The Analysis of Tunnel Collapse Mechanism and Grouting Reinforcement Measures Under the Unsaturated Seepage Effect

Yang Zhao¹,²,³,⁴, Ren Meng¹,²,³,⁴, Huang Wei¹,²,³,⁴, Yuan Qing¹,²,³,⁴

¹CCCC Second Harbor Engineering Company LTD, WuHan 430000, China
²Key Laboratory of Large-Span Bridge Construction Technology, WuHan 430000, China
³Research and Development Center of Transport Industry of Intelligent Manufacturing Technologies of Transport Infrastructure, WuHan 430000, China
⁴CCCC Highway Bridge National Engineering Research Centre Co. Ltd, WuHan 430000, China

*Corresponding author’s e-mail: growingwild@163.com

Abstract: Based on the unsaturated seepage and strength theory, the influence of seepage on tunnel deformation and stability is studied, the mechanism of tunnel collapse under seepage is deeply analyzed, and the grouting reinforcement measures are put forward. The analysis results show that the strength attenuation of unsaturated soil caused by seepage is the main inducement of tunnel collapse. The development of tunnel collapse is controlled by conducting the backpressure of surcharge, improving the softening condition of soil, and grouting reinforcement of soil with weakened strength. Finally, the risk of collapse is effectively solved.

1. Introduction

Tunnel face instability collapse is one of the common risk accidents during tunnel construction, which causes serious harm to engineering construction, personnel safety and surrounding traffic. Therefore, it is necessary to analyze the collapse reason and propose effective treatment measures, which is an important step to ensure the quality of tunnel excavation, reduce tunnel risk and improve safety performance.

There are many reasons leading to tunnel collapse risk. The previous studies attributed the main reason to poor geological conditions, unreasonable survey and design, improper construction organization and other aspects [¹-⁴]. Wang Fayu [¹] analyzed the collapse accident of Yumiao tunnel, and attributed the geological reasons of the accident to development of surrounding rock fissures accompanied by surface water infiltration, resulting in poor self-stability of surrounding rock. Jiang Jie [⁵] thinks that the collapse of Fanjialin Tunnel is caused by weak fracture zone in surrounding rock, vertical joint development, mudstone softening in water and other factors. Zhang Xiaojin and et al [⁶] analyzed the causes of tunnel collapse from the aspects of low grade of geological surrounding rock, vibration speed control of blasting construction, insufficient grouting reinforcement, and insufficient monitoring and measurement frequency, and put forward corresponding treatment measures.

At present, the research on the cause of tunnel collapse mainly focuses on the comprehensive factors, but less on the mechanical mechanism behind it. The analysis of the mechanical mechanism behind
collapse can guide more targeted treatment measures and provide experience for similar projects in the future. In this paper, the mechanism of excavation face collapse risk is analyzed in detail, and the corresponding treatment measures are put forward.

2. Project profile

From Songjiang ecological park station to Jinxiang Street Station of Harbin rail transit line 3, after leaving Songjiang ecological park station, it is laid eastward along Baojian Road, then it turns to Tongxiang street with a radius of 300 m and enters Jinxiang Street Station northward along Tongxiang street. The starting mileage of the section is DK15 + 192.011, the ending mileage is DK16 + 141.915, and the covering soil is 11 m - 21 m.

This tunnel interval is a single-line single-tube horseshoe-shaped tunnel. The whole line is constructed by mining method and is excavated by benching method retaining core soil. The superimposed soil of the tunnel is mainly plastic silty clay layer with rigid plastic and soft plastic silty clay. The distribution of silty clay in the excavation area is mainly rigid plastic and plastic silty clay layer. There is soft plastic and flow plastic silty clay in the influence range of tunnel construction, which has the characteristics of high water content, high void ratio, low strength and high permeability. It is easy to produce rheological phenomenon during tunnel excavation, resulting in poor stability of surrounding structure.

The depth of tunnel in this interval is about 16.0-25.9 m, and the pore phreatic water level in this site is about 39.1-44.5 m, which will not cause adverse effects on the excavation of the tunnel. There are many municipal drainage pipelines within the engineering areas, and some of them are old pipelines in urban area, which are in disrepair for a long time, damaged and leaking.

2.1 Overview of collapse

In the construction stage of tunnel entrance, the core soil of tunnel face has good compactness, low water content and no seepage. After entering the tunnel for 2.25m (DK15 + 794.49), there is water seepage above the main line and at the tunnel face. The water content of the soil is high, the arch roof drips continuously, and there is a small amount of water on the tunnel face on the left side of the upper bench. It is difficult to stabilize the core soil, and soil collapse often occurs.

When the left line construction reaches DK15 + 796.49, a small amount of soil collapse occurs at the working face of the vault. In order to prevent further danger expansion, the working face is temporarily closed after the completion of grid installation, and the soil moisture in front of the closed working face is detected by digging probe holes. The water content is 25.8% at 0.5 - 1.5m from the working face, 21.7% at 1.5 - 2.5m, and 15% at 2.5m - 3m, which is close to normal. When the construction is near DK15 + 799, the collapse of the 14th and 15th primary supports of the upper bench occurs. The soil collapse begins to decrease 40 minutes later and stabilize about 1 hour later. The collapse situation is shown in Figure. 1.
3. Collapse mechanism analysis

3.1. Cause analysis of increasing water content in excavation face
In the initial stage of tunnel excavation, the water content of the face is low, the soil is dense, and the self-stability is good. Considering that there are many old municipal pipelines in the project area, many surfaces water pipes have been found leaking during the excavation process (Figure. 2), and the soil around the leaking pipeline has shown obvious soft plastic and flow plastic state. The overlying soil of the tunnel is mainly silty clay. Due to the influence of viscous water film in clay and the characteristics of water absorption and expansion of clay, its permeability coefficient is generally extremely low\cite{7} and the influence range of surface seepage in silty clay is limited. However, with the emergence of free face in tunnel excavation, the overlying soil of the tunnel is disturbed to produce loose and cracks, which provides a seepage channel.

At the same time, the research results show that the permeability characteristics of unsaturated soil is different from that of saturated soil, and its permeability coefficient presents a nonlinear growth trend with the increase of water content, and when the water content is greater than a certain threshold, the growth trend of permeability coefficient increases significantly\cite{8}. According to the test of permeability coefficient of silty clay under unsaturated condition by Li Yongle et al.\cite{8}, the threshold value of water content of silty clay is about 15% - 20%. Under unsaturated condition, when the volume water content is less than the threshold value, the silty clay is in an impermeable state; when the volume water content exceeds the threshold value, the small change of water content can lead to the change of unsaturated permeability coefficient order of magnitude change.

To sum up, there are two reasons for the significant influence of surface pipeline leakage on the water content of tunnel face: on the one hand, the soil is loose and cracked due to excavation, which provides seepage path; on the other hand, when the water content of soil increases to a certain extent, its permeability coefficient will increase significantly, thus promoting the seepage.

3.2. Effect of seepage on unsaturated soil strength
The strength of unsaturated soil is closely related to its moisture content\cite{9,10}. According to the classical theoretical formula of shear strength of unsaturated soil proposed by Fredlund et al.\cite{11},

\[
\tau_{eff} = c' + (\sigma_f - u_a) \tan \phi' + (u_a - u_w) \tan \phi_h
\]  

among:
- \(c'\): effective cohesion;
- \(u_a\): pore gas pressure on failure surface;
- \((\sigma_f - u_a)\): net normal stress state on failure surface;
- \((u_a - u_w)\): matrix suction on failure surface.

Figure. 2 The Leaking pipeline

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$\varphi'$: internal friction angle related to net normal strain $((\sigma_f-\sigma_a)f)$.  
$\varphi^b$: rate of shear strength increasing with matrix suction $((u_a-u_w)f)$.  

The shear strength of unsaturated soil is related to two variables: net normal stress and matrix suction. $\tan \varphi'$ is the change rate of soil strength caused by net normal stress, and $\tan \varphi^b$ is the change rate of soil strength caused by matrix suction. The increase of water content will lead to the decrease of matrix suction $((u_a-u_w)f)$, which leads to the decrease of soil strength.  

Therefore, the significant consequence of the increase of soil moisture content is that the cohesion and internal friction angle of soil continue to decline, and the strength continues to weaken, resulting in the reduction of arching capacity and the deterioration of self-stability of tunnel face. With the continuous infiltration of water, the deformation of the overlying soil on the excavation face increases, and with the increase of the leakage time, the soil has a significant deformation characteristic with the change of the leakage area.

### 3.3. Finite element analysis of tunnel excavation under surface seepage condition

Based on the above unsaturated soil permeability and strength theory, the soil water characteristic function and permeability function related to matric suction are set in the finite element analysis to deeply analyze the influence of seepage on tunnel deformation and stress.

1. **Finite element model**
   
   As shown in Figure 3, a two-dimensional finite element model is established, with the size of 40m in length and 40m in width. Mohr Coulomb constitutive model is adopted for soil mass, and soil parameters are selected from geological exploration data (see Table 1). At the same time, the unsaturated property of soil is introduced, and the unsaturated property of soil is defined by soil water characteristic function and permeability function. Soil water characteristic curve is usually obtained by test. In this regard, many scholars have carried out experimental research on different properties of soil \[12,13\] and obtained soil water characteristic curve. Based on the experimental data of soil water characteristics of silty clay obtained by Lin Hongzhou et al. \[13\], the relationship curve between negative pore water pressure and water content is defined.

![Figure 3 The simulation model](image)

| Soil | Elastic modulus kPa | Poisson's ratio | Bulk density kN/m$^3$ | Initial void ratio | Permeability coefficient-x kx | Permeability coefficient-y ky | Cohesion kPa | Friction angle |
|------|---------------------|----------------|----------------------|--------------------|-----------------------------|-----------------------------|-------------|---------------|
| 4-2  | 17940               | 0.27           | 19.2                 | 0.762              | 1.53E-05                    | 1.53E-05                    | 33.2        | 15            |
| 4-2-3| 11550               | 0.28           | 19.1                 | 0.822              | 1.53E-05                    | 1.53E-05                    | 23.8        | 8.1           |
| 4-2-1| 24060               | 0.3            | 19.5                 | 0.665              | 1.53E-05                    | 1.53E-05                    | 50.4        | 20.2          |
| 4-2-2| 25020               | 0.3            | 19                   | 0.69               | 1.53E-05                    | 1.53E-05                    | 40          | 21            |
| 5-1  | 18690               | 0.32           | 19.7                 | 0.721              | 1.53E-05                    | 1.53E-05                    | 38.1        | 15.6          |
| 5-1-1| 26400               | 0.28           | 20                   | 0.645              | 1.53E-05                    | 1.53E-05                    | 52.2        | 19.2          |
(2) The result analysis

The normal excavation condition and the surface leakage condition after excavation are considered, respectively. Under normal excavation conditions, the settlement of tunnel vault is 0.55mm, the convergence deformation of tunnel is 18.66mm, and the maximum bending moment of steel arch is 300kN·m. If there is leakage on the surface after tunnel excavation, it can be seen from Figure 4 that with the continuous seepage at the surface leakage point, the moisture content of the soil above the excavated tunnel increases, and gradually develops from the unsaturated state to the final saturated state (leakage for 8 hours). In this process, the changes of tunnel deformation and arch stress with the leakage time are shown in the Figure 5, with the continuous leakage, the settlement of the tunnel vault gradually develops from the initial 0.55mm to 17.87mm (after 10 hours of leakage), the convergence deformation of the tunnel gradually increases from the initial 18.66mm to 21.94mm (after 10 hours of leakage), and the maximum bending moment of the steel arch frame also increases to 346 kN·m (after 10 hours of leakage).

![Figure 4 Mass water content versus seepage time](image.png)

(a) crown subsidence  
(b) clearance convergence
The above calculation results fully show that the unsaturated state of soil above the excavation surface changes due to surface leakage. According to the strength characteristics of unsaturated soil, the increase of soil moisture content caused by leakage will lead to the decrease of matrix suction, which leads to the decrease of soil strength. Therefore, with the continuous infiltration of water, the deformation of the excavated tunnel will inevitably increase, and the stress situation of the tunnel structure worsens, which leads to the continuous development of the surrounding rock plastic zone of the excavated tunnel with the continuous development of the seepage process, and the plastic zone of the soil layer above the arch roof develops rapidly, which is extremely easy to lead to the occurrence of the vault collapse.

4. Landslide treatment measures

The main causes of the accident are the decrease of soil strength and weak self-stability caused by pipeline leakage. The treatment measures are mainly divided into controlling the development of collapse by surcharge back pressure, grouting reinforcement to improve soil saturation and softening, optimizing excavation footage and construction methods.

4.1. Surcharge and backfilling

As shown in Figure 6, due to the instability of the core soil, three grid footplates are suspended, and the circumferential cracks are generated at the weak points under the upper pressure. Firstly, the cavity behind the primary support caused by soil collapse is filled with concrete, and reinforcement is made to stabilize the soil. Then, mesh and shotcrete are hung to fill the cavity caused by soil collapse. Then, the collapsed soil is simply cleaned to avoid disturbing the core soil, and the temporary inverted arch is constructed to support the suspended grid at the arch foot to prevent further settlement. Finally, the collapsed core soil is supported by earthwork backfilling, then the suspended arch foot is filled with sandbags, and the core soil is supported by sandbags.

4.2. Grouting reinforcement of overlying soil

As shown in Figure 7, a 400mm diameter hole is drilled from the ground to the vault at the collapse location, and the vault cavity is filled with concrete. Deep hole double slurry grouting is carried out at the ground within 20m above the main line of the collapse section, which is arranged in a quincunx shape, with three pipes in a row, with a spacing of 2m. The thickness of soil covering near the collapse section is 15.8m, and the depth of grouting pipe is 13.5m.
4.3. Grouting reinforcement in front of face
The grouting is carried out along the radial direction of the arch wall, and the water pockets that may exist in the surrounding rock behind the primary support are blocked. The grouting is arranged at 1 m in the circumferential direction, with a length of 3.5 m, grouting pressure of 0.4 MPa - 0.6 MPa, and a longitudinal interval of 1 m. The grouting sequence is: left side wall → right side wall → arch crown, and no grouting is carried out at the invert.

4.4. Optimizing excavation footage and supporting method
During the construction, I-steel temporary invert was added, and the step distance between the upper and lower steps was increased to more than 6 m. Increase the reserved height of the core soil and reserve the longitudinal slope of the steps. Increase the number of foot lock anchor pipes on the upper bench, set 3-foot lock anchors with a length of 3.5m on each side, and increase the radial small pipe grouting anchor pipes.

In the collapse section, increase the support parameters, and ensure that the longitudinal connecting reinforcement is welded firmly, and the mesh overlap length is sufficient. When the soil moisture content is large, spray first, then cast steel grids and sprayed concrete.

Broke the collapsed grid, erect the grid in the collapse section again with three grids simultaneously, and the erected grid should be pushed forward in close rows without interval. The excavation footage shall be controlled within 35cm each time until the settlement grid is removed, and the arch is replaced.

5. Treatment effect
On June 21, the water seepage in the main line of No.1 Tunnel basically stopped, and the initial arch roof began to be dry. At the same time, the soil moisture content was normal. The closed tunnel face was opened, and the main line of No.1 Tunnel was stepped up. On that day, the construction footage of the 21st stepped up grid was 0.25m, and on June 22, the construction footage of the two stepped up grids was 0.75m. Grouting traces are clearly observed during the excavation (Figure. 8). At the same time, the monitoring data show that the settlement and clearance convergence of the tunnel vault are gradually
stable, which indicates that the treatment measures are effective, and the tunnel collapse is effectively controlled.

![Figure. 8 Photo of grouting achievement](image1)

![Figure. 9 monitoring data](image2)

6. Conclusion

Through the optimization analysis of the causes and treatment measures of tunnel collapse section, the main conclusions are as follows:

1. The main causes of tunnel collapse in the section between Songjiang ecological park station and jinxiangjie station of Harbin rail transit line 3 are unsaturated soil seepage caused by surface leakage, soil saturation softening and strength reduction.

2. When water leakage occurs, the unsaturated characteristics of soil should be fully considered. The permeability and shear strength of unsaturated soil are closely related to water content. When the water content in soil increases, the permeability coefficient of soil increases, the cohesion and internal friction angle decrease, and the strength of soil decreases, resulting in the increase of deformation and stress of tunnel, which is easy to collapse.

3. The treatment measures mainly focus on the effective control of the development of tunnel collapse, the improvement of soil saturation and softening, and the improvement of the soft soil layer. By adjusting the support parameters and grouting reinforcement, the collapse situation is effectively controlled, and the tunnel will be excavated normally.

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