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Research Paper

Environmental risk assessment and protection measures due to dewatering during construction of Wangfuzhuang Metro Station, Jinan, China

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ABSTRACT

Jinan is famous due to its spring group with rich groundwater resources. The groundwater system should be protected during construction of the metro system. This paper presents a case study of the environmental risk assessment due to dewatering and recharge during construction of Wangfuzhuang Metro Station, Jinan, China. The Fuzzy Analytic Hierarchy Process (FAHP) is employed to evaluate the impact on the environment. Moreover, based on Darcy's law, and water inflow calculations for a submersible full well and water level line equation under the coupling action of a submersible full dewatering-recharge well group, the dewatering and recharge schemes of the deep foundation pit excavation are designed. Both results from numerical simulation and site survey show that dewatering and recharging at the Jinan R1 line site were effective in environmental protection.

1. Introduction

Jinan is located to the south of the Yellow River and north of Mount Tai, and is often referred as the 'Spring City' for its 72 artesian springs. Due to its rapid development, rail transit engineering is under construction, which involves many foundation pit engineering works. Thus groundwater protection, especially for the springs is important. Generally, well-points dewatering is employed to lower the groundwater table inside the foundation pit, which guarantees dry conditions in the foundation pit. Jinan Rail Transit R1 is sited in the western new urban district. The length of line R1 is 26.04 km, of which the underground section is 9.00 km long. There are 11 stations along the whole line, among them, four are below ground: Wangfuzhuang station, Dayangzhuang station, Jinanxi railway station, and Yangmazhuangxi station (Fig. 1).

Fig. 1. Location plan

Based on a geological survey, the gravel layer and sand layer around the underground stations in line R1, are relatively thick and are rich in ground water. In addition, there is no stable aquiclude in some regions [2]. In this case

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dewatering volumes will be significant if direct dewatering measures are used. A great deal of dewatering will not only waste valuable water resources, but also threaten the operational safety of buildings and structures. For the famous Spring City of Jinan, the traditional construction method involves a discharge of pumped groundwater directly through municipal pipes, which will damage the springs in the long-term. Therefore, how to optimise the foundation pit dewatering scheme without emergence of obvious settlement funnels and how to deal with the contradictory relationship between dewatering and spring protection problems are key problems facing engineers responsible for the Jinan rail transit underground works.

To protect the water resource in the process of construction of Jinan Rail Transit of Jinan city, this paper analyses the feasibility and suitability of *in situ* recharge using water pumped from foundation pits.

2. Engineering Geology

According to drilling data and results of laboratory soil tests, the soil layer within the exploration range of engineering site in this area can be divided into an Artificial deposit layer (Q_{4ml}), a Quaternary holocene alluvial deposit layer (Q_{4al+pl}), and a Quaternary upper pleistocene alluvial deposit layer (Q_{3al+pl}) [2].

2.1 Engineering geology

2.1.1 Quaternary holocene alluvial deposit layer (Q_{4ml})

① Miscellaneous fill layer: loose to dense. The principal components are: broken stone, concrete block, fragment of brick, dust and building waste.

⑦ Loess layer: uniform soil; pinhole structure; vertical texture; with some iron-manganese concretions and calcareous hypha. The water content is about 25%; the bulk density is about 1.91 g/cm^3; the porosity is approximately 0.770; modulus of compression (E_s) is about 5.3 MPa and it is a medium compressible soil.

⑧ Silty clay layer: uniform soil; with small amounts of iron and manganese oxides and rusty spots. The water content is about 27%; the bulk density is about 1.94 g/cm^3; the porosity is approximately 0.772; the modulus of compression (E_s) is about 5.9 MPa and it is a medium compressible soil.

⑧$_1$ Pebble bed: dense; rounded edge shape; general particle size is about 30~60 mm; the maximum particle size is greater than 100 mm; the coarse gravel content is about 60% (by mass); with sandy soil as well as small amounts of cohesive soil.

2.1.2 Quaternary upper pleistocene alluvial deposit layer （Q_{3al+pl}）

⑩$_1$ Pebble bed: dense; rounded edge shape; general particle size is about 20~60 mm; the maximum particle size is greater than 100 mm; the coarse/medium gravel content is about 65% (by mass); it includes sandy soil as well as small amounts of cohesive soil.

⑪ Silty clay layer: the liquid index is 0.25~1.0; with iron and manganese oxides and concretions, as well as broken stones in places. The water content is about 30%; the bulk density is about 1.89 g/cm^3; the porosity is about 0.862; the modulus of compression (E_s) is about 9.1 MPa and it is a medium compressible soil.

⑪$_1$ Pebble bed: dense; sub-circular; general particle size is about 30~60 mm; the maximum particle size is greater than 90 mm; the gravel content is about 55% (by mass); it includes sandy soil as well as small amounts of cohesive soil.

2.2 Hydrogeology

Fig. 2 shows the hydrogeology around Wangfuzhuang station. Aquifers mainly consist of phreatic aquifer, or are confined aquifers. Water levels between structural roofs and structural floors necessitate dewatering to ensure safe excavation.

Phreatic aquifer

Phreatic water: groundwater depth is 3.00~11.70 m; the water level elevation is 27.99~9.57 m; the aquifer is mainly filled with ⑧ Silty clay layer, which is mainly recharged from precipitation and groundwater flow in mountainous areas and discharged through lateral runoff and artificial exploitation. Due to the influence of annual amplitude, the groundwater level varies from wet to dry seasons.

Confined aquifer

Confined water: the burial depth and static hydraulic head are 12.20~13.58 m; the elevation of static hydraulic head is 27.85~28.76 m; the aquifer is mainly composed of ⑧$_1$ pebble bed, ⑩$_1$ pebble bed, and ⑪$_1$ pebble bed, and is mainly recharged from atmospheric precipitation infiltration, and penetration of pore water from the Quaternary loose rock, and discharged mainly through artificial exploitation. Based on the results of pumping tests, the recommended hydrogeological parameter for dewatering construction is the permeability coefficient K of 250.0 m/d.

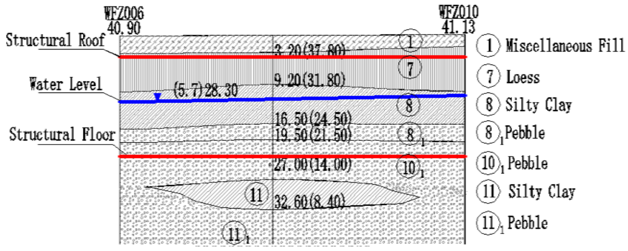

Fig. 2. Typical geological section: Wangfuzhuang station

3. Dewatering and Recharge Scheme

3.1 Requirements

(1) To guarantee the safety of foundation pit excavation, the water level inside each pit should be reduced to 1 m below the pit bottom. That is to say the water level should be reduced by at least 15 m.

(2) To protect the neighbouring buildings from damage, groundwater table fluctuations around such buildings should be minimised.

(3) The pumped water from each dewatering well in the foundation pit should be recharged to the neighbouring underground aquifer as far as is possible to avoid the waste of groundwater resources.

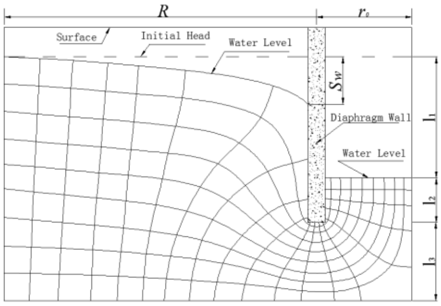

Fig. 3. Flow net around curtain wall

3.2 Design of dewatering scheme

In the design of dewatering, the foundation pit for a station can be equivalent to a huge round dewatering well, whose equivalent radius r_0 can be calculated according to equation (1):

$$r_0 = 0.29(a+b) \quad [1]$$

Where:
a - long side of foundation pit
b - short side of foundation pit

There is a waterproof curtain outside the building envelope of the station, and the dewatering wells are laid on the inner side of curtain. When the groundwater is in a steady seepage state during the process of dewatering, the flow net (representing the seepage field) around the curtain is as shown in Fig. 3. The equipotential lines on the central axis at the bottom of the curtain are vertical, therefore, the seepage field around curtain can be considered to be the combination of the seepage fields inside and outside the curtain [7]. It can be seen from Fig. 3 that:

$$H = l_1 + l_2 + l_3 \quad [2]$$

$$h = l_2 + l_3 \quad [3]$$

$$S_w = H - h' \quad [4]$$

Where:
H = initial hydraulic head value, m;
l_1 = drawdown value inside curtain, m;
l_2 = distance between curtain bottom and water level inside the curtain, m;
l_3 = distance between curtain bottom and relatively impermeable layer, m;
h = hydraulic head value of water level inside the curtain
S_w = the maximum drawdown value of water level outside the curtain, m;
h' = hydraulic head value of water level outside the curtain, m;

The flow of groundwater inside the curtain of the foundation pit excavation is approximately one-dimensional and vertical, and can be modelled by Darcy's law. The water inflow can be calculated by using equation 5:

$$Q_i = \frac{4K\pi r_0^2 h(h'-h)}{(l_2+h+r_0)^2} \quad [5]$$

where:
K = coefficient of permeability, m/d

According to previous construction experience, a waterproof curtain has a better effect in loess layers, silty clay layers, and fine sand layers, while has a poor effect in gravels. Therefore the waterproofing of ⑦, ⑧, and ⑧$_2$ can be seen as the wall of a dewatering well, and the waterproofing of ⑩$_1$ is akin to the filter in dewatering. Since ⑪ is a relatively impermeable layer, the overall waterproof curtain can be seen as a submersible full well, whose water inflow Q_o can be calculated using equation (6) [8]:

$$Q_o = 1.366K\frac{(2H-S_w)S_w}{\lg(1+\frac{R}{r_0})} \quad [6]$$

Where $R = 2S_w\sqrt{HK}$ (m), is the radius of influence of dewatering. When the dewatering of a foundation pit excavation is stable, the water inflow of stratum far from the foundation pit is equal to the pumped output of the dewatering well inside the foundation pit, therefore:

$$Q_i = Q_o \quad [7]$$

Water flow from the foundation pit can be obtained, under conditions of constant head, by solving simultaneous equations (1) ~ (7). The water flow in a single dewatering well (q) can be calculated using equation (8) [8]:

$$q = 120\pi rl\sqrt[3]{K} \quad [8]$$

Where:
r = radius of filter pipe, m;
l = effective length of filter pipe, m.

The number of dewatering wells *n* is given by equation [9]:

$$n = 1.1\frac{Q}{q} \quad [9]$$

Where Q is the flow from the foundation pit, m^3/d. The space between dewatering wells can be determined thus:

$$D = 2\frac{a+b}{n-1} \quad [10]$$

Where:
D—space between dewatering wells
a —length of the foundation pit
b—of the foundation pit
n—quantity of dewatering wells

What can be deduced from the engineering situation here is: a = 340 m, b = 20 m, l_1 = 15.0 m, l_2 = 2.5 m, l_3 = 6.2 m, and K = 32.7 m/d; by calculation using equations (1) to (10): r_0 = 104.4 m, H = 23.7 m, h = 8.7 m, S_w = 8.2 m, R = 456.6 m, Q = 19,695.2 m^3/d, q =1494.1 m^3/d， n = 15, and D = 51 m.

Since the foundation pit widths are only 20 m, which is much smaller than the space between single dewatering wells. Thus during practical dewatering of the foundation pits, the dewatering wells are as shown in Fig. 4: the space between dewatering wells is 30 m; the depth reaches the bottom of the ⑩$_1$ pebble layer.

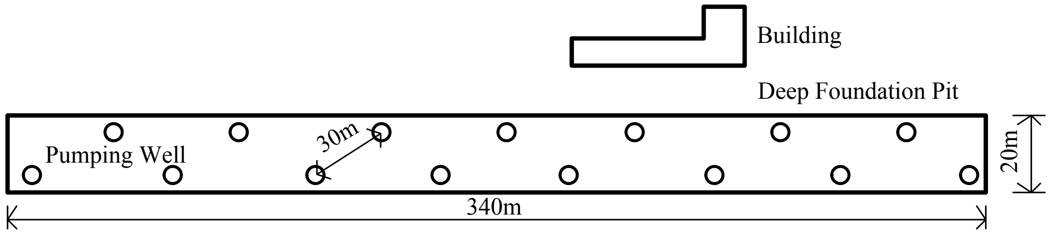

Fig. 4. Layout of dewatering well in metro station

3.3 Design of recharge scheme

Suppose that m dewatering wells and n recharge wells are laid at random; according to the principle of superposition of potential functions of each submersible full well, the water level equation can found thus::

$$z^2 = H^2 - \sum_{i=1}^{m}\frac{q_i}{\pi K}\ln\frac{R_i}{r_i} \quad [11]$$

The water level in a recharge well group is:

$$z^2 = H^2 + \sum_{j=1}^{n}\frac{q'_j}{\pi K}\ln\frac{R'_j}{r'_j} \quad [12]$$

The water level equation under the coupled effects of dewatering-recharge well groups is:

$$z^2 = H^2 - \sum_{i=1}^{m}\frac{q_i}{\pi K}\ln\frac{R_i}{r_i} + \sum_{j=1}^{n}\frac{q'_j}{\pi K}\ln\frac{R'_j}{r'_j} \quad [13]$$

Where:
z = water level of a certain point near the foundation pit, m;
H = thickness of aquifer, m;
K = permeability coefficient of stratum, m/d;
q_i = water flow in the dewatering well, m^3/d;
R_i = influence radius of dewatering well, m;
r_i = distance from a point near a foundation pit to each dewatering well, m;
q'_j = recharge amount from a recharge well, m^3/d;
R'_j = influence radius of recharge well, m;
r'_j = distance between a point near a foundation pit to a recharge well, m.

Suppose that the respective water level of the two points near the buildings under the effect of a dewatering well group are z_1 and z'_2, meanwhile, the respective water levels of the certain two points under the effect of a recharge well group are assumed to be z'_1 and z'_2. To guarantee the safety of adjacent buildings, the groundwater level of these two points should be equal after recharge.

$$z_1 + z'_1 = z_2 + z'_2 \quad [14]$$

Based on the layout scheme of recharge wells, the recharge volume and the water table level can be obtained from use of simultaneous equations (11) ~ (14).

Recharge can be seen as the inverse of pumping; however, permeabilities obtained from recharge experiments are 15~20% lower than those from pumping tests. To avoid the water in recharge well directly returning to the dewatering well, the distance between recharge wells and dewatering wells should be no less than 6 m [12]. Since the recharge work in Jinan should take not only the safety of buildings, but also the protection of groundwater resources, into consideration, the number of recharge wells is 1.2 times greater than that of dewatering wells. Moreover, more recharge wells are required in areas adjacent buildings (Fig. 5).

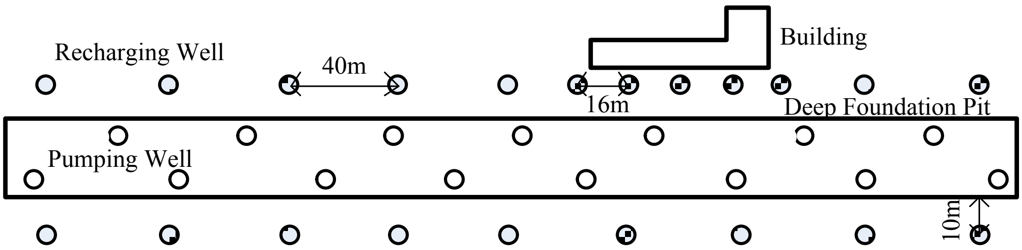

Fig. 5. Layout of recharge wells

According to the dewatering scheme described in Section 3.2 and the layout of dewatering wells, combining equations (11) to (15), the recharge volume q' and water table at selected points around building z can be deduced: q' =1078.2 m³/d, z = 8.8 m.

4. Risk Evaluation

4.1 AHP (analytical hierarchy process)

According to the analysis of factors influencing recharge, the hierarchy model for recharge suitability analysis at Jinan R1 can be established (Fig. 6).

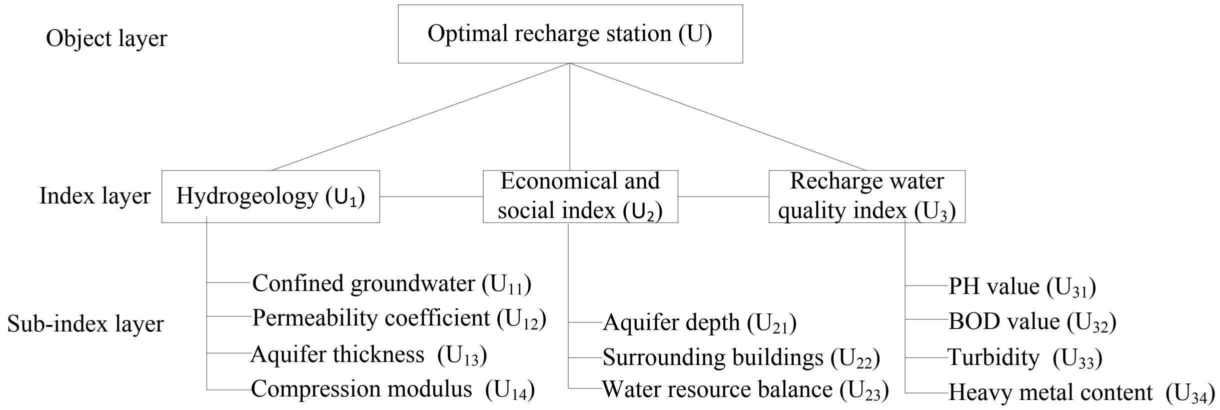

Fig. 6. Hierarchy model for recharge appropriateness analysis: Jinan rail transit R1

Table 1. Judgment matrix: factor levels

U	*U*₁	*U*₂	*U*₃	*W*ᵤ
U_1	1	2	6	0.6
U_2	½	1	3	0.3
U_3	1/6	1/3	1	0.1

Table 2. Judgment matrix: index level U_1

	U_{11}	U_{12}	U_{13}	U_{14}	W_{u1}
U_{11}	1	1/6	1/6	1/4	0.058
U_{12}	6/1	1	1/1	2/1	0.371
U_{13}	6/1	1/1	1	2/1	0.371
U_{14}	4/1	1/2	1/2	1	0.200

Table 1 shows the judgment matrix of factor level of hydrogeological index (U_1), economic and social index (U_2), and recharge water quality index (U_3). Based on λ_{max} = 3.0001 (λ_{max} is the maximum eigenvalue of judgment matrix U), consistency ratio CR = 9.62 × 10^5 < 0.1 can be obtained. Consistency of the matrix is acceptable.

The judgment matrix of index level U_1 is as shown in Table 2. Based on λ_{max} = 4.011 (λ_{max} is the maximum eigenvalue of judgment matrix U_1), the consistency ratio can be calculated as CR = 4.11 × 10^{-3} < 0.1. The consistency of the matrix is acceptable. In the same way, the maximum eigenvalue of judgment matrices U_2 and U_3 can be obtained as 3.0 and 3.871, respectively. Weight vectors are respectively W_{u2} (0.111; 0.667; 0.222), W_{u3} (0.25; 0.25; 0.25; 0.25), and each matrix passes a consistency check.

4.2 Fuzzy evaluation

When engineering information is incomplete, or there is a lack of standard guidance, even experienced engineers cannot render a precise assessment. In this case, linguistic variables are needed, the main function of which is to provide a systematic method to approximately describe complicated characteristics without clear definition. For example, during the evaluation of a scheme, domain of discourse *Q* is “suitability”, thus “very suitable, suitable, not quite suitable and unsuitable" is fuzzy subset of domain of discourse Q, which is called the domain of remark grading. Here, we assess recharge indices around Jinan rail transit works, and build a set of remarks: V = (very suitable, suitable, not quite suitable, unsuitable). Then, we replace "very suitable, suitable, not quite suitable and unsuitable" by corresponding values: V= (4; 3; 2; 1).

The Delphi method is employed to obtain the evaluation matrix for suitability evaluation of foundation pit dewatering and recharge. Take hydrogeological index B_1 as an example, on the basis of the conditions listed in Section 2, an expert grading matrix for each station is as summarised in Table 3.

A fuzzy operator is seen as dot product of these two matrices, which means that a weighted average fuzzy comprehensive evaluation model is used. Thus the set of the memberships of each station's hydrogeological indices is as follows:

$$T_1 = B_1 W_{u1}$$

$$= \begin{bmatrix} 1.4 & 2.5 & 1.3 & 4.4 \\ 4.0 & 3.8 & 4.0 & 4.0 \\ 3.6 & 1.8 & 2.6 & 3.5 \end{bmatrix} \begin{bmatrix} 0.058 \\ 0.371 \\ 0.371 \\ 0.200 \end{bmatrix} = \begin{bmatrix} 2.371 \\ 3.926 \\ 2.541 \end{bmatrix}$$

Similarly, T_2 = (3.178; 3.322; 3.066)^T; T_3=(3; 3; 3)^T can be obtained, and then the set of total membership can be obtained:

T=(T1, T2, T3) W_u=(2.6760；3.6522；2.7444)^T

On the basis of the maximum membership, the following result can be obtained: in terms of the suitability of foundation pit dewatering and recharge, R1 stations are ranked: Dayangzhuang, West Yanmazhuangxi, and Wangfuzhuang.

It was noticed that, in the set of membership for hydrogeological index T_1, the value for Wangfuzhuang station was the lowest. Through further analysis of the hydrogeological conditions around Wangfuzhuang station, the permeability coefficient there was large, and the groundwater therefore highly mobile. In addition, the sandy gravel layer under the station is too thick, and it is rather difficult to guarantee the construction effect of foundation pit supporting structures therein; besides, there is a risk of leakage, and in this case, same-layer recharge in the sandy gravel layer under the foundation pit bottom will have a negative influence on the safety and stability of the supporting structure. Therefore, further analysis and design are required here before adopting such a recharge scheme design aruind Wangfuzhuang station.

Based on the above analysis, the risk in the construction of Wangfuzhuang station is the biggest. It means that we should work to optimise the dewatering and recharging system to ensure foundation pit excavation safety and to protect the groundwater resource. Thus, it is the best to take Wangfuzhuang station as an example to introduce such a dewatering and recharging system.

Table 3. Judgment matrix: index level B_1

	B_{11}	B_{12}	B_{13}	B_{14}
Wangfuzhuang	1.4	2.5	1.3	4.4
Dayangzhuang	4.0	3.8	4.0	4.0
West Yanmazhuang	3.6	1.8	2.6	3.5

5. Monitored Results and Analysis

5.1 Water level

Fig. 7 shows the trends in water level around Wangfuzhuang station. As the recharging became steady, water levels in observation wells increased monotonically. This indicates that the recharging system is able to keep water levels in the surroundings steady, and thus protects the groundwater environment from the effects of the dewatering. Change of water level in the phreatic groundwater is bigger than those in the confined aquifer, because the recharging well works mainly to the benefit of the phreatic water. There is a big up-lift between 50 days to 80 days, mainly because of rainfall over the area.

5.2 Land settlement

Fig. 8 shows subsidence of surrounding land around Wangfuzhuang station foundation pit works. Both subsidence and uplift occur: the maximum subsidence is about 5.5 mm, while the maximum uplift is about 3.3 mm. Generally, the subsidence is small, telling us that land subsidence is under control and is within safe limits.

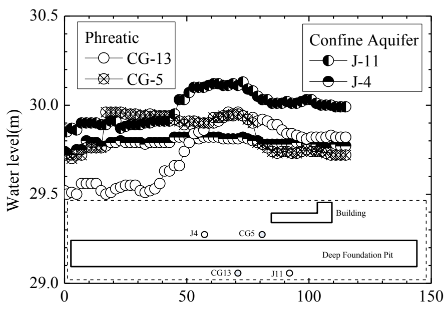

Fig. 7. Trends in water-levels: Wangfuzhuang station

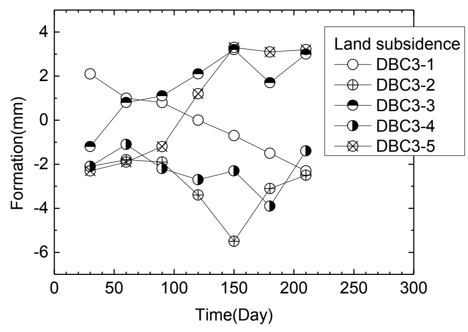

Fig. 8. Subsidence of surrounding ground: Wangfuzhuang station

6. Conclusions

Analysis of the feasibility and suitability of *in situ* recharging using the pumped water from foundation pits using a fuzzy comprehensive evaluation was undertaken. The following conclusions were reached:

(1) A prior design method for foundation pit dewatering and recharging systems has been established, ensuring foundation pit excavation safety and minimising the influence on its surroundings during dewatering.
(2) Better aquifer recharge occurs at higher permeabilities and *vice versa*.
(3) Subsidence of soil outside the pit would be limited by recharging measures, perhaps stratum vertical stresses being improved were responsible for this.

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