Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1346

Optimization for groundwater recharge system of excavation with leaky aquifers considering the influences of periodic redevelopment

Qinghan Li, Gang Zheng, **Xuesong Cheng**, Shilong Zhou
Department of Civil Engineering, Tianjin University, China, cheng_xuesong@163.com

Xinwang Zhang, Yongsheng Ma, Bing Li
China Construction Eighth Engineering Division Co. Ltd., China

ABSTRACT: Groundwater recharge is a critical mitigation strategy for managing groundwater drawdown and ground settlement in excavation engineering with leaky aquifers. Recharge well (GR well) clogging significantly reduces injection efficiency and hinders widespread groundwater recharge. While periodic redevelopment through pumping water from GR wells can effectively alleviate clogging, it often induces groundwater drawdown and ground settlement. To date, solutions for alleviating the settlement caused by the redevelopment of GR wells are lacking. In this study, the coupled effects of groundwater recharge operations and periodic redevelopment on groundwater dynamics in leaky aquifer systems are discussed. Numerical simulations demonstrate that compared with systems without groundwater recharge, increasing pumping rates within excavation systems is essential for maintaining anti-gushing stability during groundwater recharge. Two optimization methods, namely, well spacing optimization and adjacent well recharge under pressure, are proposed to mitigate the adverse influences induced by the periodic redevelopment of GR wells. The effects of the two methods are validated and discussed. These findings provide a technical framework for optimizing groundwater recharge systems in excavation projects while addressing clogging challenges.

KEYWORDS: Excavation engineering, recharge clogging, redevelopment, numerical simulation, recharge strategy.

1 INTRODUCTION

Rapid urbanization has spurred the proliferation of ultradeep excavations, and the requirements for mitigating the environmental impacts of excavation activities are becoming increasingly stringent. In water-rich geological settings, groundwater management is critical for ensuring both construction safety and environmental protection. Excavation dewatering can be performed to create a dry working environment for construction and to avoid uprush damage to a confined aquifer below the bottom of an excavation. However, this process is likely to cause groundwater drawdown and ground settlement outside excavations with leaky aquifers. Groundwater recharge is often applied in excavation engineering projects to control groundwater head and reduce ground settlement.

Groundwater recharge, as an important technique for regional water resource management (Long, et al., 2020; Yang, et al., 2022), is an effective measure for excavation engineering to reduce the influences of dewatering. Groundwater recharge tests and applications have been conducted in water-rich sand strata, such those in Shanghai (Li, et al., 2021) and Beijing (Guo, et al., 2022), China. The feasibility of groundwater recharge and its effect on groundwater control in sand have been validated.

In regions such as Tianjin, China, aquifers that are mainly composed of silt and silty sand are separated by aquitards composed of silty clay, which are prone to aquifer leakage (Li, et al., 2025; Zheng, et al., 2024). Moreover, the hydraulic conductivity of aquifers is lower than that of sand, which makes groundwater recharge systems prone to clogging (Zheng, et al., 2023). This problem can lead to a decrease in the water injection rate of recharge wells (GR wells), or even complete failure, which severely affects the application and promotion of groundwater recharge (Zhou, et al., 2025). In engineering, it is common to pump water from GR wells for redevelopment when clogging occurs. However, pumping inevitably induces groundwater drawdown and ground settlement. In response to this issue, a combined recharge method has been proposed (Zeng, et al., 2019). When the main GR well is pumped, a backup well is used for groundwater recharge, thereby avoiding the adverse influences of redevelopment. The combined recharge scheme requires an additional backup well for each GR well, resulting in a significant increase in costs. Therefore, this scheme is rarely applied in actual engineering projects. To date, there are no economical and effective countermeasures for the adverse influences of the redevelopment of GR wells, which is worthy of further research.

In this study, the adverse influences of the periodic redevelopment of a groundwater recharge system are discovered through numerical simulation. Countermeasures for periodic redevelopment namely, well spacing optimization and adjacent well recharge under pressure, are proposed. The effectiveness of each proposed method is verified. This study provides reference data for the optimization of groundwater recharge systems in excavation engineering.

2 NUMERICAL MODEL

2.1 *Basic model of a subway station*

Numerical simulations are conducted based on an excavation project of an underground two-story station in Tianjin, China. The stratum distribution and parameters are shown in Table 1. The phreatic aquifer is marked as Aq0. The first and second confined aquifers are marked as AqI and AqII, respectively. The aquitard between Aq0 and AqI is marked as AdI. The aquitards beneath AqI and AqII are marked as AdI and AdII, respectively. The soil properties in the same aquifer or aquitard are unified, and the values are derived from investigations and related studies (Zheng, et al., 2024).

Table 1. Stratum distribution and parameters.

Stratum	Depth (m)	Weight γ (kN/m^3)	Void ratio e	K_H (m/d)	K_V (m/d)	Modulus of compression Es (kPa)	Specific storage S_S (1/m)
Aq0	15	19.5	0.83	0.5	0.5	4354.81	0.0023
Ad0	20	20.0	0.67	0.0005	0.0001	717.59	0.0014
AqI	30	20.2	0.78	2	1	14775.26	0.00068
AdI	35	20.3	0.69	0.2	0.1	53485.79	0.00019
AqII	45	20.7	0.69	2	1	96961.94	0.00010
AdII	60	20.3	0.69	0.0004	0.0001	93428.62	0.00011

The excavation is 200 m in length and 20 m in width. The depth of the excavation is set to 17 m, which is close to AqI. The depth of the diaphragm wall is set to 32 m to enter AqII, but it does not completely cut off AqII. The groundwater head of Aq0 is 2 m below the ground surface (BGS), and the those of AqI and AqII are both 3 m BGS. In accordance with the anti-gushing requirements, the groundwater head of AqI must be reduced by 11.5 m, and AqII does not need to be pumped.

The model is 530 m in length, 350 m in width, and 60 m in depth, with boundary distances from the excavation exceeding the maximum influence range. The buildings to be protected are positioned outside the long edges of the excavation at twice the excavation depth (34 m). The pressure relief well (PR well) are arranged at 10 m intervals in the excavation. A total of 10 PR wells are numbered PR1 to PR10, with their filter screens penetrating the AqI from depths of 20 m to 30 m. To monitor the groundwater head in the confined aquifer within the excavation, observation points are stablished at different locations within the excavation, numbered IO1 to IO22. The observation points are set up at the locations of protected buildings, numbered OO1 to OO22. Each observation point simultaneously monitors the groundwater head in both AqI and AqII. The planar layout of the observation points is shown in Figure 1. The duration of dewatering is set to 20 d, and the pumping rate of the PR wells is adjusted to ensure that the groundwater head in AqI within the excavation meets the anti-gushing requirements. Moreover, the pumping rate is minimized to prevent the loss of water resources.

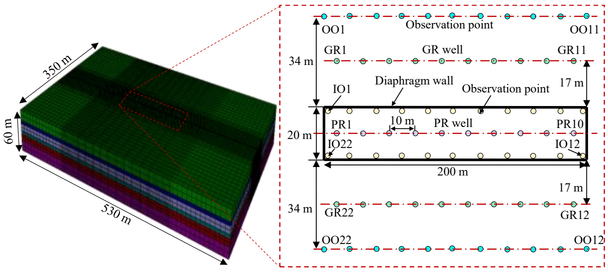

Figure 1. Numerical model.

2.2 *Influence of dewatering*

After the pumping rate of each PR well is adjusted to 3 m^3/h, the groundwater level variations at the observation points within the excavation are detected, as shown in Figure 2. Considering symmetry, only 6 observation points, namely, IO1 to IO6 are displayed. After dewatering begins, the drawdown in AqI rapidly increases, reaching stability after 7 d, with slow changes occurring thereafter. The calculation time of 20 d is considered adequate. Compared with the other observation points, IO1 has the smallest amplitude of drawdown, which is attributed to its relatively greater recharge from the horizontal direction. The drawdowns at all observation points within the excavation meet the anti-gushing requirements after 7 d. For convenience of discussion, all subsequent models in this study need to meet the requirement that the minimum drawdown in the AqI at each observation point within the excavation is exactly 11.5 m after 7 d of dewatering.

Figure 2 shows the drawdowns in AqII at observation points IO1-IO6. Although no dewatering is applied to AqII, drawdown occurs because of aquifer leakage. Similar to the drawdown trend observed in AqI, rapidly increasing drawdown occurs after dewatering begins, and stability is reached after 7 d. Among the observation points, IO1 has the smallest amplitude of drawdown. The maximum drawdown measured among the observation points occurs at IO6, with a maximum value of 5.4 m.

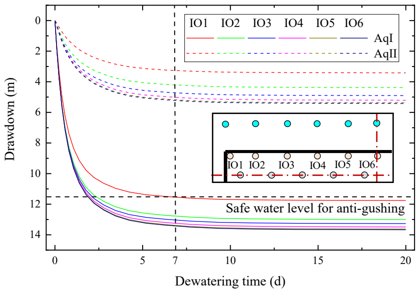

Figure 2. Drawdowns at the observation points inside the excavation.

Since AqII is not cut off by the diaphragm wall, significant drawdown in AqII inside the excavation inevitably induces drawdown outside the excavation. Figure 3 shows the drawdowns in AqI and AqII at observation points OO1-OO6 near the protected buildings outside the excavation. The drawdowns in AqII at the same observation points are greater than those in AqI. This phenomenon occurs because the drawdown in AqI is induced by the drawdown in AqII due to aquifer leakage. The drawdowns at the observation points inside the excavation stabilize after approximately 7 d. Conversely, those outside the excavation take approximately 10 d to stabilize, as the observation points outside are farther from the dewatering centre and thus require more time to stabilize. The maximum drawdown in AqI observed near the protected buildings outside the excavation is 3.0 m, whereas in AqII, it is 3.4 m. Significant drawdown still occurs at twice the excavation depth, i.e., at 34 m. Groundwater recharge can be implemented to control groundwater level and prevent settlement of the protected buildings.

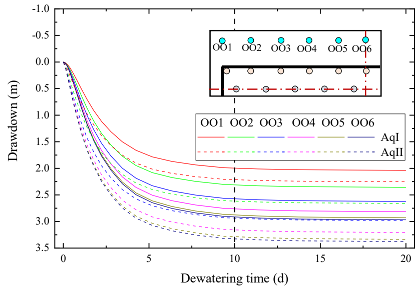

Figure 3. Drawdowns at the observation points outside the excavation.

3 INFLUENCES OF GROUNDWATER RECHARGE

There are two options for the aquifer to be recharged: AqI and AqII. In this section, the influences of groundwater recharge in different aquifers on groundwater levels are discussed. The GR wells does not apply additional pressure; that is, the groundwater level in each well remains at the height of the wellhead, close to the ground surface, and recharge is carried out by gravity alone. The locations of the GR wells are shown in Figure 1 and are numbered GR1 to GR22.

3.1 *Analysis of groundwater levels when AqI is recharged*

When the distance between the GR wells and the excavation is one times the excavation depth (17 m), at least 20 wells are distributed evenly along the longer sides of the excavation to prevent the groundwater levels at the protected building from dropping through calculation. The recharge rate of each well is approximately 2.4 m^3/h. To ensure that the groundwater levels inside the excavation meet the dewatering requirements, the pumping rate of each PR well inside the excavation needs to be increased to 4.1 m^3/h. Compared with the condition without recharge, the total pumping rate increases by approximately 36.7%, with the increase in the pumping rate accounting for approximately 22.9% of the total recharge rate.

When AqI is recharged, the drawdowns in AqI and AqII inside the excavation are shown in Figure 4. The drawdown trend is essentially the same as that without groundwater recharge. Among all the observation points, the maximum drawdown in AqII still occurs at IO6 (2.1 m), which is 3.3 m lower than that without recharge (5.4 m), indicating a difference of approximately 61.1%.

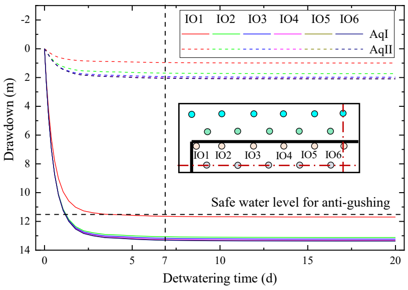

Figure 4. Variations in groundwater levels inside the excavation when AqI is recharged.

When AqI is recharged, the variations in groundwater levels at observation points near the protected buildings in AqI and AqII are shown in Figure 5. Under the effect of recharging AqI, the groundwater levels mainly increase. After dewatering and recharging begin, the groundwater levels first rapidly increase but then gradually decrease until they stabilize. Compared with those in AqII, the increases in groundwater levels in AqI are generally greater. The closer the observation point is to the centre of the longer side of the excavation, the greater the increase in water level. The maximum water level increase occurs at observation point OO6, with AqI experiencing a maximum increase of 1.89 m and AqII experiencing a maximum increase of 0.40 m. Additionally, the peak groundwater level for AqII occurs earlier than that for AqI, as AqII outside the excavation is more significantly affected by dewatering inside the excavation.

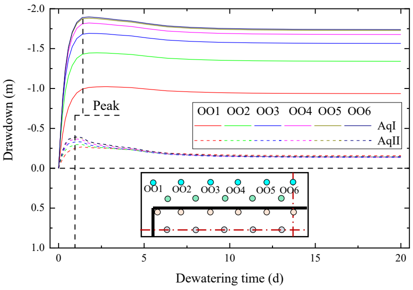

Figure 5. Variations in groundwater levels outside the excavation when AqI is recharged.

3.2 *Analysis of groundwater levels when AqII is recharged*

When AqII is recharged, only 10 GR wells are needed to prevent the groundwater levels at the protected building from decreasing. The recharge rate of each well is approximately 4.2 m^3/h. The recharge rate is higher than that of the AqI recharge scheme. Compared with AqI, AqII experiences greater drawdown, resulting in a greater difference in groundwater levels between the GR wells and the surrounding soil, thus leading to a higher recharge rate. At this point, the pumping rate for each PR well is 4.1 m^3/h, which requires the pumping rate to increase by approximately 36.7% compared with that under the condition without recharge. Similar to the AqI recharge scheme, whether the AqI or AqII recharge scheme is adopted, the influence on the required dewatering rate inside the excavation is essentially the same. Furthermore, the total recharge rate for the AqII recharge scheme is lower than that for the AqI recharge scheme, indicating greater efficiency in groundwater level control. The increase in the pumping rate accounts for approximately 26.2% of the total recharge rate in this case.

The variations in groundwater levels inside the excavation when AqII is recharged are shown in Figure 6. Unlike the conditions without and with recharge for AqI, the groundwater levels of AqII slightly increase when both dewatering and GR wells are in operation at the initial stage, with the maximum increase of 0.97 m occurring at observation point IO6. This phenomenon is attributed to the significant influence of groundwater recharge on the groundwater levels in AqII, which gradually decreases as dewatering progresses. In practical engineering, if groundwater recharge is conducted for confined aquifers that are not completely cut off, the recharge rate should be reduced during the initial dewatering stage, and the groundwater level changes in this aquifer within the excavation should be monitored to prevent water gushing.

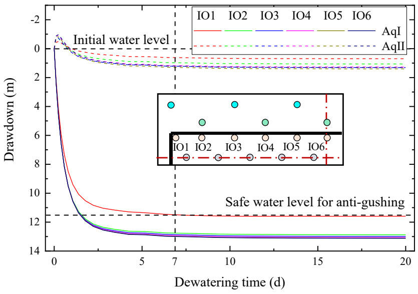

Figure 6. Variations in groundwater levels inside the excavation when AqII is recharged.

When AqII is recharged, the groundwater level variations near the protected buildings are shown in Figure 7. The groundwater levels of both aquifers remain above the initial value. In contrast to those in the shallow AqI recharge scheme, the groundwater levels in AqII are directly influenced by groundwater recharge, resulting in generally greater water level increases at the same locations as those in AqI. The maximum groundwater level increase occurs at observation points closer to the centre of the long edge of excavation, with OO3 recording the highest values (0.70 m for AqI and 1.21 m for AqII).

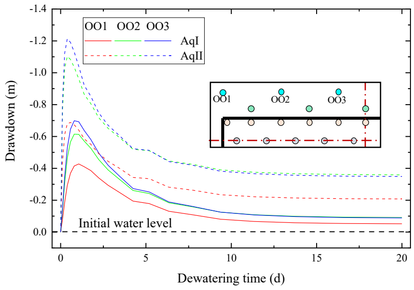

Figure 7. Variations in groundwater levels outside the excavation when AqII is recharged.

Overall, adopting the AqII recharge scheme results in higher efficiency. However, since AqII is not cut off, its influence on the groundwater levels inside the excavation is more significant. Therefore, close monitoring of fluctuations in the groundwater levels of the aquifers inside the excavation is essential to prevent water gushing and damage.

4 INFLUENCES OF PERIODIC REDEVELOPMENT

To prevent well plugging during the long-term operation of groundwater recharge, periodic redevelopment of GR wells should be conducted. Redevelopment should be conducted approximately every 3 days, with each session lasting 3 to 4 h. During redevelopment, the pumping rate is typically approximately twice the normal operating recharge rate (Phienwej, et al., 1998). The influences of periodic redevelopment on groundwater levels will be discussed.

4.1 *Influences of redevelopment when AqI is recharged*

Based on the model in Section 3.1, a pumping process with a duration of 3 h and a pumping rate of 4.8 m^3/h is sequentially applied to all the GR wells. The groundwater level variations near the protected buildings are shown in Figure 8. Periodic redevelopment has minimal influence on the groundwater levels inside the excavation and will not be discussed. During the periodic redevelopment of the GR wells in AqI, the groundwater levels near the protected buildings exhibit cyclic fluctuations with a period of 3 d. During each cycle, the maximum drawdown increases with the increasing number of cycles, reaching a plateau at approximately 20 d. The maximum fluctuation in groundwater levels within each cycle is 1.0 m for AqI and 0.37 m for AqII. Compared with AqII, AqI is directly influenced by the redevelopment of GR wells, resulting in larger fluctuations in groundwater levels. During periodic redevelopment, the groundwater levels of AqI are never lower than the initial value, whereas the groundwater levels of AqII gradually decrease and fall below the initial value.

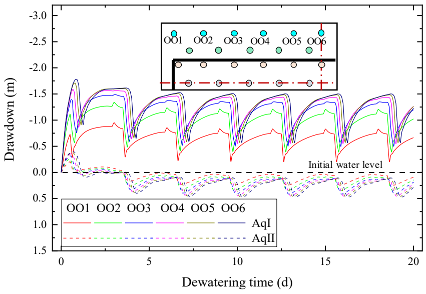

Figure 8. Variations in groundwater levels during periodic redevelopment for the GR wells in AqI.

4.2 *Influences of redevelopment when AqII is recharged*

Based on the model in Section 3.2, a pumping process is sequentially applied to all the GR wells with a duration of 3 h and a pumping rate of 4.8 m^3/h. The groundwater level variations near the protected buildings are shown in Figure 9.

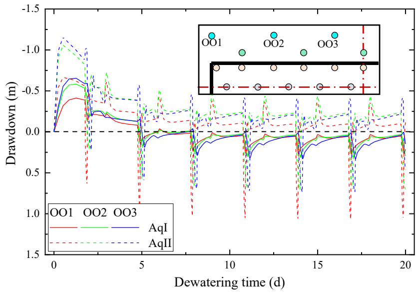

Figure 9. Variations in groundwater levels during periodic redevelopment for the GR wells in AqII.

The groundwater levels exhibit cyclic fluctuations with a period of 3 d. During each cycle, the maximum fluctuations in groundwater levels are 0.23 m for AqI and 1.43 m for AqII. After the start of excavation dewatering and recharge, the groundwater levels of AqI first increase and then gradually decrease as periodic redevelopment progresses, with the maximum drawdown being 0.33 m. The groundwater levels in AqII generally maintain an upwards trend, but the maximum drawdown during redevelopment is still below the initial value, with a maximum drawdown of 1.07 m. Therefore, the periodic redevelopment of GR wells can reduce the control effect of the groundwater recharge system on groundwater levels. Specifically, the influences of periodic redevelopment on groundwater levels are more pronounced in aquifers that have not been recharged.

5 WELL SPACING OPTIMIZATION

Based on the calculations in Section 4, it is evident that the original groundwater recharge scheme, which met the control requirements for protecting the buildings, clearly induced groundwater drawdown after the periodic redevelopment of the GR wells. This is because the recharge rate for each GR well reaches the maximum value. Under these conditions, if a well cannot maintain its recharge rate, groundwater levels decrease. To address this issue, an optimization of the GR well layout is needed. By reducing the spacing between the GR wells and increasing the number of wells, the potential recharge capacity of the groundwater recharge system can be enhanced. The recharge rate of the GR wells near the well for redevelopment can increase during the process of redevelopment, ensuring that the amount of water recharged within a small area remains unchanged. The following discussion of well spacing optimization is based on the two conditions of AqI recharge and AqII recharge.

5.1 *Well spacing optimization when AqI is recharged*

Based on the model in Section 4.1, the spacing of the GR wells is reduced, and additional GR wells in AqI are added. When the number of GR wells is increased to 26, the groundwater levels at the protected buildings can be maintained at no lower than the initial value, representing a 30% increase in the number of wells and recharge project cost.

When AqI is recharged with 26 wells and without periodic redevelopments, the average recharge rate for each well is 1.8 m^3/h, and the pumping rate for each PR well needs to increase to 4.1 m^3/h, representing an increase in the pumping rate of approximately 23.5% of the total recharge rate. When stability was reached, the groundwater levels in the GR wells increased by 2.8 m BGS, and the recharge rates did not reach their maximum values. The groundwater level variations when AqI is recharged with 26 wells are shown in Figure 10. The drawdowns at IO1 inside the excavation are minimal. Thus, when the groundwater level at IO1 meets the anti-gushing requirements, the entire excavation area meets the requirements. Similarly, the groundwater level rise at OO1 outside the excavation is minimal. Therefore, when the groundwater level at OO1 meets the requirements for building protection, all observation points around the protected buildings can meet the requirements. Hence, only the groundwater levels at IO1 and OO1 are shown in Figure 10 for the 26-well recharge scheme. After 7 d of dewatering, the drawdown in AqI at IO1 exceeds 11.5 m, and the groundwater levels at OO1 for both AqI and AqII exceed the initial value, meeting the requirements.

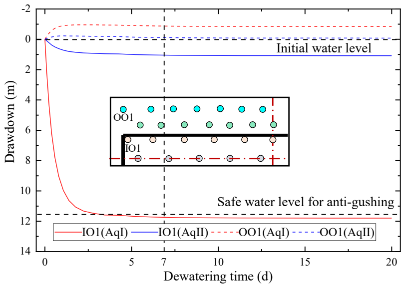

Figure 10. Variations in groundwater levels when AqI is recharged with 26 wells.

Performing periodic redevelopment with 26 GR wells involves a constant pumping rate of 3.6 m^3/h for each well for a duration of 3 h, while the adjacent GR wells maintain the maximum recharge rate. The groundwater level variations outside the excavation are shown in Figure 11. The maximum groundwater level fluctuations within the period are 0.44 m for AqI and 0.10 m for AqII. Compared with the condition with 20 wells, the magnitude significantly decreases. Moreover, the groundwater levels of AqI and AqII predominantly increase, and even the lowest groundwater level is still higher than the initial value. By optimizing the well spacing, the magnitude of groundwater level fluctuation within the periodic redevelopment can be reduced, thereby mitigating the adverse influences caused by the periodic redevelopment of the GR wells.

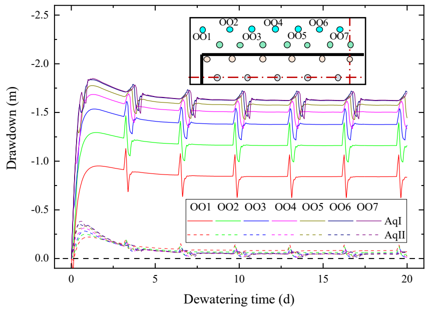

Figure 11. Variations in groundwater levels during the periodic redevelopment of 26 AqI wells.

5.2 *Well spacing optimization when AqII is recharged*

Based on the model in Section 4.2, when the spacing of the GR wells is reduced and the number of GR wells in AqII is increased to 14, the groundwater levels at the protected buildings can be maintained no lower than the initial value when periodic redevelopment occurs, representing a 40% increase in the number of wells and recharge project cost.

When AqII was recharged with 14 wells and without periodic redevelopments, the average recharge rate for each well was 3.0 m^3/h, and the pumping rate for each PR well also needed to increase to 4.1 m^3/h, representing an increase in the pumping rate of approximately 26.2% of the total recharge rate. When the stability was reached, the groundwater levels in the GR wells rose by 1.2 m BGS, and the recharge rates did not reach their maximum values. The groundwater levels at IO1 and OO1 are shown in Figure 12. After 7 d of dewatering, the drawdown in AqI at IO1 exceeds 11.5 m, and the groundwater levels at OO1 for both AqI and AqII exceed the initial value.

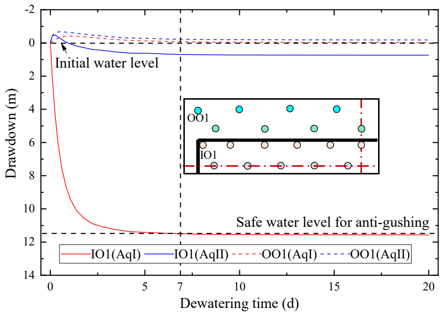

Figure 12. Variations in groundwater levels when AqII is recharged with 14 wells

Periodic redevelopment is conducted for the 14 GR wells, with each well maintaining a pumping rate of 6 m^3/h for a continuous period of 3 h during redevelopment. The other GR wells maintain the maximum recharge rate. The variations in groundwater levels at observation points outside the excavation are calculated, as shown in Figure 13. Except for the observation point OO1 at the corner of excavation, the groundwater levels in both AqI and AqII primarily trend to increase and remain greater than the initial values. The groundwater levels of observation point OO1 at the corner of excavation are difficult to control during the redevelopment of the adjacent GR well. In practical engineering, redevelopment of the GR well at the corner of excavation should be avoided. Excluding OO1, the maximum groundwater level fluctuation within a single redevelopment circle is 0.19 m for AqI and 1.0 m for AqII. Compared with the condition with 10 GR wells in AqII, there is a significant decrease in the fluctuation amplitude.

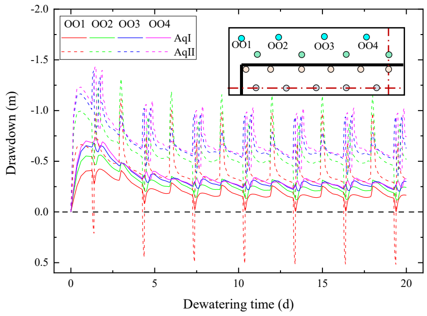

Figure 13. Variations in groundwater levels during the periodic redevelopment of 14 AqII wells

In conclusion, whether it is recharging AqI or AqII, increasing the number of GR wells by optimizing the well spacing is effective at eliminating the adverse influences induced by the redevelopment of GR wells, with the increase in recharge costs ranging from 30% to 40%.

6 ADJACENT WELLS RECHARGED WITH PRESSURE

Well spacing optimization leads to an increase in the number of wells and additional demands for both cost and construction space. If the number of wells and cost are not increased, to increase the recharge rates of wells adjacent to the redevelopment well, additional artificial pressure must be applied to the wells.

6.1 *Adjacent wells recharged with pressure in AqI*

Based on the calculation model in Section 4.1, the pressure applied to the GR wells adjacent to the redevelopment well is gradually increased, and the variations in groundwater levels during the periodic redevelopment of the GR wells are calculated. An additional pressure equivalent to a water head height of 2.0 m is applied to GR wells adjacent to the redevelopment well, and the groundwater levels can always remain no lower than the initial value during periodic redevelopment of GR wells, as shown in Figure 14. At this point, the recharge rates of the adjacent GR wells reach 6.0 m^3/h.

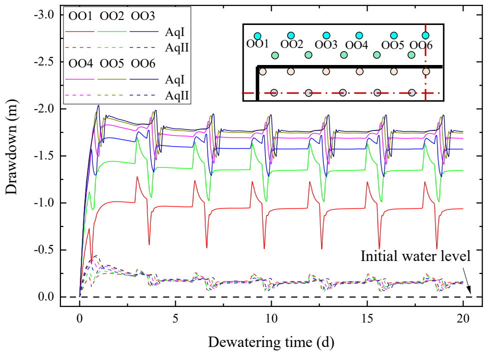

Figure 14. Variations in groundwater levels under adjacent wells recharged with pressure during periodic redevelopment in AqI

6.2 *Adjacent wells recharged with pressure in AqII*

Based on the calculation model in Section 4.2, the variations in groundwater levels during the periodic redevelopment of the GR wells are calculated, and the pressure is applied to the GR wells adjacent to the redevelopment well. An additional pressure equivalent to a water head height of 5.0 m is applied to the GR wells adjacent to the redevelopment well, and the groundwater levels during the periodic redevelopment of the GR wells, except those observed at observation point OO1 at the corner of the excavation, can always remain no lower than the initial value, as shown in Figure 15. At this point, the recharge rates of the adjacent GR wells reach 12.6 m^3/h.

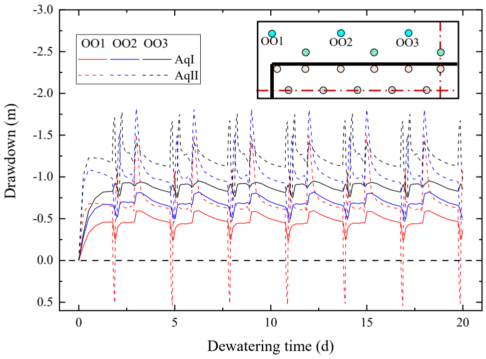

Figure 15. Variations in groundwater levels under adjacent wells recharged with pressure during periodic redevelopment in AqII

The results of the analysis demonstrate that when AqI or AqII are recharged, applying additional pressure to the GR wells adjacent to the redevelopment well to increase the recharge rates can eliminate the adverse influences caused by periodic redevelopment for the GR wells, and the cost of the recharge system hardly increases.

7 CONCLUSIONS

Based on numerical simulations of basic models of subway stations with leaky aquifers, the influences of selecting recharge aquifers and periodic redevelopments on the effectiveness of groundwater level control are revealed. Two methods for mitigating the adverse influences induced by periodic redevelopment for GR wells, that is, well spacing optimization and adjacent wells recharged with pressure, are presented. The effects of the two methods are validated. The main conclusions are as follows:

(1) In excavation engineering, when PR wells are uniformly distributed inside the excavation, the drawdown is greater at the centre of the excavation and smaller at the corners. Although only AqI has been pumped using PR wells inside the excavation, owing to aquifer leakage, AqII still experiences significant drawdown, further leading to drawdown in the confined aquifers outside the excavation.

(2) When groundwater recharge is used, increasing the total pumping rate inside the excavation is necessary to meet the groundwater level control requirements for anti-gushing. According to the calculation results, regardless of whether AqI or AqII is recharged, the total pumping rate increases by 36.7%. Under the same control requirements of groundwater levels and without additional recharge pressure, the number of GR wells required for AqI recharge is approximately twice that of the AqII recharge scheme. The total recharge rate of the AqI recharge scheme is also greater than that of the AqII recharge scheme, indicating higher efficiency in controlling water levels with AqII recharge. However, owing to the lack of cutting off in AqII, the influence of groundwater recharge in AqII on aquifers inside the excavation is more significant, and more detailed monitoring of groundwater level fluctuations is needed to prevent water gushing and potential damage.

(3) The periodic redevelopment of the GR wells can reduce the control effect of the groundwater recharge system on groundwater levels. Specifically, the influences of periodic redevelopment on groundwater levels are more pronounced in aquifers that have not been recharged.

(4) Without additional recharge pressure, increasing the number of GR wells by optimizing the well spacing is effective at eliminating the adverse influences induced by the redevelopment of the GR wells. According to the calculation results, the number of GR wells and the cost of the recharge system need to be increased by 30% to 40%.

(5) Without increasing the number of GR wells, when the GR well is used to pump water for redevelopment, artificial pressure can be applied to nearby GR wells to increase recharge rates, effectively preventing drawdown caused by redevelopment. The cost of the recharge system hardly increases. At this point, it is necessary to pay attention to whether artificial pressure will cause damage to the GR well and the soil structure.

8 ACKNOWLEDGEMENTS

This work is supported by the Tianjin Science Foundation for Distinguished Young Scientists of China (No. 241CQJC00170), the China Postdoctoral Science Foundation under Grant Number (No. 2025M773243), and the Postdoctoral Fellowship Program of CPSF under Grant Number (No. GZC20252133). Their support is gratefully acknowledged.

9 REFERENCES

Guo, F., Wang, G., and Li, Z. 2022. Influence of artificial recharge in a phreatic aquifer on deep excavation dewatering: a case study of Dongguantou Nan Station in Beijing, China. *Hydrogeology Journal* 30, 673-689.

Li, M., Chen, J., Xu, Y., Tong, D., Cao, W., and Shi, Y. 2021. Effects of groundwater exploitation and recharge on land subsidence and infrastructure settlement patterns in Shanghai. *Engineering Geology* 282, 105995.

Li, Q., Zheng, G., Cheng, X., Shi, X., Zhang, N., Zhou, S., and Cheng, W. 2025. Deformation and protection of tunnels influenced by excavation dewatering in soft soil strata with leaky aquifers. *Tunnelling and Underground Space Technology* 159, 106468.

Long, D., Yang, W., Scanlon, B., Zhao, J., Liu, D., Burek, P., Pan, Y., You, L., and Wada, Y. 2020. South-to-North Water Diversion stabilizing Beijing's groundwater levels. *Nature Communications* 11, 3665.

Phien-wej, N., Giao, P., and Nutalaya, P. 1998. Field experiment of artificial recharge through a well with reference to land subsidence control. *Engineering Geology* 50, 187-201.

Yang, W., Long, D., Scanlon, B., Burek, P., Zhang, C., Han, Z., Butler Jr, J., Pan, Y., Lei, X., and Wada, Y. 2022. Human Intervention Will Stabilize Groundwater Storage Across the North China Plain. *Water Resources Research* 58, e2021WR030884.

Zeng, C., Zheng, G., and Xue, X. 2019. Responses of deep soil layers to combined recharge in a leaky aquifer. *Engineering Geology* 260, 105263.

Zheng, G., Li, Q., Cheng, X., Ha, D., Shi, J., Shi, X., and Lei, Y. 2024. Diaphragm wall deformation and ground settlement caused by dewatering before excavation in strata with leaky aquifers. *Geotechnique* 74, 1-17.

Zheng, G., Li, Q., Cheng, X., Liu, X., Jia, J., Jiao, Y., and Ha, D. 2023. Study on the hydraulic parameter differences between pumping and recharge in a confined aquifer of a soft soil area. *Hydrogeology Journal* 31, 947-965.

Zhou, S., Cheng, X., Li, Q., Zheng, G., Zhang, X., Ma, Y., and Li, B. 2025. Experimental study on the mechanism and countermeasures of recharge plugging induced by soil particle migration. *Journal of Hydrology* 657, 133115.