Experimental Study on Groundwater Dewatering and Recharge of Deep Foundation Pit of a Subway Station in Jinan Water-Rich Area

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Abstract. A large amount of groundwater dewatering is beneficial to the foundation pit construction, but it will cause surface collapse, waste groundwater resources and damage the groundwater environment. In order to maintain the stability of groundwater level and the safety of surrounding buildings in the construction of deep foundation pit, the combination of dewatering and recharge is adopted. Taking the construction of deep foundation pit of a subway station in Jinan water-rich area as an example, the theoretical model of recharge quantity, stratum parameters and groundwater level was obtained through the backward derivation of the precipitation calculation model. 78 dewatering wells and 78 recharge wells were designed, and the on-site dewatering and recharge teat was carried out. The test results show that the water level of a single dewatering well decreases sharply in the initial stage of precipitation, and then the depth drops gradually to a stable level, and finally maintains a fixed value. The water inflow of a single well ranges from 34.54~57.07 m^3/d, and the groundwater level can be lowered to 1.53~2.79 m below the foundation pit floor. The recharge volume of a single well in the natural recharge state is 146.88~ 241.44 m^3/d, and the higher the recharge pressure, the stronger the recharge capacity of the recharge well. Through field test research, it is found that the recharge capacity of single well of recharge well is much greater than the pumping capacity of single well of dewatering well, and 56 recharge wells can make the recharge rate reach 100%, which optimizes the dewatering and recharge design of deep foundation pit.

Keywords: dewatering, recharge, dewatering well, recharge well, field test, recharge capacity.

1. Introduction

With the rapid development of economic construction, ground space is increasingly tight, and urban underground space has become the construction space of public transportation and foundation engineering, and the construction of these deep and large underground engineering mostly adopts deep foundation pit excavation [1-5].Since the beginning of the 21st century, with the large-scale construction of urban underground rail transit and major transportation hubs, the foundation pit engineering of underground engineering construction has become more and more complicated. In the construction, the control of groundwater level and the protection of surrounding environment have become the difficulty and focus of construction. In the early stage of underground engineering construction, it is necessary to reduce the groundwater level of the aquifer in the excavation soil layer which may cause the bearing water outburst of foundation pit bottom. However, with the decrease of the groundwater level, the effective gravity stress of the soil below the original water level of the foundation increases, leading to the consolidation of the soil. Furthermore, uneven settlement, tilt, cracking and other phenomena occur on the ground and buildings within the influence range of precipitation, which endangers the construction safety and normal use [6-9]. Large-scale dewatering will cause the waste of groundwater resources and damage the groundwater circulation system.

Jinan is famous for its spring water. It has four major spring areas: Baotu Spring Area, White Spring Area, Baimai Spring Area, and Changxiao Water Source Area. It is a world-renowned "Spring

City". The subway construction is faced with the double difficulties of engineering construction and spring water protection. Taking a long time and a wide range of dewatering during the deep foundation pit construction of the subway station will not only cause security risks to the strata and buildings, but also have an irreversible adverse impact on the underground spring water system of Jinan City. The most direct and effective way to control the stability of groundwater level is groundwater recharge. The combination of dewatering and recharge is adopted for foundation pit dewatering. Dewatering is done inside the foundation pit, and the extracted groundwater is recharged to the outside of the foundation pit after water treatment.

Groundwater dewatering and recharge belong to groundwater dynamics. Theis [10] proposed the unsteady well flow formula of intact confined water wells, which laid the foundation for the theory of unsteady groundwater runoff. Based on Theis formula, Jacob [11] established the stable flow solution of confined aquifer in infinite area considering the vertical recharge of aquifer. Li and Neuman [12] proposed a five-layers aquifer system, and obtained the closed analytical solution by using Laplace transform. Malama et al. [13,14] deduced the analytical solution considering multi aquifer system according to different hydrogeological conditions. He et al. [15] verified that in the case of recharge, inserting the filter pipe into the soil layer with good water permeability can improve the precipitation effect by the finite element method. Niu et al. [16] found that the ground settlement around the foundation pit de-creased significantly after recharge, and the ground settlement near the recharge well de-creased more significantly by the Processing Modflow. Huang and Xu [17] conducted three-dimensional simulation on the dewatering and recharge process of deep foundation pit, and found that the recharge amount was directly proportional to the recovery of water level. However, numerical simulation only provides a guidance for recharge design, which is lack of practical significance. Li and Wang [18] calculated the hydraulic conductivity and permeability coefficient of deep con-fined aquifer according to the pumping test, and calculated the maxi-mum recharge volume of the single well recharge test.

However, analytical calculation cannot analyze the reinjection operation process in complex strata. At present, the design of groundwater recharge in the deep foundation pit is still based on personal subjective judgment, and there are still some misunderstandings in the number, spatial layout, pressure value and other aspects of dewatering and recharge, lacking theoretical support and normative guidance. Field dewatering and recharge test is one of the most important methods to study the design of water supply and drainage in the deep foundation pit. Lu et al. [19] studied the layout and recharge rate of the replenishment well through field pumping and replenishment test before construction. Wang et al. [20] determined the overall design scheme of dewatering and recharge through the dewatering-recharge test, and controlled the settlement of subway column piles within 10 mm. Li et al. [22] studied the duration process of water level change and settlement change, as well as the influence rule of dewatering and recharge on surrounding land settlement based on the field test of dewatering and recharge at a subway station in Nantong water-rich area. Guo et al. [22] carried out a recharge experiment from the south of Fengyi Bridge to the end point of Beijing Metro, and the average daily recharge reached 94,627.1 m^3, realizing the same amount of water pumped, which proved the feasibility of water resource protection recharge in the thick gravel diving layer.

Based on the lack of current research on dewatering and recharge of deep foundation pits in water-rich areas, this paper takes the construction of deep foundation pits in a subway station in Jinan water-rich area as the background, and designs a dewatering and recharge scheme based on theoretical calculation. The dewatering capacity and recharge capacity of station foundation pits are obtained through field tests, and the dewatering and recharge design scheme is optimized.

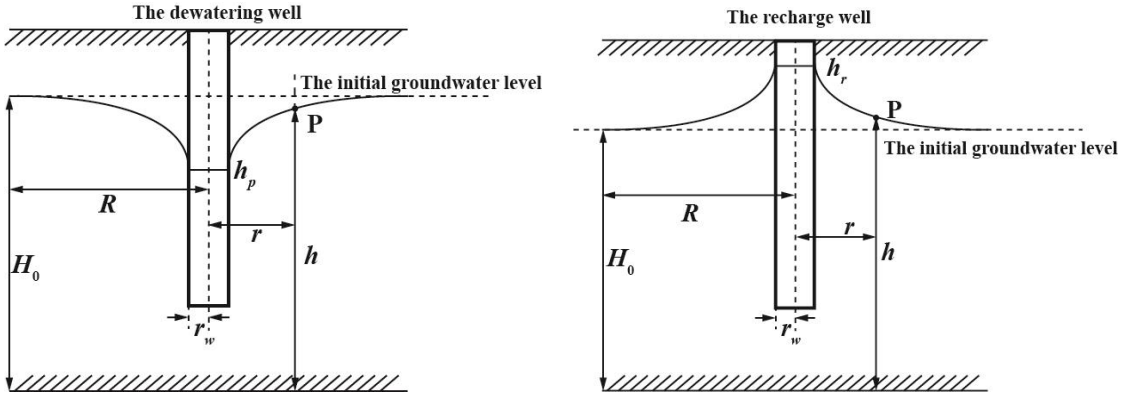
2. Calculation method and recharge equipment

2.1. Calculation method of dewatering and recharge in a phreatic aquifer

Jinan is a city rich in water, with abundant underground springs. In practical engineering, the recharge well is a submersible recharge well because it passes through complex rock and soil layer

and can not completely penetrate the whole aquifer or arrange filter pipes in the whole aquifer. Therefore, the dewatering model and recharge model are established for the dewatering well and recharge well in a phreatic aquifer.

As shown in Fig. 1(a), there is a water-rich aquifer, and the initial groundwater level is H_0. There is a dewatering well in a phreatic aquifer, and the groundwater level around the dewatering well drops. After a period of time, the groundwater level remains stable. The water level in the well is h_p, the influence radius is R, and the flow rate of the dewatering well is Q.



(a) (b)

Fig. 1 The dewatering model and recharge model for the dewatering well and recharge well in a phreatic aquifer. (a) The dewatering model; (b) The recharge model.

According to Darcy's law, groundwater flow in the dewatering well can be obtained:

$$k \cdot 2\pi rh \cdot \frac{dh}{dr} = Q \tag{1}$$

Where k is the permeability coefficient of aquifer and r is the distance from any point P in the aquifer to the center of the dewatering well. h is the water level at point P, and Q is the flow rate of the dewatering well.

By deforming equation (1), we can obtain:

$$h \cdot dh = \frac{Q}{2\pi k} \cdot \frac{1}{r} dr \tag{2}$$

Then, by integrating from the borehole wall r_w ($h = h_p$) to the influence radius R ($h = H_0$), we can get:

$$\int_{h_p}^{H_0} h \cdot dh = \int_{r_w}^{R} \frac{Q}{2\pi k} \cdot \frac{1}{r} dr \tag{3}$$

Where r_w is the distance from the center of the dewatering well to the wall, and R is the influence radius. H_0 is the stable water level outside the influence radius. h_p is the water level at the well wall (Default h_p is the water level in the dewatering well).

In this way, we can get the flow formula of the dewatering well:

$$Q = \frac{\pi k\left(H_0^2 - h_p^2\right)}{\ln\left(\frac{R}{r_w}\right)} \tag{4}$$

Formula (4) is the relationship between the flow rate of the dewatering well, the formation parameters and the groundwater level. Similarly, the calculation and analysis of the recharge well can be regarded as the inverse process of the dewatering well. As shown in Figure 2(b), at any point P in the aquifer from the recharge well, the water head is h. According to Darcy's law, we can get:

$$k \cdot 2\pi rh \cdot \frac{dh}{dr} = -Q \tag{5}$$

Then, by integrating from the borehole wall rw (h=hr) to the influence radius R (h=H0), we can get:

$$\int_{h_p}^{H_0} h \cdot dh = \int_{R}^{r_w} \frac{Q}{2\pi k} \cdot \frac{1}{r} dr \tag{6}$$

Where h_r is the water level at the recharge well wall (Default h_r is the water level in the recharge well).

In this way, we can get the flow formula of the recharge well:

$$Q = \frac{\pi k\left(h_p^2 - H_{p0}^2\right)}{\ln\left(\frac{R}{r_w}\right)} \tag{7}$$

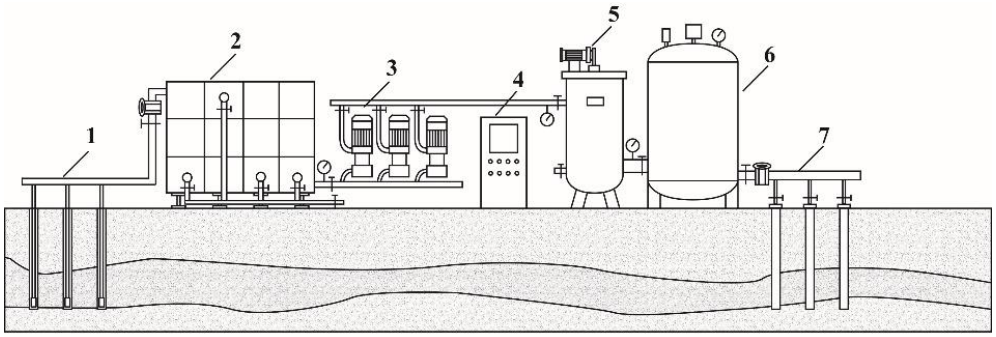
Formula (4) and Formula (7) are flow expressions of dewatering well and recharge well in a phreatic aquifer. Combined with engineering stratum conditions and design requirements, it can be used to calculate, analyze and design dewatering and recharge of deep foundation pit.

2.2. An integrated system of dewatering and recharge

In view of the requirements and difficulties of groundwater recharge in Jinan rich-water area, we independently developed an integrated system of dewatering and recharge. As illustrated in Fig. 2, the integrated system of dewatering and recharge is com-posed of seven parts: a pumping system, an assembled water tank, a variable frequency pressure system, a cleaning and filtering system, a recharge pressure tank, a recharge well system and a central control system.

The pumping system is used to extract groundwater and transfer it to the assembled water tank. And the assembled water tank is used to hold the extracted groundwater and plays a transitional role. The groundwater recharge power is provided by the variable frequency pressure system. The cleaning and filtering system can clean and filter groundwater to improve recharge quality. The recharge pressure tank is used for the diversion, and balance of water and pressure to avoid the frequent opening of the pump system. After being pressurized, filtered, and diverted by the equipment, the groundwater is injected into the recharge well system, which then seeps into the under-ground aquifer. In addition, we can control the opening state and operation mode of the whole system through the central control system, and can view and process the recharge data. In the following section, we will introduce each part of the system in detail.

The integrated system can realize intelligent automatic control according to the monitoring data, including the switch of the variable frequency pressure system, the adjustment of the recharge pressure, the adjustment of the pump speed, the switch of the cleaning and filtering system. Through the central control system, the operation of the precipitation and recharge is ensured in a stable, visual and controllable state. The operation of the whole system does not require staff to operate on site, and it can be remotely monitored and adjusted by computer or mobile phone.



1.The pumping system
2.The assembled water tank
3.The variable frequency pressure system
4.The central control system
5.The cleaning and filtering system
6.The recharge pressure tank
7.The recharge well system

(a)



(b)

Fig. 2 The integrated system of dewatering and recharge. (a) The parts of the integrated system of dewatering and recharge; (b) The field application of the integrated system of dewatering and recharge.

3. Field tests of dewatering and recharge

3.1. Project overviewof the deep foundation pit

The project is a deep foundation pit of a subway station in Jinan. The is a two-story underground island station, which adopts deep foundation pit construction. The main scale of foundation pit is 512 m × 21.7m, the well has a span of 15m, the excavation area is 11,276.8 m2, and the depth of foundation floor is 18.27m (as shown in Fig. 3).



Fig. 3 The deep foundation pit of a subway station in Jinan

The foundation pit adopts the structure of underground diaphragm wall and inner supporting enclosure. According to the preliminary investigation report, 78 dewatering wells are arranged inside the foundation pit according to the dewatering calculation model, with the spacing between the wells being 12~15 m and the depth of the wells being 21~25 m. The diameter of the dewatering well is 325 mm. The upper 6 m of the dewatering well pipe is a solid pipe, and the lower part is a filter pipe. The filter material is filled around the filter pipe, and the solid pipe part is fixed by concrete pouring.

Groundwater recharge requires in-situ recharge in the same stratum and the same type of groundwater recharge. According to the recharge calculation model, the ratio between the recharge well and the dewatering well in the pit is designed to be 1:1 to ensure that 100% of the groundwater extracted inside the foundation pit is pumped back into the ground. The recharge well is 16~22 m deep and the spacing between the wells is 6 m. The diameter of the recharge well is 325 mm. 3 m

thick clay balls and 6 m thick concrete are used in the upper part of the recharge well to pour to the ground. The upper part of the well pipe was a 9 m long solid steel pipe, and the lower part was a filter pipe.

3.2. Engineering geological condition

The project area is an alluvial-diluvial inclined plain geomorphic unit with relatively flat terrain. After investigation, it is found that the main exposed strata of the proposed site are Quaternary artificial fill, clay, macadamia clay, residual soil, gravel, consolidated conglomerate, Yanshan fully weathered diorite, strongly weathered diorite, moderately weathered diorite and other strata. The permeability coefficient of each rock layer is shown in Table 1.

Table 1. The permeability coefficient of each rock and soil layer

rock and soil layer	Combined permeability coefficient /(m/d)
Plain fill soil	0.5
Miscellaneous fill	2.0
Crushed stone	15.0
clay	0.01
Crushed stone	15.0
Consolidated conglomerate	5.0
Macadam clay	0.2
Residual soil	0.5
Fully weathered diorite	1.0~2.0
Highly weathered diorite	0.3~2.0

3.3. The test process of the dewatering and recharge

3.3.1 Dewatering test

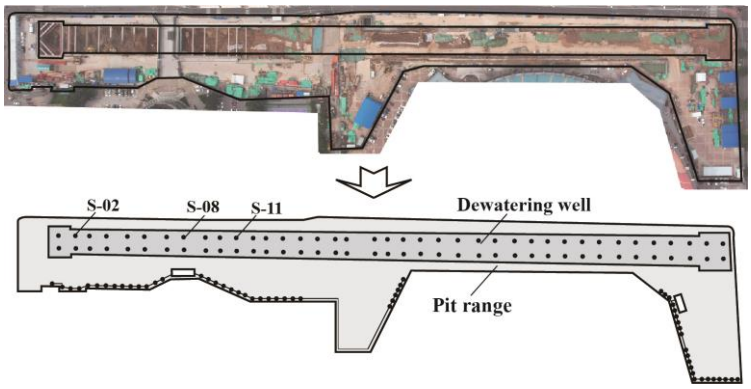


Fig. 4 The test well selection of the dewatering well

As shown in Figure 4, the dewatering well S-02 (well depth 23 m), S-08 (well depth 21 m) and S-11 (well depth 21 m) in the foundation pit were selected for single well test. The test process was as follows:

(1) Preparation before the test. The circuit system must ensure that all the dewatering test wells can work at the same time without tripping, and ensured that other electrical equipment was not connected to the special dewatering electrical box to prevent tripping. Further, it was need to check the specific coordinates and elevation of each well, and record the initial water level of each well.

(2) Stable water level observation. The groundwater level in the dewatering well and the observation well should be observed continuously for 48 hours. If the variation amplitude of the water level was less than 5.0 cm for several consecutive times (2-hour intervals), the groundwater level should be considered to be in a stable state. The observation frequency could be manual monitoring, and the data could be measured every 30-60 minutes.

(3) Dewatering test start. We checked the power supply, water pump intact, calibration line, unified time starting point, personnel and equipment in place, drainage channels through. The water yield of dewatering test should remain constant, and the allowable fluctuation rate should be less than 3% if there was any change. The duration of each group of the dewatering test was determined according to the curve of the relationship between water level decline and time in the observation well. If the curve showed a gentle section after the inflection point, the pumping could be stopped when the maximum water level decline value could be derived after 8~12 hours of stability.

(4) Water level monitoring. The water level of the dewatering well and the observation well should be observed in the first 1, 5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100 and 120 minutes after the start of the formal dewatering test. It should be observed every 30 minutes in the first 2-4 hours and adjusted to 60 minutes in the later period according to the dewatering condition until the water level was stable.

(5) Comparison of water level of internal and external observation wells. At the same time, the data collection of the observation well outside the foundation pit should be carried out. The changes of water level inside and outside the foundation pit should be compared after the formation of records.

(6) After the single well dewatering test, a group well dewatering test should be carried out. Nine dewatering wells in the pit (S-01, S-02, S-04, S-05, S-06, S-07, S-08, S-10 and S-11) were taken as the group test wells, and S-03 and S-09 are taken as the observation wells in the pit.

3.3.2 Recharge test

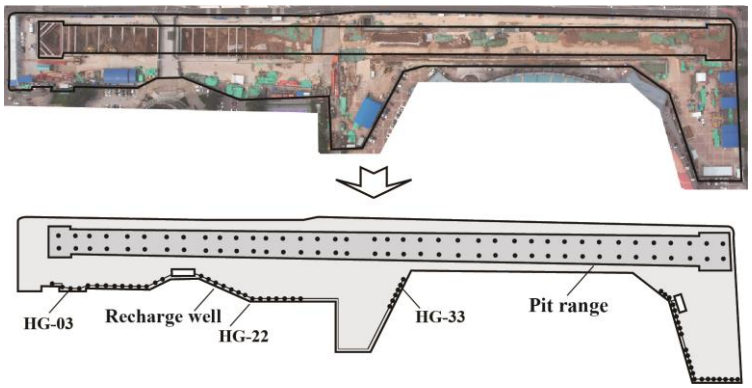


Fig. 5 The test well selection of the recharge well

As shown in Figure5, HG-3, HG-22 and HG-33 recharge wells were selected as the test wells of single well recharge test (the depth of recharge wells was all 21 m). The single well recharge test process was as follows:

(1) Preparation. Record the initial water level of each recharge well. The recharge system must be checked to ensure normal operation throughout the recharge test. Further check the specific coordinates and elevation of each recharge well.

(2) Determine the recharge test well and the water level observation well, check the water meter and the recharge parameters.

(3) Carry out the recharge test under the condition of natural recharge (No pressure recharge). After the start of the recharge test, the recharge was recorded at 1, 5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100 and 120 minutes, and the observation was made every 30 minutes in the first 2-4 hours, and adjusted to 60 minutes in the later period according to the situation of recharge.

(4) The recharge test under pressure recharge condition was carried out. The first wellhead pressure value was P1, and the recharge volume was recorded according to step (3). After the recharge was stable, the pressure could be continued with 0.01 MPa each time and the maximum pressure shall not exceed 0.1MPa.

(5) Before and during the recharge test, the water level of the observation well, the recharge pressure of the recharge test well and the recharge volume must be measured synchronously.

(6) Sorting out the recharge test data. Here, when natural recharge was carried out, the recharge equipment does not apply pressure. However, due to the height limitation of the equipment, there is

an initial recharge pressure of 0.01MPa. Therefore, the recharge under the condition of 0.01MPa was regarded as natural recharge.

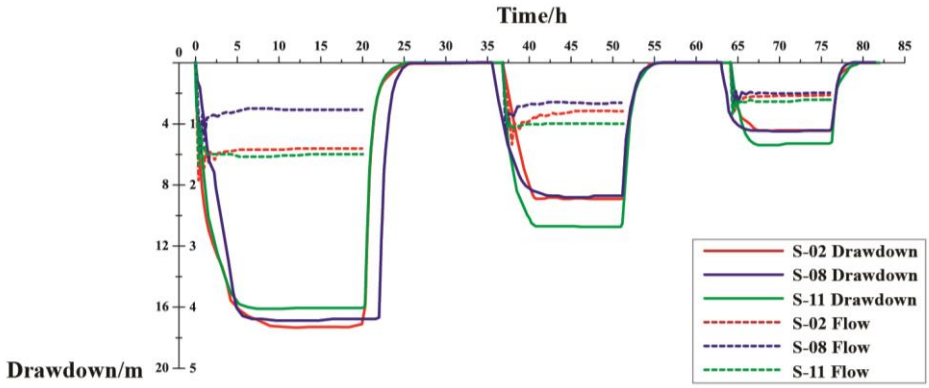
4. Result

4.1. Single well dewatering test

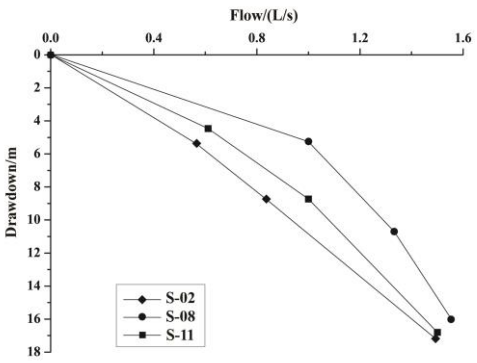
The drop depth, flow rate, permeability coefficient and influence radius of the test well were obtained by the single well dewatering test, and converted into the water inflow of the unified standard (diameter 219 mm, drop depth 5 m), as shown in Table 2. According to the test results, the relationship curve between water inflow and drawdown of single well dewatering test are drawn as Fig. 6.

Table 2. The results of the single well dewatering test

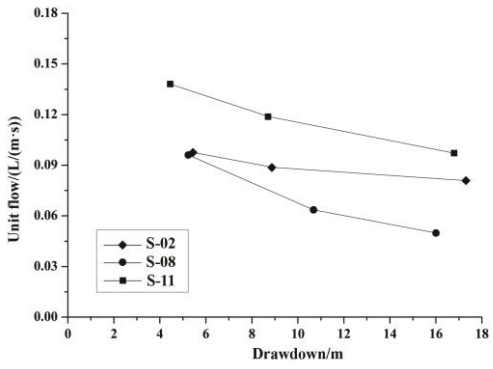
Well numbering	Test well drawdown/m	Observation well drawdown /m	Dewatering Flow /(m3/d)	Permeability coefficient /(m/d)	Influence radius /m	Water flow per well /(m^3/d)
S-02	17.31	1.38	120.96	0.175	66.30	46.76
	8.92	0.95	68.40	0.267	42.15	42.48
	5.44	0.62	45.84	0.341	29.13	42.60
S-08	16.05	0.78	67.24	0.103	47.76	34.54
	10.73	0.53	57.62	0.159	39.64	31.63
	5.28	0.25	43.21	0.305	26.98	38.75
S-11	16.80	1.16	129.62	0.192	70.69	57.07
	8.73	1.02	86.41	0.351	49.62	55.13
	4.46	0.76	52.83	0.543	31.52	58.33



(a)



(b)

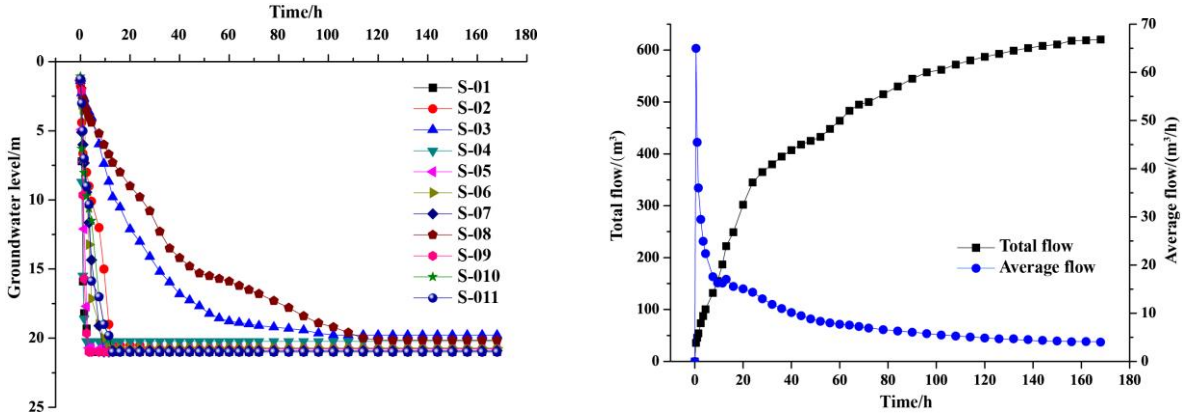


(c)

Fig. 6 Comprehensive diagram of the single well dewatering test. (a) Flow and depth curve over time; (b) Relationship curve between drawdown and flow; (c) Relationship curve between unit flow and drawdown.

It can be seen from Table 2 and Fig. 6 that the water level of the dewatering well decreases sharply in the early stage of dewatering, and then the dewatering depth gradually tends to be stable and finally remains at a stable value. The variation law of the dewatering depth of the observation well in the pit and the main well is consistent. The maximum water flow by a single well of the dewatering test well S-02, S-08 and S-11 are 120.96 m³/d, 67.24 m³/d and 129.62 m³/d, respectively. After conversion to the standard of diameter 219 mm and depth drop of 5 m, the water inflow of a single well is: 46.76 m³/d, 34.54 m³/d, 57.07 m³/d. The foundation pit floor depth is 18.27 m, the initial groundwater level is 3.75m, and the water level of the three test wells can be reduced to 2.79 m, 1.53 m and 2.28 m below the foundation pit floor, fully meeting the requirements of foundation pit excavation.

4.2. Group well dewatering test



(a) (b)

Fig. 7 Variation curve of group well dewatering test. (a) Groundwater level curve over time; (b) Total Flow and average flow curve over time.

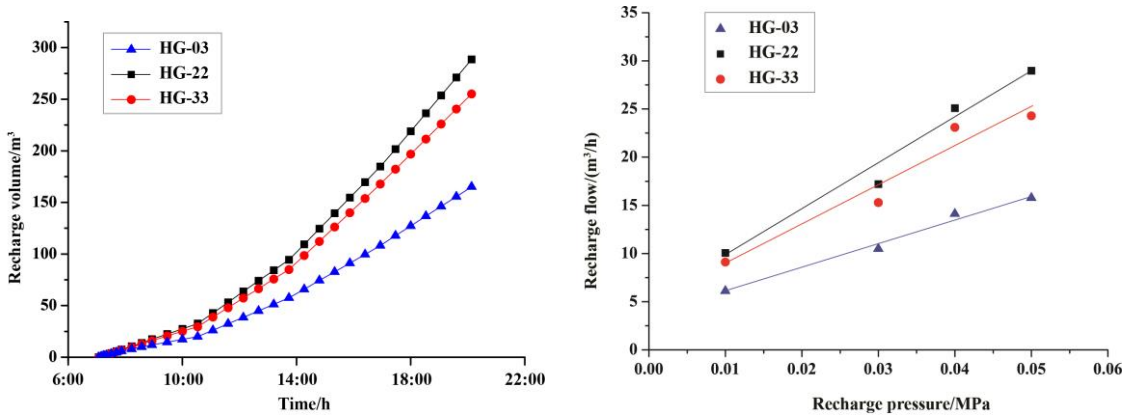
As shown in Fig. 7(a), the groundwater level in the recharge well decreases sharply in the initial stage of precipitation, and then remains stable, located at 1.50~2.73 m below the foundation pit floor. The groundwater level of the observation wells in the pit is located at 1.50 m and 1.87 m at the bottom of the foundation pit respectively, and the lower water level in the pit is reduced to 1 m below the foundation pit floor, which meets the requirements of foundation pit excavation. As can be seen from Figure 7(b), the total flow of dewatering gradually increases, while the average flow gradually decreases. In the late dewatering period, the flow is stable in the range of 88.8~108.0 m³/d.

4.3. Single well recharge test

The single well recharge test results of HG-3, HG-22 and HG-33 wells under natural recharge conditions (0.01 MPa) and under 0.03 MPa, 0.04 MPa and 0.05 MPa recharge pressures were obtained, as shown in Table 3, and the variation curve of single well recharge test was drawn (as shown in Fig. 8).

Table 3. The results of the single well recharge test

Well numbering	Recharge pressure /MPa	Average flow /(m^3/h)	Recharge time /h	Recharge volume /m^3	Observation well water level lifting /m
	0.01	6.12	3.25	19.9	0.04
HG-03	0.03	10.5	3	31.5	0.19
	0.04	14.13	3	42.4	0.32
	0.05	15.78	3	47.3	0.42
HG-22	0.01	10.06	3.25	32.7	0.06
	0.03	17.2	3	51.6	0.22
	0.04	25.09	3	75.3	0.36
HG-33	0.05	28.97	3	86.9	0.47
	4.46	0.76	52.83	0.543	31.52



(a) (b)

Fig. 8 Variation curve of single well recharge test. (a) Recharge volume curve over time; (b) Relationship curve between unit recharge flow and recharge pressure.

It can be seen from Table 3 and Fig. 8(a) that the recharge volume of a single recharge well increases slowly first and then linearly over time. Under natural recharge conditions (0.01 MPa), the hourly recharge rates of HG-3, HG-22 and HG-33 were 6.12 m3, 10.06 m3 and 9.12 m3. When the recharge pressure increases to 0.05 MPa, the hourly recharge volume increases to 15.78 m^3, 28.97 m^3 and 24.30 m^3. After a period of recharge, the recharge amount changes linearly with the recharge time, indicating that the recharge capacity remains stable after a period of recharge. As shown in Figure 8(b), the recharge volume of a single well basically presents a linear increase trend with the increase of the recharge pressure. The larger the recharge pressure is, the stronger the recharge capacity of the recharge well will be. For the sake of safety, the maximum should not exceed 0.1 MPa.

According to the recharge test, after optimizing the 78 recharge wells designed in the original design scheme and adjusting them to 56 recharge wells, the recharge rate can reach 100%, which can completely recharge the water into the ground and meet the requirements of the recharge design.

5. Summary

Reducing the groundwater level in deep foundation pit is beneficial to engineering construction, but a large range of dewatering will produce many adverse consequences. And the most direct and effective way to control the stability of the underground water level is groundwater recharge. This paper mainly studies groundwater dewatering and recharge of deep foundation pit in water-rich area.

Based on the calculation model of dewatering well, we deduced the relationship between recharge quantity of recharge well, formation parameters and groundwater level. Taking a deep foundation pit project in Jinan as the background, the dewatering model and recharge model were used for theoretical analysis and design. 78 recharge wells were designed, and the ratio of recharge wells and dewatering wells was designed at 1:1. The design scheme was optimized through on-site dewatering and recharge tests. The water level of a single dewatering well decreases sharply in the initial stage of dewatering, and then the depth gradually tends to be stable, and finally maintains a stable value. The water inflow of a single well ranges from 34.54 to 57.07 m³/d, which can drop to 1.53 m to 2.79 m below the foundation pit floor. The total flow of dewatering gradually increases, while the average flow gradually decreases gradually. In the late dewatering period, the flow is stable in the range of 88.8~108.0 m³/d. In the natural recharge state, the recharge capacity of a single well is 6.12~10.06 m3/h, that is, 146.88~241.44 m^3/d. The greater the recharge pressure, the stronger the recharge capacity of a single well, the recharge capacity of a single well is much greater than the dewatering capacity of a single well of a dewatering well. And 56 recharge wells can make the recharge rate reach 100%. This provides a scientific method for the dewatering and recharge design of foundation pit in water-rich area.

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