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Study on the Law of Influence of Seepage Field Anomalies on Displacement Field Induced by Leakage of Enclosure Structure

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Abstract: The leakage of an enclosure structure will cause abnormal changes in the seepage flow field, which in turn can lead to the deformation of the enclosure structure and affect the surrounding geotechnical body. In this paper, a fiber-optic temperature measurement system is used to detect the location of the seepage points in a station of the Qingdao subway during open pit excavation, and the abnormal variation of the seepage field caused by the seepage points is obtained by numerical calculation and field measurement. Then, numerical simulation is performed to analyze the effects of seepage field anomalies on the deformation of the enclosure structure and surface settlement. It is found that the seepage flow caused by the leakage point has a significant influence on the surface settlement and the deformation of the enclosure structure. With the increase of excavation depth, the deformation of the enclosure structure increases and the maximum deformation position shifts downward. The deformation of the enclosure structure decreases when the leakage point exists. The surface volume also increases gradually with the excavation, and the maximum surface settlement position shifts outward significantly. The settlement range becomes larger when the leakage point exists.

Keywords: leakage detection; seepage field variation; envelope deformation; surface settlement

1. Introduction

With the rapid development of urban underground space engineering, foundation pits become bigger, deeper, and closer. The disasters caused by foundation pit engineering increases correspondingly, especially in areas rich in groundwater. Many practical projects show that the leakage of the deep pit retaining structure is the main factor causing large deformation or cracking around the foundation pit [1–3], as shown in Tables 1 and 2. Therefore, it is necessary to analyze the deformation characteristics of the retaining structure and soil when the retaining structure leaks in the water-rich area, so as to ensure the safety of foundation pit engineering and surrounding building. The groundwater in the research area of this paper is relatively rich and is mainly divided into quaternary pressurized water and bedrock fracture water. The preliminary geological survey shows that the geology of this area is complex; the weathering of the rock body is serious; and the tectonic joint and fracture are very developed, indicating a secondary geological structure.
Scholars have carried out a lot of research on the deformation characteristics of foundation pit precipitation excavation and fruitful results have been achieved. He et al. [4–6] studied the influence of dewatering depth and waterproof curtain depth on deformation characteristics of foundation pit. Feng et al. [7] experimentally studied the centrifugal model of the deep foundation pit support structure of the pumping station. The influence of key deformation on foundation pit stability is analyzed. Zhang et al. [8] numerically analyzed the deep foundation pit excavation-precipitation process in Yinchuan area based on HS-Small principal structure model. With the excavation of the foundation pit, the deformation of the foundation pit slope increases gradually, and the maximum displacement finally appears at the positive angle of the top of the foundation pit. The axial force of the bolt increases with the increase of excavation depth, and the deformation control ability is related to the position. Yang [9] investigated the deformation law of deep foundation pit excavation based on Flac 3D. The results showed that the heave of the pit bottom is caused by vertical unloading and the combined support of concrete retaining pile and prestressed anchor cable can effectively control the deformation of the foundation pit. Yu et al. [10] conducted a numerical simulation of the deformation of the enclosure structure and surrounding soil caused by the construction of a sandy foundation pit and compared the simulation results with measured data. Wang et al. [11] studied the characteristics of groundwater influence on soft ground. Zhang et al. [12–14] performed finite element analysis of seepage flow stress coupling for the deformation of the foundation pit project. According to the coupling situation, the causes of leakage of the water stop curtain were analyzed, and the corresponding treatment measures and construction matters needing attention were put forward. Zhang et al. [15] studied the effect of groundwater level change on the seepage characteristics of foundation pits in coastal areas. The analytical method, finite element numerical method, and model test methods were adopted. Then, the groundwater level change in response to pore pressure around the foundation pit was investigated. The change and distribution of soil and water pressure on both sides of the supporting structure were studied deeply. Lu et al. [16] found that the drop of groundwater level outside the pit caused by the excavation of the station pit is very likely to lead to consolidation settlement of the surrounding strata and, uneven settlement and structural deformation of the ground buildings. Qiu et al. [17,18] used numerical simulation and field measurement methods to comparatively study the lateral displacement of foundation pit retaining wall, surface settlement behind the wall and internal force variation of retaining pile wall before and after local leakage of water stop curtain in a sandy soil site. Tan et al. [19] analyzed the causes of seepage during deep foundation pit excavation in Shanghai subway and studied the change law of vertical and horizontal surface displacement of the enclosure wall caused by water and sand leakage. Jo et al. [20] investigated the development law of ground subsidence caused by seepage during deep foundation pit excavation through on-site investigation. Koltuk et al. [21,22] analyzed the seepage and deformation of the deep foundation excavation precipitation process through numerical simulation and studied the deformation law of foundation pit construction under the action of seepage.
the deformation law of foundation pit construction by comparing nearly 300 working conditions and common foundation pit support types. Zheng et al. [26,27] conducted experimental research and numerical simulation of the development process of water and sand leakage disaster in underground engineering. In summary, pit leakage changes the pit seepage field and stress field, which exerts an important influence on the pit deformation and stability, but related engineering practice data and theoretical research are rare.

Based on a foundation pit of Qingdao subway, this paper studies the change of the seepage field caused by the leakage of the enclosure structure and the effect on the change characteristics of the enclosure structure and the surrounding soil of the foundation pit through a series of numerical simulations. In this paper the horizontal displacement law and surface settlement law of the water stop curtain are summarized through numerical simulation, which provides a reference for foundation pit leakage treatment.

2. Leakage Point Detection and Groundwater Level Monitoring

2.1. Spot Detection of Foundation Pit Leakage

The fiber optic temperature measurement system was set up by using DTS-10 (Manufactured by Beijing TOP Photonics Co., Ltd.) copper network internal heating temperature sensing fiber optic cable and OFDR (OSI-C) high precision distributed optical frequency domain strain temperature analyzer [28], as shown in Figure 1. The fiber optic temperature measurement system was used after the construction of the foundation pit enclosure structure is completed (before the excavation of the foundation pit). Details of fiber optic deployment and on-site detection are shown in Figure 2. OFDR (OSI-C) analyzer can achieve a spatial resolution of 1 mm within 50 m sensing range and a resolution of 1 cm within 100 m sensing range, which guarantees high precision detection of leakage points in this project.

![Figure 1. The photo of temperature measurement fiber and temperature analyzer.](image)

The optical fiber was heated using 8 W power. During the heating process, the temperature change at different locations and depths of the enclosure structure were obtained. Then the data were analyzed to obtain the variation curve of fiber temperature with depth and location.
2.2. Groundwater Level Monitoring near the Seepage Point

The distributed optical fiber field test shows that the temperature variation was small in temperature at depths of 0–24 m of the foundation pit, and was within 7.5–10 °C. The temperature dropped significantly at depths of 24–27 m. After analyzing the causes of abnormal temperature, it was pointed out that there may be leakage points in this range. Subsequent excavation verifies that there is a water seepage point in the water stop curtain of the foundation pit. The water leakage point is located at the excavation depth of 25 m of the foundation pit, as shown in Figure 3.

In order to monitor the change of groundwater level near the seepage point in real time and verify the reasonableness of the calculation and analysis results, groundwater level monitoring points (DSW01-DSW05) were set near the pre-detected seepage point...
before the excavation of the foundation pit. The internal support structure and water level
monitoring system are shown in Figures 4 and 5, respectively. The foundation pit adopted
a retaining pile, the envelope adopted a rotary jet pile. The concrete material was used
retaining pile and envelope. Water level monitoring points were spaced 5 m apart.

![Diagram of foundation pit structure and leakage location](image-url)

**Figure 4.** Foundation pit structure and leakage location.

![Diagram of water level monitoring layout](image-url)

**Figure 5.** Water level monitoring layout diagram.

Long-term monitoring of groundwater level was carried out during the excavation of
the foundation pit, and the change of groundwater level near the leakage point is shown
in Figure 6. Due to the existence of the water curtain leakage point, the water level at the
leakage point is about 1–2 m lower than that in other parts.
3. Numerical Simulation and Analysis of Seepage Field Anomalies

Based on the on-site detection of the foundation pit and the actual excavation condition, the influence of enclosure structure leakage on the percolation field was studied by numerical simulation. The results show that there was an anomaly in the seepage field of the foundation pit when leakage occurred. The detailed results of as follows.

Considering the uncertainty in the existence of enclosure structure leakage, a two-dimensional model of the seepage field was established using Geo Studio (CnTech is the supplier) finite element software to further study the influence of the leakage of the enclosure structure on the seepage field of the foundation pit. Four calculation conditions were established, condition 1: the leakage point is 0.01 m wide; condition 2: the leakage point is 0.005 m wide; condition 3: the leakage point is 0.001 m wide; condition 4: no leakage. The geotechnical parameters are shown in Table 3, and the structural parameters are shown in Table 4.

Table 3. Geotechnical layer parameters.

| Soil                     | Bulk Density (kN·m⁻³) | Permeability Coefficient (cm·h⁻¹) | Cohesive Force c/(kPa) | Angle of Internal Friction ϕ/(°) | Poisson’s Ratio | Layer Depth (m) |
|--------------------------|-----------------------|-----------------------------------|------------------------|---------------------------------|----------------|-----------------|
| plain fill               | 17                    | 0.29                              | 20                     | 18                              | 0.30            | 4               |
| silty clay               | 18.7                  | 0.36                              | 22.7                   | 9.5                             | 0.30            | 6               |
| silty clay               | 18.3                  | 0.51                              | 18.5                   | 20                              | 0.33            | 7               |
| coarse sand with clay    | 20                    | 2.24                              | 20                     | 30                              | 0.28            | 4               |
| strongly weathered      |                       |                                   |                        |                                 |                 |                 |
| coarse-grained granite   | 22                    | 0.11                              | 50                     | 48                              | 0.35            | the following   |

Table 4. Structural material parameters.

| Soil          | Unit Type  | Bulk Density (kN·m⁻³) | Modulus of Elasticity E/(GPa) | Poisson’s Ratio |
|---------------|------------|-----------------------|-------------------------------|-----------------|
| steel support | truss unit | 78                    | 206                           | 0.26            |
| concrete bracing | truss unit | 25                    | 30                            | 0.20            |
| retaining piles | plate unit | 25                    | 30                            | 0.2             |
The excavation method of the foundation pit is step-by-step excavation. The specific excavation steps are as follows: (1) enclosure structure establishment and perform initial ground stress balance; (2) the First precipitation to −6 m, first excavation to −5 m, and first concrete support; (3) the second precipitation to −11 m, second excavation to −10 m, and second steel support; (4) the third precipitation to −16 m, the third to excavation to −15 m, and the third steel support; (5) the fourth precipitation to −21 m, the fourth excavation to −20 m, and the fourth steel support; (6) the fifth precipitation to −26 m, the fifth excavation to −25 m, and the fifth steel support; (7) the sixth precipitation to −30 m, the sixth excavation to −29 m, and the sixth steel support.

As shown in Figure 7, in the absence of leakage in the envelope structure, water level pressure difference will occur during foundation pit dewatering, and groundwater will flow around the bottom. In the case of leakage of enclosure structure, ground-water flow is disordered with the groundwater, not only flowing from the bottom of the enclosure structure around the flow, but also flowing from the leakage into the foundation pit. The drop of groundwater level increases with the increase of seepage size.

![Figure 7. Underground flow path diagram of retaining structure with leakage (left) and without leakage (right).](image)

As can be seen from Figures 8–11, when there is leakage in the envelope, the groundwater flow through the leakage is larger than that through the bottom of the envelope. The water flow through the leakage increases with the increase of the leakage size. The total groundwater flow into the foundation pit through the bottom of the retaining structure and the leakage is greater than the total flow into the foundation pit through the bottom of the retaining structure without leakage. In addition, the water level drop of the retaining structure with leakage is 2–3 m more than that of the retaining structure without leakage, which will promote the effective stress change of the soil around the foundation pit, and enhance the adverse impact on the surrounding environment. When the seepage is intense, a large seepage force is generated, and the water pressure at the seepage point is greater than that of the nearby part without leakage. The reason is that when there is a leakage point in the retaining structure, the difference of water head inside and outside the pit will become larger. With the water head difference, the water outside the pit overcomes the viscous resistance of soil particles and flows into the foundation pit, resulting in greater water pressure. In other words, when leakage of palisade structure exists, with the increase of leakage point flow field, water poured into the foundation pit will continue to increase, and the underground water level of the retaining structure outside the foundation pit will gradually decline. Therefore, in the process of the excavation of the foundation pit, precipitation leakage of the retaining structure produces unfavorable impacts on surrounding buildings.
Figure 8. The curve of flow rate at the leakage and bottom of the envelope with precipitation time.

Figure 9. Flow curve with precipitation time at the leakage with different sizes.

Figure 10. The curve of the total flow rate of the leaky and non-leaky envelope with precipitation time.
As can be seen from Figures 12–15, when there is leakage in the envelope, the maximum flow velocity and hydraulic gradient appear at the leakage of the envelope, and the hydraulic gradient varies greatly. The reason for this phenomenon is that the groundwater entering the foundation pit from the leakage of the retaining structure has a small seepage path and the thickness of the leakage is small, which causes local effects, and then the groundwater velocity and hydraulic gradient become larger at the leakage of the retaining structure. Subsequently, the effective stress of the soil around the retaining structure will change dramatically, which will damage the soil, and then cause developmental damage. These damages will have an adverse effect on the foundation pit engineering. The flow velocity and hydraulic gradient increase with the increase of leakage size.

Figure 11. Variation curve of groundwater level of the envelope with and without leakage.

Figure 12. The curve of water flow velocity with precipitation time in the envelope with and without leakage.
Figure 13. The curve of water velocity in leakage of different sizes with precipitation time.

Figure 14. The diagram of the hydraulic gradient with precipitation time of the envelope with and without leakage.

Figure 15. The curve of the hydraulic gradient with precipitation time at the leakage with different sizes.
As can be seen from Figure 16, the water level pressure difference inside and outside the pit will gradually increase during the excavation and precipitation of the pit, and the water level outside the pit will also change to a certain extent. When there is no seepage point, the maximum drop of the water table is about 6 m, and the drop depth of the water level outside the pit near the water stop curtain is about 20% of the depth of the excavation and precipitation in the pit. When the leakage point is 10 mm wide, the maximum drop of groundwater level is about 9 m, and the drop of groundwater level outside the pit near the water stop curtain is about 30% of the depth of excavation in the pit.

![Figure 16](image)

**Figure 16.** Numerical analysis and comparison of the amount of groundwater level change in the actual project.

Combined with the actual engineering data and numerical simulation results, we found that (Figure 16), the actually monitored water level and the simulated water level consistent, indicating that the seepage simulation results and the actual engineering situation in agreement. The degree of agreement is high, and it can be presumed that the actual seepage point width is 1–5 mm.

4. **Numerical Simulation of the Displacement Field**

According to the previous analysis, the leakage of the retaining structure will change the seepage field of the foundation pit. In order to study the influence of leakage on the displacement field of the foundation pit, further modeling and analysis were carried out.

The finite element software GTS Midas (Developed by MIDAS IT) was used to establish the numerical calculation model of soil-envelope interaction of the foundation pit considering leakage and not considering the action. The excavation depth of the foundation pit was taken to be 29 m and the pit size was 21 m × 250 m. Four models with different leakage sizes (without leakage point, leakage point width 0.01 m, leakage point width 0.005 m, leakage point width 0.001 m) were established. For the concrete material, a linear elastic model was used, and a Mohr-Coulomb model was used for each layer of soil. The influence of the soil layers on the deformation of the foundation pit was analyzed using solid unit action mainly from two aspects: the horizontal displacement of the enclosure structure and the ground settlement around the foundation pit. The finite element model diagram is shown in Figure 17.
In this paper, we mainly studied the deformation law of the perimeter during the precipitation excavation of the foundation pit. The thick soil layer used is cohesive soil. The Mohr-Coulomb model fits better with the deformation of the perimeter settlement and the simulation values are more appropriate. Moreover, the parameters required by the Mohr-Coulomb model are easier to obtain. Therefore, the Mohr-Coulomb model was used in this paper.

4.1. Analysis of Horizontal Displacement of the Enclosure Structure

During foundation excavation, soil change is a dynamic equilibrium process. When the soil body is unloaded, in order to reach a new balance, it will move from the position with high stress pressure to the position with low stress pressure. The soil bodies at different depth have distinct stress states and deformation. With the increase of excavation degree, the water pressure inside and outside the pit increases, and the seepage force generated by the groundwater infiltration increases. Therefore, in the process of excavation, the enclosure structure is deformed and moves sideways under the influence of soil and groundwater seepage force around the pit.

It can be seen from Figure 18 that the maximum horizontal displacement of the enclosure structure is increasing during the construction of the foundation pit, and the maximum value is 3.8 mm in the first excavation, 7.4 mm in the second excavation, 13.8 mm in the fourth excavation, 23.5 mm in the fourth excavation, 41.2 mm in the fifth excavation, and 53.3 mm in the sixth excavation. The horizontal displacement of the enclosure structure was not obvious in the first excavation, and the maximum horizontal displacement of the enclosure structure increased significantly with excavation times. The location of maximum deformation gradually moved down with the excavation. After the excavation was completed, the maximum horizontal deformation was located at about 0.9 times the depth of the pit, near the bottom of the pit.

From Figures 19–22, it can be seen that there are differences in the values of horizontal displacement of the enclosure structure with and without a leakage point in the construction process of the foundation pit. The maximum horizontal displacements of the enclosure structure are 36.1 mm, 39.1 mm, and 43.5 mm when the leakage point is 0.01 m wide, 0.005 m wide, and 0.001 m wide, respectively, and the maximum horizontal displacement was 53.3 mm when there is no leakage point. The overall deformation trend is consistent, and the curves are bell-shaped with small values at both ends and large values in the middle.

The leakage of the enclosure structure does not change the form of horizontal displacement of the enclosure structure, and the displacement of the enclosure structure gradually decreases as the leakage defect increases. This is due to the total pressure reduction at the outer wall-soil interface of the enclosure structure. In other words, this phenomenon is ascribed to the fact that the increase in horizontal effective stress is smaller than the reduction in pore water pressure. Therefore, the horizontal displacement of the enclosure structure with leakage defects caused by the pre-fall is smaller than the horizontal displacement of the enclosure structure without leakage defects.
Figure 18. The cloud of horizontal displacement of foundation pit excavation enclosure structure without seepage point.

Figure 19. Horizontal displacement curve of foundation pit excavation enclosure structure with a seepage point at 0.01 m.
Figure 20. Horizontal displacement curve of foundation pit excavation enclosure structure with a seepage point at 0.005 m.

Figure 21. Horizontal displacement curve of foundation pit excavation enclosure structure with a seepage point at 0.001 m.

Figure 22. Horizontal displacement curve of foundation pit excavation enclosure structure without seepage point.
4.2. Surface Settlement Analysis around the Foundation Pit

From Figures 23–26, it can be seen that: when the widths of the leakage point are 0.01 m, 0.005 m, 0.001 m the maximum surface settlements around the foundation pit are 49 mm, 42 mm, 31 mm, respectively. When there is no leakage point, the surface settlement is 27 mm. When the water level in the construction process of the foundation pit is different, surface settlement is different, but the overall trend is the same, with the curve being funnel-shaped.

Figure 23. Surface settlement curve during foundation pit excavation with a 0.01 m-wide seepage point.

Figure 24. Surface settlement curve during foundation pit excavation with a 0.005 m-wide seepage point.

With the excavation, the ground settlement becomes larger, and the area with larger soil settlement expands. The ground settlement starts from the edge of the pit and then decreases, and the maximum settlement appears at the completion of excavation. After the maximum settlement position is exceeded, the surface settlement of the soil outside the pit is gradually reduced by the excavation of the pit until it is beyond the excavation influence area. The influence range of surface settlement expands with the excavation depth, and the maximum surface settlement shifts “outward” with the increase of excavation depth. This is mainly related to the consolidation of soil caused by groundwater seepage variation,
so the surface settlement deformation value around the foundation pit is larger than that when the water level is low at the same excavation progress.

![Surface settlement curve during foundation pit excavation with a 0.001 m-wide seepage point.](image1)

**Figure 25.** Surface settlement curve during foundation pit excavation with a 0.001 m-wide seepage point.

![Surface settlement curve during foundation pit excavation without seepage point.](image2)

**Figure 26.** Surface settlement curve during foundation pit excavation without seepage point.

Although the overall trend is the same when there is a leakage point in the enclosure structure and when there is no leakage point, the surface settlement range of the pit increases with the increase of the leakage point. This will cause more damage to the surrounding buildings and will lead to irreversible accidents without in-time treatment.

4.3. **Comparison with Actual Monitoring Data**

As can be seen from Figures 27 and 28, under the action of soil stress and seepage around the foundation pit, the variation trend of the numerical simulation curve is basically consistent with that of the actual monitoring result curve, indicating good agreement. The horizontal displacement of the envelope tends to increase with the increase of excavation depth. With the increase of excavation depth, all aspects of deformation will change. The horizontal displacement of the retaining structure will increase, and the surface settlement outside the foundation pit will show the same trend, suggesting a positive correlation between them. It can be concluded that the numerical simulation results have high precision.
and this finding is of guiding significance for further study on the treatment of foundation pit leakage in water-rich areas.

![Figure 27](image-url). Comparison between numerical simulation and measured horizontal displacement of envelope structure.

![Figure 28](image-url). Comparison between numerical simulation and measured surface settlement.

5. Conclusions

Based on the actual situation that the leakage of the enclosure structure will affect its deformation and the surrounding geotechnical body, the change of seepage flow field was studied by assuming different degrees of leakage with numerical simulation. The following conclusions were obtained:

1. When there is no seepage point or when the seepage point is 10 mm wide, the drop of groundwater level outside the pit near the water stop curtain under the action of seepage flow force is about 20% and 30% of the depth of excavation and water drop in the pit, respectively. When there is leakage in the envelope, the local waterproof failure will lead to the abrupt change of the seepage field. When there is leakage in the envelope, the groundwater flow through the leakage of the envelope is greater than the flow at the bottom of the envelope. The total flow of groundwater into the foundation pit through the bottom of the retaining structure and the leakage is larger than the total flow into the foundation pit through the bottom of the retaining structure and the leakage.
structure. Groundwater velocity and hydraulic gradient are also large in the envelope with leakage, which can easily lead to soil and seepage damages.

2. The horizontal deformation law of the enclosure structure is basically the same as the change law of the enclosure structure reflected by the numerical simulation results when considering the seepage point, but there is a certain difference in the value of the change. The total pressure at the outer wall-soil interface of the enclosure structure in the presence of leakage point decreases. The numerical simulation shows that the maximum deformation of the enclosure structure without a seepage point is about 53.3 mm, which is larger than the deformation value in the presence of a leakage point. The seepage point causes the peak position of the horizontal displacement of the enclosure structure to show a sinking trend.

3. During the excavation of the foundation pit, when the water level is different, the surface deformation pattern around the foundation pit is basically similar and it is “funnel-shaped”. In addition, the maximum position is shifted outward to a certain extent. However, the existence of leakage points will expand the influence scope of foundation pit settlement, resulting in greater adverse effects.

4. The finite element analysis results are close to the field monitoring results. The horizontal displacement of the enclosure structure and the surface settlement curve around the pit are almost the same with or without considering the effect of the seepage point, which indicates that the numerical simulation results are accurate. This finding provides guidance for further research on the treatment measures of seepage points of pits in water-rich areas.

Inhibiting the expansion of seepage channels and stopping the aggravation of soil erosion are effective ways to control the deterioration of foundation pit seepage disaster. In addition, in order to reduce the risk of foundation pit seepage disaster, the foundation pit enclosure structure system should be reasonably selected to ensure the construction quality and seepage prevention effect of the water barrier structure.

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