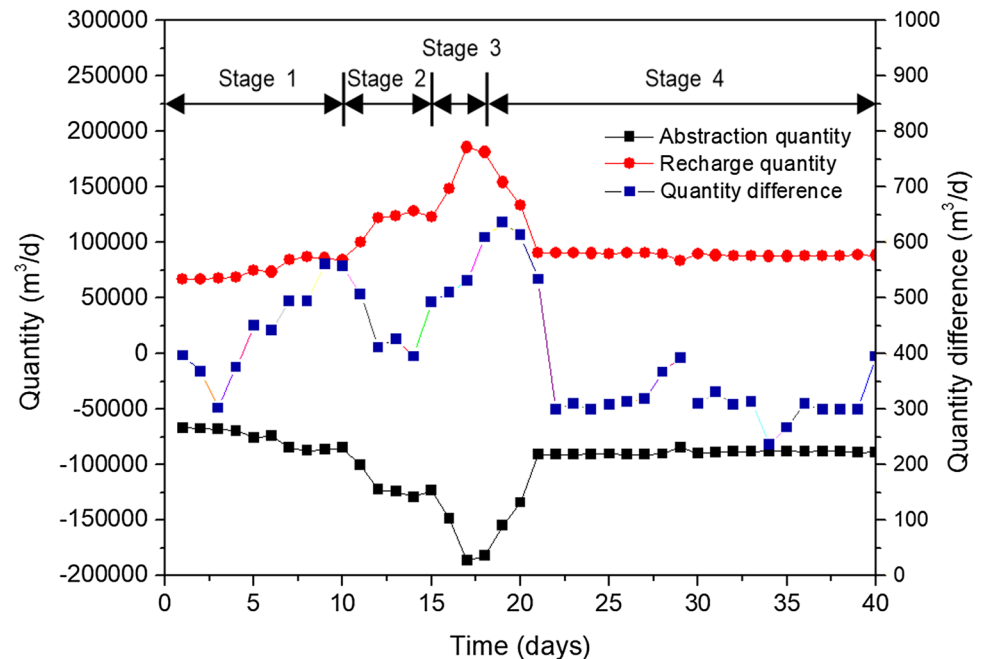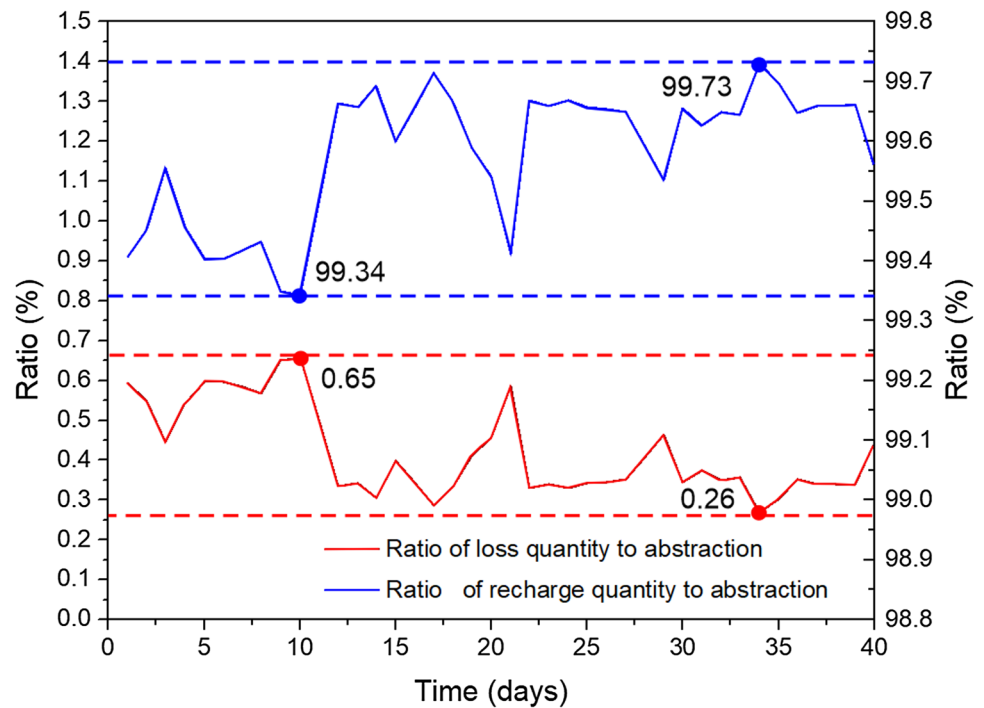
Fig. 8 The ratio of loss quantity and recharge quantity to abstraction

injected into the aquifer, replenishing the aquifer during deep excavation dewatering.

To maintain the excavation pit at a safe groundwater level of 15 m amsl, before the test, the amount of water that was needed to be pumped from the pits was approximately 66,943.7 m^3/day. However, when the pumping-recharge test reached a steady state in stage 4, the abstraction quantity rose to 88,646.1 m^3/day. Compared with the case without recharge, the abstractions from excavation pits increased by 21,702.4 m^3/day, and its rate of increase was 32.42%.

As stated previously, the results show that it is feasible to apply artificial recharge to a deep excavation dewatering to recover the abstracted water and replenish aquifers. In the tests, pumping and recharge are carried out in a phreatic gravel aquifer, in which artificial recharge increases the abstractions from excavation pits. The abstraction quantity is positively correlated with the recharge quantity. To ensure the successful operation of the pumping-recharge system and avoid adverse impacts to excavation pits, determining appropriate abstraction and recharge rates (or quantities) is crucial. Furthermore, spare pumping and recharge wells should be prepared to ensure smooth and safe construction.
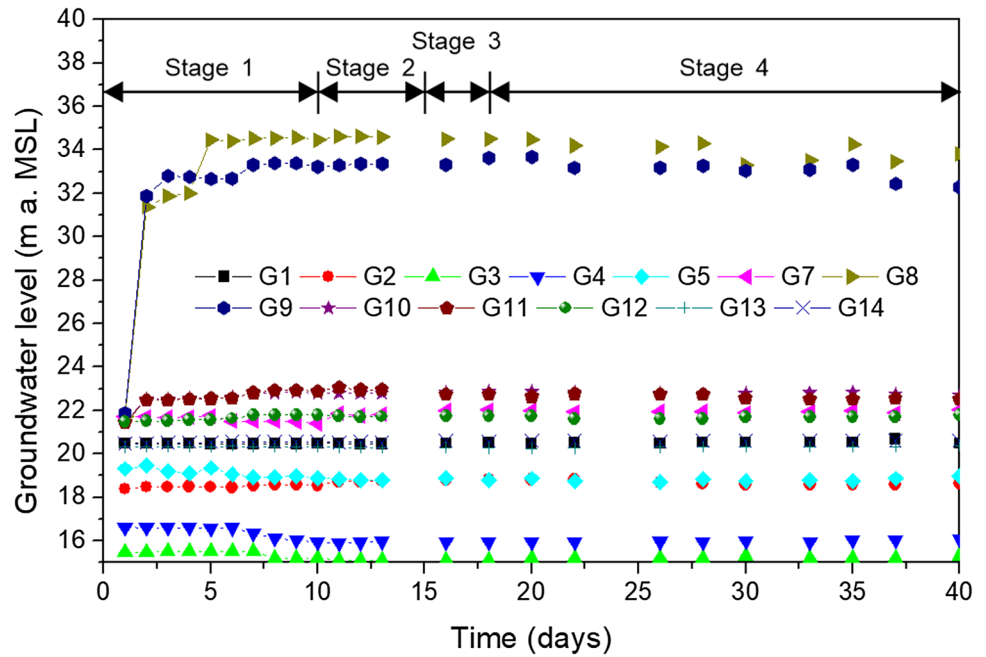
Groundwater levels

To investigate the influence of artificial recharge on groundwater levels at the test site, the groundwater level fluctuations of each observation well during the test were compiled, as shown in Fig. 9. Because the observation data of G6 were abnormal, it was not adopted for subsequent analysis.

During the test, the groundwater levels of wells G2, G7, G8, G9, G10, G11, G12, G13, and G14 rose gradually with the increase in the recharge quantity in stage 1, stage 2, and stage 3; then, as the abstraction quantity was decreased in stage 4, the injected water was reduced, and the groundwater levels dropped accordingly. Specifically, the groundwater levels of wells G8 and G9 rose significantly. It can be inferred that they received replenishment and mainly fluctuated with the change in injection. In contrast, the groundwater levels in wells G3, G4, and G5 dropped with increasing abstraction quantity and rose with decreasing abstraction quantity. Furthermore, wells G2, G3, G4, and G5 were below the aquifer's initial water level all the time, indicating that pumping wells mainly controlled their water levels. In addition, wells G1, G13, and G14 had almost no fluctuations; changes in abstraction and recharge quantities had little influence on them.

As shown in Fig. 10, wells G8, G9, G10, and G11 had apparent responses to recharge in the first stage, especially wells G8 and G10; their rises reached 12.715 and 11.345 m, respectively. Wells G4, G5, and G7 also rose significantly. The recharge quantity continuously increased during the second and third stages, but the groundwater level changes in observation wells gradually became insignificant. In the fourth stage, as the number of wells pumping and the discharge rates were reduced, the water transported to the recharge site also decreased; therefore, the injection decreased sharply, and the groundwater levels of wells G8, G9, G10, and G11 dropped. However, groundwater levels in the other observation wells rebounded slightly. Finally, the

Fig. 9 Groundwater level in each observation well during the multi-well tests

groundwater levels in the test site reached relatively stable values. Figures 9 and 10 show that the artificial recharge mainly affected the groundwater levels around the recharge wells and had little influence on groundwater levels in the excavation sites or other sites. G3 was placed adjacent to the air shaft pit, and its groundwater level was constantly below

15 m amsl without obvious changes. This proves that it is possible to conduct artificial recharge to recover the pumped water during deep excavation dewatering and simultaneously maintain dry workable conditions at excavation sites.

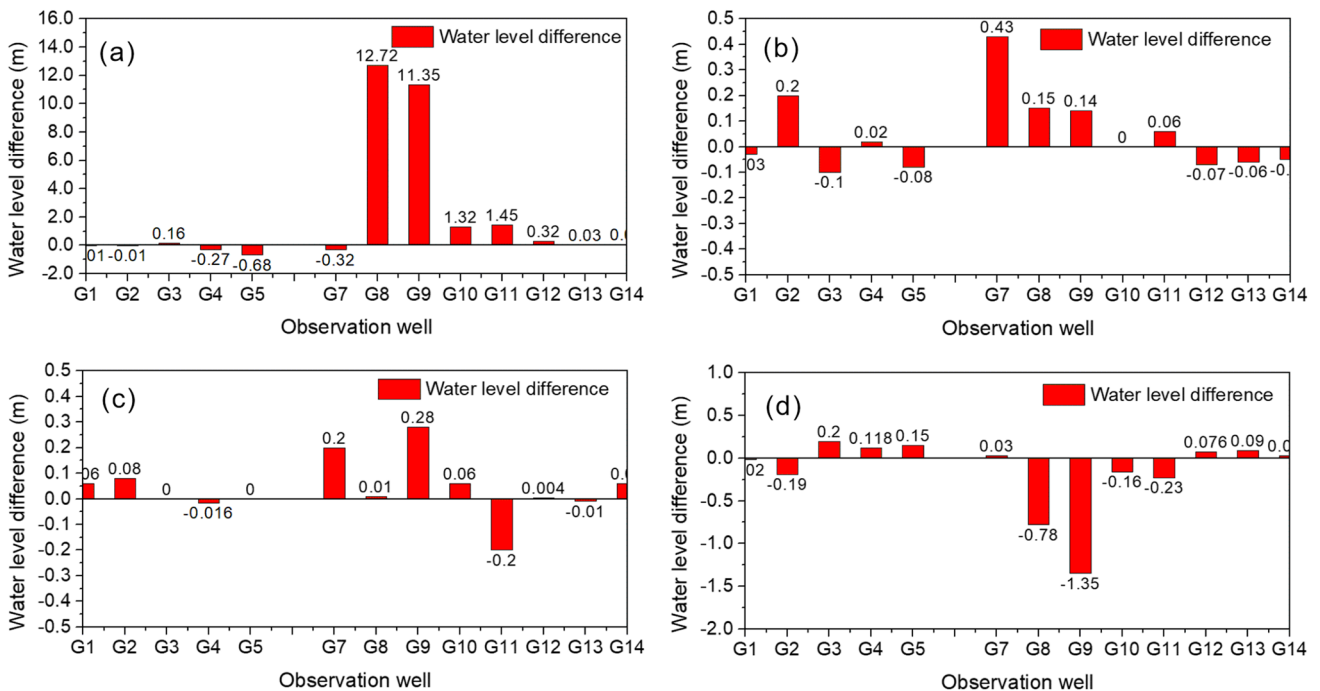Compared to the aquifer's initial water level, the groundwater level in the excavation sites was stable at 15 m amsl,

Fig. 10 Groundwater-level changes of each observation well in the test site: **a** after the completion of stage 1; **b** after the completion of stage 2; **c** after the completion of stage 3; **d** after the completion of stage 4

which was a drop of 6.1 m. The average groundwater level in the recharge site was approximately 27.8 m (from the four observation wells), which was an increase of 6.7 m. The abstraction quantity and recharge quantity (source and sink items) in the test were almost equal, and the groundwater-level increases and drops were similar, indicating that the phreatic aquifer can meet the requirements and that it is suitable as an aquifer being recharged.

Seepage state of injected water

Figure 11 depicts the groundwater-level contour map after the competition of each stage based on observation data. Under the combined effect of pumping and recharge, the groundwater formed a pumping depression cone around the excavation pits, with the lowest groundwater level at the center point of approximately 15.12 m amsl, and a recharge rising cone was formed at the recharge site, with the highest groundwater level at the center point of nearly 34.6 m amsl. The groundwater level difference between the recharge site and the excavation pit was the largest in the test site, with a maximum of 19.48 m. Groundwater movement in a phreatic aquifer transforms gravitational potential energy into kinetic energy (Chen et al. 2011; Dupuit 1863; Handel et al. 2016). When the groundwater level is higher, the potential energy of the groundwater is greater, and the groundwater seepage

velocity is faster. Due to the large groundwater level difference and the excellent hydraulic conductivity in gravel strums, it can be inferred that the injected water would mainly seep in the direction of excavation sites.

According to Darcy's law, the groundwater seepage velocity was $v = ki = k \cdot \Delta h/l$, where i is the hydraulic gradient, $i = \Delta h/l$; Δh (m) is the head loss; and l (m) is the length of the seepage path. Figure 12 shows the groundwater seepage velocity from the rising cone center to each observation well outside the recharge site. The groundwater seepage velocities of wells G3, G4, G5, and G7 were apparently higher than others, in which well G3 was adjacent to the excavation pit, and wells G4, G5, and G7 were located between the recharge site and the excavation pits. The seepage velocity is much smaller than the actual groundwater velocity, but it can reflect the actual groundwater velocity to some extent. The results show that the injected water seeped faster in the direction of excavation pits and slower in other directions. Thus, it can be deduced that the injected water seeped into the excavation pits and infiltrated the pumping wells, resulting in a significant increase in the abstraction quantities mentioned previously.

Wells G8, G9, G10, and G11 were placed in the recharge site. Wells G8 and G9 rose significantly during the test; their highest elevations reached 34.61 m and 33.67 m amsl, respectively, which are to the tops of these recharge wells'
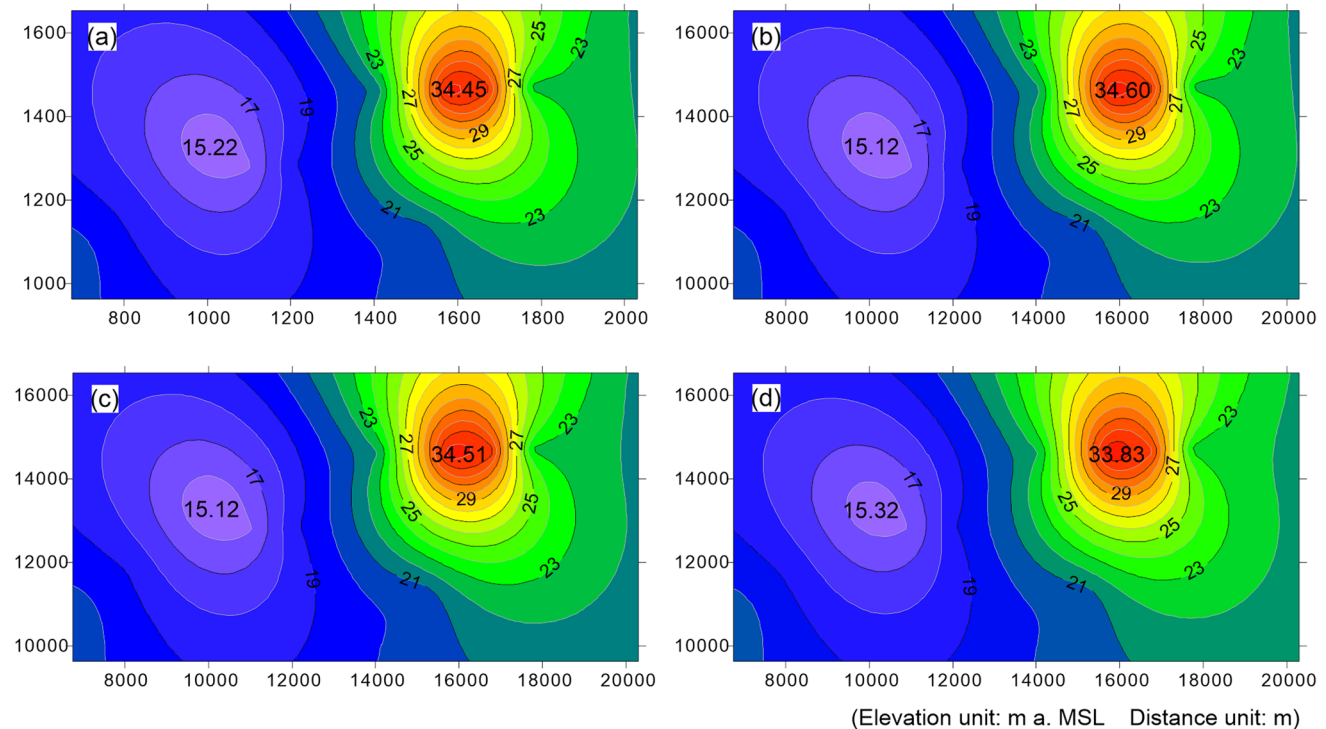

Fig. 11 Groundwater-level contour map in the test site: **a** after the completion of stage 1; **b** after the completion of stage 2; **c** after the completion of stage 3; **d** after the completion of stage 4

Fig. 12 The seepage velocity from the rising-cone center to each observation well outside the recharge site: **a** after the completion of stage 1; **b** after the completion of stage 2; **c** after the completion of stage 3; **d** after the completion of stage 4
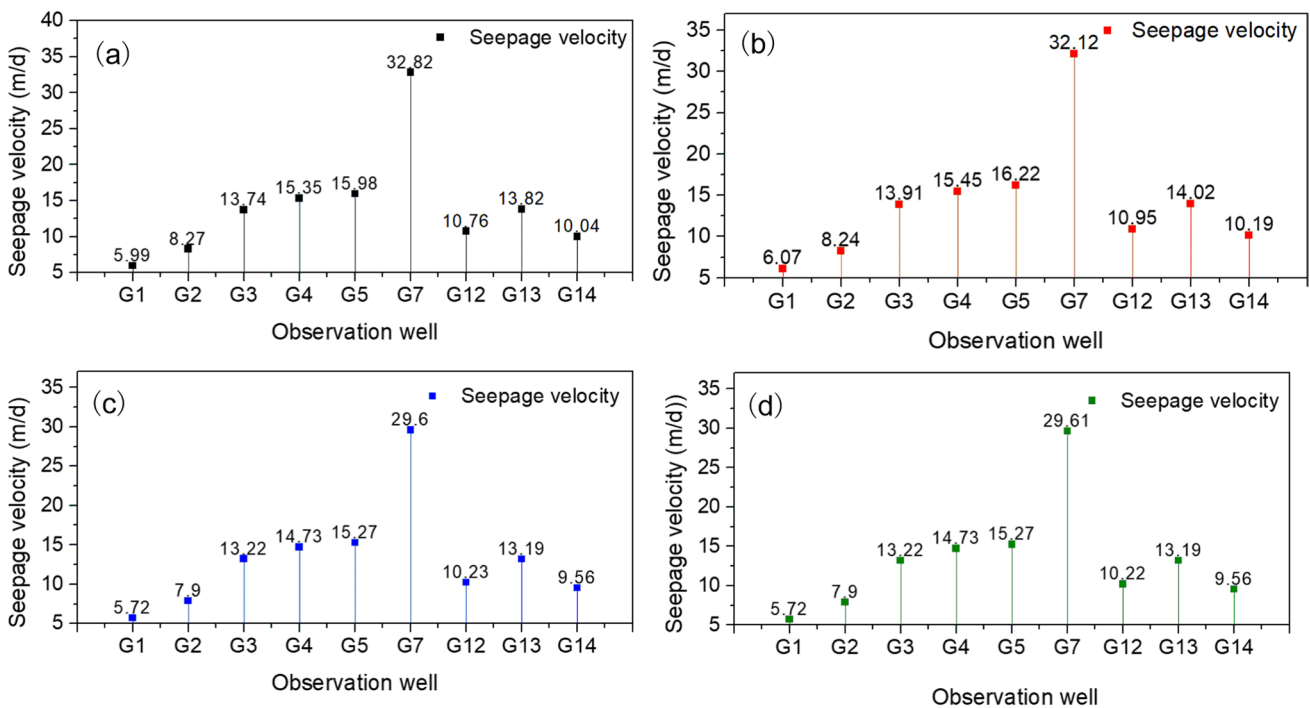
screens. However, groundwater levels in wells G10 and G11 fluctuated between 21 and 23 m amsl. The reason for that is the pumped water that was transported to the recharge site and entered the recharge collection pipe; the water flowed from the recharge collection pipe to branch pipes with gravity (without artificial pressure) and then infiltrated into the phreatic aquifer through the recharge wells. The injected quantity of each recharge well was decreased from west to east causing the groundwater levels to drop from G8 to G11. There were large groundwater level differences in the recharge site, which helped the injected water re-seep to the excavation sites and is not beneficial to the safe operation of the pumping-recharge system. It is recommended that recharge wells be installed with pressure control in similar projects to ensure that injection water levels of recharge wells are the same, which would help keep the injected water seepage evenly in all directions, thereby mitigating the re-flow phenomenon.

Water inflow under the combination of pumping and recharge

Based on the foregoing analysis, artificial recharge carried out in the pumped aquifer influenced the excavation dewatering, in which the abstraction quantity increased by 32.42%, although the distance of the excavation site and the recharge site exceeded 600 m. To ensure the success of the

pumping-recharge system and maintain excavations in dry workable conditions all the time, and to improve the applicability of this type of artificial recharge, it is crucial to study the influence of recharge on deep excavation dewatering, predict the discharge rate (or quantity), and then rationally design a pumping-recharge system.

In stage 4, pumping and recharge operated steadily on the 25th–40th days of the test. The test parameters remained constant. The abstraction quantity fluctuated between 87,756.7 and 90,818.5 m^3/day, while the recharged quantity changed from 87,520.7 to 90,504.1 m^3/day. The groundwater levels in each observation well were relatively stable; hence, this is a suitable period for investigating the influence of artificial recharge on excavation dewatering.

This analysis is based on the Dupuit theory (Bakker 2010; Dupuit 1863; Handel et al. 2016; Xue 2010), including assumptions, namely: (1) the phreatic aquifer is approximately horizontal, homogeneous, and infinite; (2) the lower confining bed is horizontal and infinite; and (3) the vertical component of groundwater seepage velocity can be ignored. Considering that when a pumping well has pumped water for a period, a stable depression cone is formed; the drawdown at point i in the cone of depression caused by the pumping wellis

$$s_i = \frac{Q}{2\pi KM} \ln \frac{R}{r} \tag{1}$$

where s_i (m) is the drawdown at a point i in the depression cone caused by the pumping well; Q (m³/day) is the flow rate of the pumping well; K (m/day) is the hydraulic conductivity of the aquifer; M (m) is the thickness of the aquifer; R (m) is the radius of influence; and r (m) is the radius of the pumping well.

If there are n pumping wells with the same structure and discharge rate, considering the interference and superposition of wells, then

$$s_i = \sum_{i=1}^{n} \frac{Q_i}{2\pi KM} \ln \frac{R_i}{r_i} \tag{2}$$

Equation (2) has another form in a phreatic aquifer

$$H_0^2 - h_i^2 = \sum_{i=1}^{n} \frac{Q_i}{\pi K} \ln \frac{R_i}{r_i} \tag{3}$$

where H_0 (m) is the thickness of the phreatic aquifer; and h_i (m) is the thickness of the aquifer at a point i in the depression-cone. In addition, R can be obtained from the Kusakin formula

$$R = 2s_w \sqrt{H_0 K} \tag{4}$$

where s_w (m) is the drawdown in the pumping well.

Recharge can be regarded as an inverse process of pumping. Similarly, it was assumed that there are m recharge wells with the same structure and recharge rate. Thus, under the combined effect of pumping and recharge, the groundwater level at point i is

$$H_0^2 - h_i^2 = \sum_{i=1}^{n} \frac{Q_i}{\pi K} \ln \frac{R_i}{r_i} - \sum_{j=1}^{m} \frac{Q_j}{\pi K} \ln \frac{R_j}{r_j} \tag{5}$$

Based on the preceding assumptions, Eq. (5) can be simplified as

$$H_0^2 - h_i^2 = \frac{nQ_i}{\pi K} \ln \frac{R_i}{r_i^*} - \frac{mQ_j}{\pi K} \ln \frac{R_j}{r_j^*} \tag{6}$$

where r_i^* (m) is the equivalent distance of pumping wells, $r_i^* = \sqrt[n]{r_1 \cdot r_2 \cdot r_3 \cdots r_i}$; r_j^* (m) is the equivalent distance of recharge wells, $r_j^* = \sqrt[m]{r_1 \cdot r_2 \cdot r_3 \cdots r_j}$.

Therefore, under the combination of pumping and recharge, the groundwater level in the excavation pit reaches the expected drawdown, and the amount of water that needs to be abstracted is

$$Q' = \frac{\pi K (H_0^2 - h_i^2)}{\ln R_i - \ln r_i^*} + \frac{mQ_j (\ln R_j - \ln r_j^*)}{\ln R_i - \ln r_i^*} \tag{7}$$

where Q' (m³/day) is the water inflow of the pits (the amount of water needs to be abstracted) affected by artificial recharge under steady-state conditions and stated assumptions.

Based on this project, the groundwater level in the excavation pits was expected to remain below 15 m amsl ($h_i = 9$ m). As almost all the water abstracted from the excavation pits is injected into the recharge wells, Eq. (7) gives $Q' = 90,822.52$ m³/day for $h_i = 9$ m, while Eq. (3) gives $Q = nQ_i = 66,498.16$ m³/day. As shown in Fig. 13, the abstraction quantity Q_c was calculated by the preceding analytical methods, based on the parameters from the multi-well pumping-recharge tests. These values are then compared with the abstraction quantity Q_m measured in the field tests (Cashman and Preene 2010). It shows that the calculated abstraction quantity is within a factor of two times greater than or less than the abstraction quantity measured in the tests, and the calculated value is approximately equal to the measured value, indicating that the calculation method is feasible. The abstraction water affected by artificial recharge has increased by 24,324.36 m³/day, an increase of 36.58%. The calculated value is slightly larger than the experimental value of 32.42%. The reason is that the well radius r appears in the form of a logarithm in the Dupuit formula (Dupuit 1863; Xue 2010); when the well radius increases, the discharge (or recharge) rate increases slightly with it, so the well radius has a little influence on the flow rate. Moreover, in the Dupuit assumption, the vertical velocity of the groundwater movement and the existence of a hydraulic jump are not considered (Dupuit 1863; Xue 2010). However, the actual situation is not so. This analytical method could evaluate the discharge rate (or quantity) when the parameters of aquifers and wells are known. Note that this method's premise is that the source and sink terms in the aquifer should be approximately equilibrious to reach a stable state. Otherwise, an inaccurate result will be achieved.

In summary, conducting artificial recharge during deep excavation dewatering can recover the pumped water,
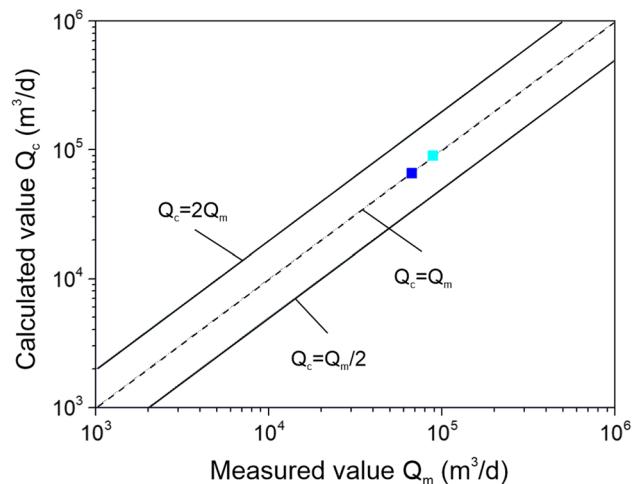

Fig. 13 Comparison of calculated and measured discharge quantity from the multi-well pumping recharge tests

increase aquifer storage, and alleviate groundwater overdrawn. However, as the test and the analysis show, artificial recharge will affect the excavation dewatering and increase abstraction quantity. Therefore, it is crucial to predict the influence of artificial recharge on deep excavation dewatering and then rationally design the pumping-recharge system. The analysis methods used in this study can provide a reference and guidance.

Discussion

Because of the widespread groundwater overexploitation in cities and dewatering projects in deep excavations (to prevent groundwater seepage into excavation pits), urban groundwater levels have been continuously declining. This report provides a method of infiltrating pumped water into subsurface water bodies (pumped aquifers) through recharge wells. In contrast, this method is different from other artificial recharge studies conducted during deep excavation dewatering to mitigate land subsidence. The differences are as follows: (1) the purpose of this artificial recharge is to infiltrate the pumped groundwater into the aquifers during dewatering and realize the sustainable use of groundwater resources instead of controlling dewatering-induced settlement and protect the surrounding structure (Shi et al. 2016; Wu et al. 2018; Zeng et al. 2019a); (2) this artificial recharge was conducted in a phreatic aquifer rather than confined aquifers, as was done in other similar studies (Wang et al. 2012a, b; Zhang et al. 2017a; Zheng et al. 2018); therefore, the vertical velocity of groundwater movement and elastic water release were not considered in the analysis and calculation (Boulton 1954; Neuman 1975; Gao et al. 2019); (3) unlike other artificial recharge situations, in which recharge wells were arranged around protected buildings (Zeng et al. 2019a, b), in these tests the recharge site was chosen in a green space; (4) the distance between the pumping wells and the recharge wells exceeded 600 m; (5) the recharge rate (or quantity) of the recharge wells was relatively high, far greater than the quantities reported in Zhang et al. (2017a and b) and Zheng et al. (2018 and 2019) in their tests. The results and analysis stated in the preceding show that artificial recharge infiltrated all of the pumped water to the pumped aquifer instead of draining it through municipal pipelines, increasing aquifer storage and benefiting the sustainable use of groundwater resources. Dry workable conditions in excavation pits can be maintained by a reasonable pumping-recharge system to ensure smooth and safe construction.

In this report, the well structures, e.g., pumping wells, recharge wells, and observation wells were described, the arrangement of the test wells was illustrated, the correlation between abstraction quantity and recharge quantity was determined, the analytical method of calculating the discharge rate under the combination of pumping and recharge was provided, and some problems encountered during the tests and recommendations were discussed, so these can be referenced in similar projects. The artificial recharge conducted at this test site is one example of deep excavation engineering, and the experience given is only for a phreatic aquifer. The feasibility and applicability of such pumping-recharge systems in confined aquifers are still unclear. Therefore, theoretical and experimental studies of artificial recharge in deep excavation projects need to be further investigated to better help the continuous use of water resources.

Conclusion

This report presents a series of multi-well pumping-recharge tests in a phreatic gravel aquifer outside the Dongguantou Nan Station of the Beijing Metro. The feasibility and effectiveness of artificial recharge used to increase aquifer levels and mitigate urban groundwater overdraft during dewatering was studied. As part of this effort, the influence of artificial recharge on the excavation dewatering effect was analyzed. The following conclusions can be drawn:

1. In the case of a phreatic gravel aquifer with excellent hydraulic conductivity, water can be injected into the aquifer with gravity (without artificial pressure). The highest recharge rate with gravity for a single well was 2,400 m^3/day. The abstraction quantity and recharge quantity (source and sink items) in the tests were almost equal, and the groundwater-level rise and drop were similar, indicating that the phreatic aquifer was suitable for recharge as the aquifer was being recharged. Artificial recharge is an efficient method to increase groundwater levels and aquifer storage. In this project, water was infiltrated into the pumped aquifer by 84 recharge wells, at recharge rates of up to 185,983 m^3/day. During deep excavation dewatering, artificial recharge was conducted to recover the abstracted water and increase aquifer storage to mitigate groundwater overdraft; almost all of the extracted water was injected into the pumped aquifer and dry workable conditions in the excavation pits were maintained.

2. The abstraction quantity is positively correlated with the recharge quantity. Pumping and recharge were conducted simultaneously within a phreatic aquifer, resulting in a significant increase in the abstraction water. To maintain the pits at a safe groundwater level of 15 m above mean sea level, the amount of groundwater that needs to be pumped rose by 20,458 m^3/day compared to the conditions without recharge; this is an increase

of 32.42%. Additionally, artificial recharge generally raised the test site's groundwater levels; the groundwater level difference between the recharge-rising cone and the pumping-depression cone was 19.48 m, which was the chief reason that the injected water seeped towards the excavation pits and infiltrated the pumping wells, increasing the abstraction quantity of the excavation pits. To mitigate the re-seepage phenomenon, recharge wells should be installed with pressure control to ensure that the groundwater levels of recharge wells are the same, which would help even out the injected water seepage in all directions.

3. Artificial recharge provides a method of infiltrating the pumped water into subsurface water bodies (the pumped aquifer) through recharge wells, avoiding the loss of groundwater resources, and is beneficial to the sustainable management of urban water resources. To ensure the successful operation of the pumping-recharge system and maintain the excavation in dry workable conditions all the time, it is crucial to determine the appropriate abstraction and recharge rates (or quantities). An analytical method of calculating the discharge rate (or quantity) under the combination of pumping and recharge was provided to facilitate smooth and safe construction, which is based on steady state and Dupuit assumptions. The usefulness of this method was demonstrated with data from field tests.

Declarations

Conflicts of interest All authors declare that: (1) no support, financial or otherwise, has been received from any organization that may have an interest in the submitted work; and (2) there are no other relationships or activities that could appear to have influenced the submitted work.

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