Research on Failure Mechanism of Floor Heave in Underlying Expansive Soil Railway Tunnel

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Abstract. Floor heave deformation of railway tunnel is a common disease in the operation stage of high-speed railway in recent years. Due to its complex deformation mechanism, there is no specific and reliable evaluation method at present. In order to investigate the deformation rule and failure mechanism of the invert arch of railway tunnel when subjected to the expansion force of the bottom swelling surrounding rock, the tunnel floor heave loading test system is designed independently. The working conditions of the tunnel invert under different expansion forces are simulated. The test results show that (1) The circumferential stress on the outside of the arch foot and the inside of the invert arch is tensile stress, and the inside of the arch foot and the outside of the invert is compressive stress, and its maximum value is at the arch foot. The arch foot and the invert are more sensitive to the expansion of the basement, and it is easy to destruction. (2) After the invert bottom is bulging, the inner side of the invert and the outer side of the arch foot are strained. For concrete lining, the tensile strength is far less than the compressive strength, that is, these parts are prone to tensile damage, so they are the weak positions of the entire lining. It is recommended to properly reinforce at this position in practical engineering. (3) Under the action of basement expansion of the tunnel, the surrounding rock at both sides of the tunnel and the position of the arch is easy to fail and weaken the bearing arch effect, thus aggravating the deformation and failure of the lining.

Keywords: Tunnel engineering; Invert arch; Floor heave deformation; Model test

1 INTRODUCTION

Invert arch is an important part of improving the overall stability of tunnel. When the tunnel passes through the water-rich expansive soil layer, the invert floor heave deformation and failure are easy to occur. Under the action of tunnel excavation, groundwater disturbance and construction disturbance, the surrounding rock of expansive soil will expansion and contraction, and generating force on the invert of tunnel. This can cause floor heave disease at the bottom of the invert, especially dur-

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ing the operational phase. Domestic and foreign scholars have studied the phenomenon of tunnel floor heave: Chen Guihong[1], Deng Penghai[2], Huang Hua[3] et al believe that after tunnel excavation, the surrounding rock deteriorates and the strength of rock mass decreases leading to tunnel floor heave; The research of C. Butscher[4], Wang Yang[5] et al. shows that tunnel floor heave may be related to the interaction of high contact stress and horizontal stress caused by rock water absorption and expansion. Xu Huairen[6], Yuan Wei[7] et al believe that the local stress concentration caused by stress redistribution after tunnel excavation causes the surrounding rock to creep, and the creep pressure causes the tunnel floor heave. B Schädlich[8], Du Mingqing[9] et al. studied the failure mode of tunnel floor deformation and believed that tunnel floor heave was caused by the compression of expansive mudstone under the action of earth stress. Meng Lingbao[10] et al. showed that the instability and slip failure process of tunnel surrounding rock may lead to tunnel floor heave, and the floor heave deformation is divided into active failure zone, extrusion transition zone and passive failure zone. The results of Wang Zijiang[11] et al. 's research on tunnel floor deformation and failure modes show that local high ground stress may be a inducing factor of tunnel floor heave, and the extent of floor heave may be affected by factors such as rock mass strength. Based on the strength deterioration theory, Gao zhen[12] et al. studied the floor heave mechanism of tunnel in shale sedimentary rock strata and concluded that the floor heave degree of tunnel will gradually increase with the decrease of cohesion of surrounding rock. These studies include investigating the expansion mechanism of expansive surrounding rocks and the stress characteristics of tunnel vaults under special surrounding rock conditions, as well as the causes of bottom heaving. However, there is a lack of research on the basic failure modes, fundamental mechanisms, and evolutionary mechanisms of tunnel vaults in high-speed railway tunnels.

Therefore, it is necessary to carry out experimental research on the stress and deformation failure mechanism of invert structure under the action of expansive force. In this paper, the basic failure mode of invert floor heave of high-speed railway tunnel is studied by using indoor model tests, and the key damaged locations of invert are explored, in order to provide reference and basis for the design and construction of high-speed railway tunnel invert.

2 EXPERIMENTAL DESIGN

2.1 Engineering Background

Based on Ankang Tunnel project of Xikang high-speed Railway, a model test was conducted to study the mechanism of disaster caused by bottom heave deformation of tunnel through expansive soil layer under water-rich environment. As shown in Figure 1, the cross-sectional diagram of Ankang Tunnel shows that the tunnel is single-hole and double-line, with a total length of 7001m and a maximum buried depth of 160m and a minimum buried depth of 2m. Among them, DK170+894~DK171+220 is a medium water-rich area with shallow burial depth, and the tunnel body range is all expansive soil, boulder soil and sand soil, which is a Class I high-risk tunnel, and it is easy to cause water gushing and collapse during excavation.

The excavation section of the tunnel adopts three step excavation temporary transverse support, advance support measures: φ89 middle pipe shed +φ42 single-layer small conduit, φ108 large pipe shed, auxiliary construction measures: curtain grouting in the tunnel, horizontal rotary jet pile reinforcement, vertical rotary jet pile reinforcement, isolation pile. Large deformation of surrounding rock and floor heave deformation are easy to occur during tunnel construction in expansive soil layer. Engineering practice shows that the tunnel bottom is prone to problems such as invert breakage and basement surrounding rock hollowing under long-term train operation.

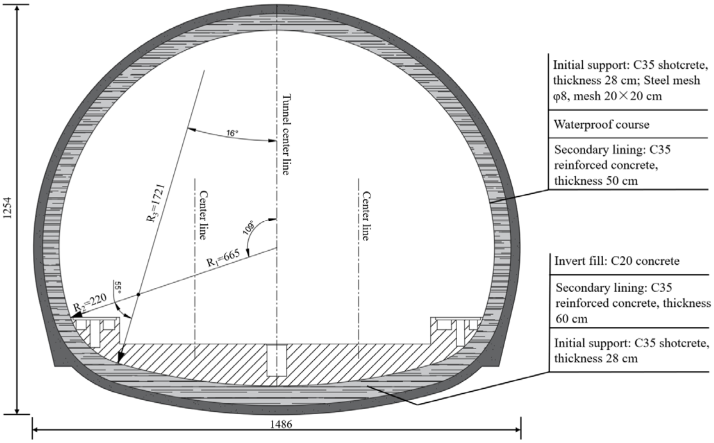


Fig. 1. Ankang tunnel structure profile.

2.2 Test System Design

In order to investigate the deformation rule and failure mechanism of the floor heave when the invert of the railway tunnel is subjected to the swelling force of the bottom surrounding rock, the tunnel floor heave loading test system is designed independently. The system consists of the test model box, the floor heave loading system and the data monitoring and acquisition system. The size of the model box is related to the boundary conditions of the model test. Therefore, its size should not be too small, otherwise the boundary effect will significantly affect the test results. As shown in figure 2, the dimensions of the model box selected for this test are: length × width × height = 2m×1m×1.5m, which ensures that the distance from the center of the tunnel model to the left and right boundaries of the box is not less than 3 times the tunnel diameter. The model box is made of welded angle steel, and transparent organic glass panels are installed on all four sides of the box, the bottom surface is laid with wooden boards, and the center of the wooden board is provided with a 5cm diameter hole for the jack piston rod to pass through. The whole model box is supported by bricks, and the bottom bulge loading system under it which is composed of a jack (rated load 2T) and a round cast iron loading plate (diameter 12cm, thickness 2cm). The loading plate and the saddle on the upper part of the jack piston rod are welded to increase the loading area. The data monitoring and acquisition system is composed of DH3816N static data acquisition box, soil pressure sensor and strain gauge.

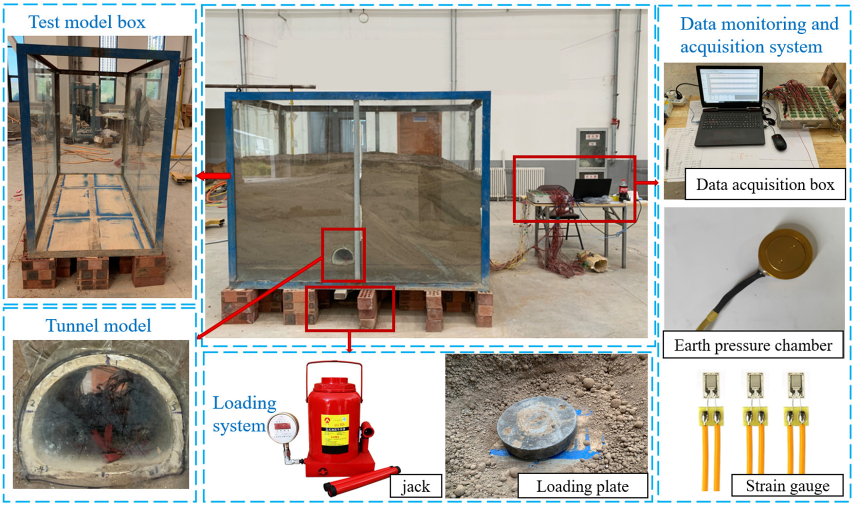


Fig. 2. Test system and composition.

In order to prevent the tunnel model from being lifted as a whole during the loading process, both ends of the tunnel model were fixed at the bottom of the model box with 7×19 wire ropes.

2.3 Surrounding Rock Similarity Ratio Design

In order to meet the above test purposes, this test takes geometric similarity ratio, density similarity ratio and bulk density similarity ratio as the basis, uses dimensional analysis and three similarity theorems to determine the test similarity ratio, and obtains the similarity ratio of physical and mechanical parameters between the prototype and the model through calculation:

1)Geometric similarity ratio C_L=85
2)Unit weight similarity ratio C_γ=1
3)Density similarity ratio C_ρ=1
4)Poisson's ratio, internal friction Angle similarity ratio $C_\varphi=C_\mu$=1
5)Similarity ratio of cohesive force and elastic modulus $C_c=C_E$=85

Due to the limitations of existing test instruments and conditions, only three parameters of cohesion, internal friction Angle and volume weight were considered in this orthogonal test. The ratio of test soil samples was determined by orthogonal test, and the materials were yellow clay, fine sand, barite powder and bentonite. Finally, the ratio of soil in the simulation test can be obtained as follows: yellow clay: fine sand: barite powder: bentonite: water =8:10:3:24. The shear strength parameters of soil samples measured by direct shear test are shown in Table 1:

Table 1. Parameters of prototype materials and similar materials in orthogonal test.

Category	Cohesion c(kPa)	Angle of internal friction φ(°)	Unit weight γ(kN/m^3)
Prototype	92	25	17.85
Similar value	1.08	25	17.85
Formulated value	5	23	18.0

2.4 Model Design and Production

The maximum span of the tunnel prototype is 14.5m and the height is 12.68m. According to the geometric similarity, the maximum span of the model is 17cm, the height is 15cm and the thickness is 0.6cm. The width of the model box is: 1m, so the tunnel length is designed to be 90cm. The tunnel lining is mainly made of a mixture of gypsum powder and water in a ratio of 1.1:1. The effectiveness of gypsum as a similar material to simulate C30 concrete has been demonstrated in previous studies[13]. A wire mesh with a diameter of 0.2mm is used to approximate the circumferential main reinforcement and distributed reinforcement in the lining structure.

2.5 Sensor Selection and Layout

The sensors used in the test mainly include strain gauge and soil pressure box. The sensor layout position is shown in Figure 3. The tunnel model is 90cm long. Three sections are arranged along the longitudinal length of the model, with 6 soil pressures and 6 pairs of strain gauges deployed on each section. One soil pressure is assigned to the vault and bottom of the arch at the midpoint of section A and Section B, and one earth pressure is assigned to the vault and bottom of the arch at the midpoint of section B and section C. total of 36 strain gauges and 22 earth pressures are deployed.

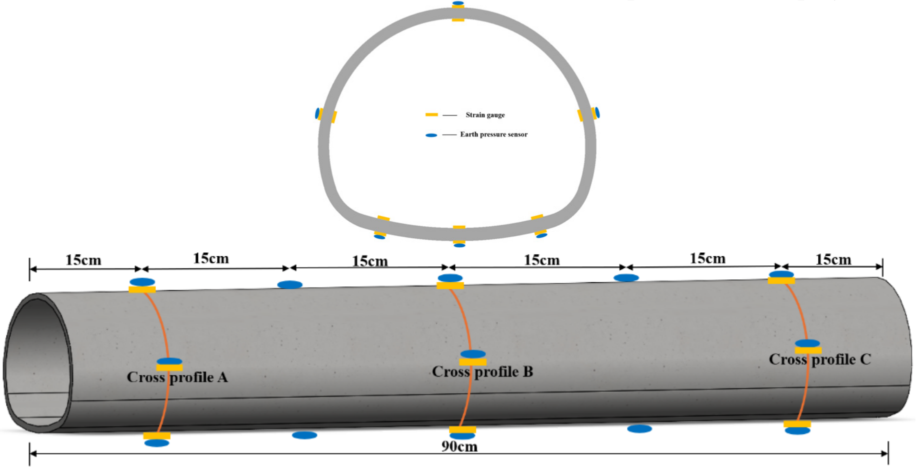


Fig. 3. The sensor used in the test and its arrangement.

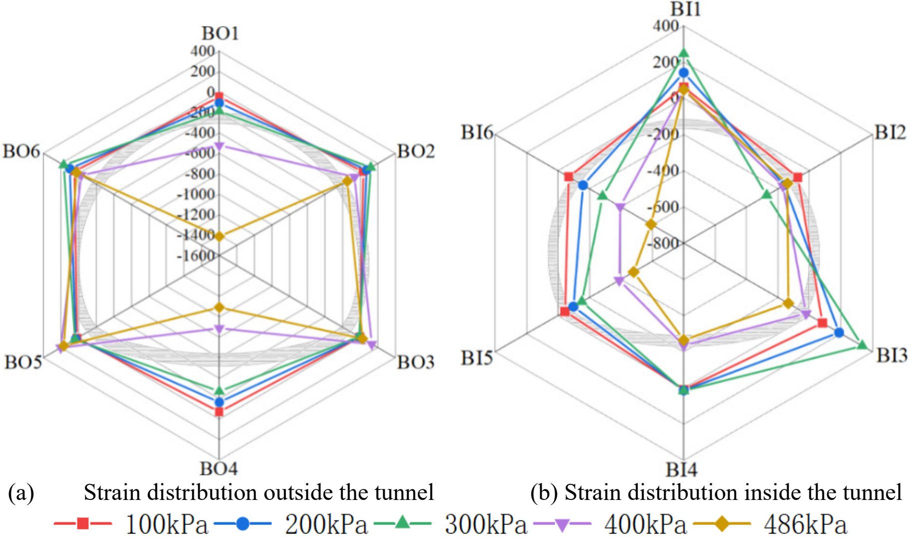
2.6 Experimental Loading Scheme.

The force exerted on the crown by the expansion of the surrounding rock can be simplified as the uplift force from the bottom of the crown. Therefore, in the test, the force is applied vertically upward from the bottom of the tunnel, and the other three directions of the model are fixed boundaries. The test adopts a step-by-step loading method, using a hydraulic pump with a jack to apply a controllable level of forced pressure to simulate the expansion of the base surrounding rock. The pressure on the loading plate increases by 100 kPa for each loading level, and the pressure is increased after the data stabilizes for each level. The test can be stopped when the bottom heave failure of the crown structure occurs.

3 ANALYSIS OF TEST RESULTS

3.1 Analysis of Lining Deformation Characteristics

Section B directly above the loading plate is taken as the research cross section, I represents the inner strain of the tunnel, O represents the outer strain of the tunnel, for example, I1 represents the strain corresponding to the measurement point 1 inside the tunnel. The annular strain distribution inside and outside the tunnel is shown in the figure below.



(a) Strain distribution outside the tunnel (b) Strain distribution inside the tunnel

Fig. 4. Strain distribution diagram of tunnel

The annular strain distribution of the inner and outer lining of section B is significantly different. As shown in Figure 4(a), the outer arch top (BO1) and arch bottom (BO4) of the lining are under pressure and the pressure increases with the increase of the load value. The strain value increases rapidly after the load reaches 300kPa, indicating that the lining structure suffers brittle failure at this time. The maximum value is 1414με when the corresponding loading value is 486kPa at the arch top. The strain at the arch waist (BO2, BO6) and arch foot (BO3, BO5) is mainly tensile, and the strain increases first and then decreases with the increase of the loading value, which is related to the coordinated deformation of the lining and the redistribution of surrounding rock stress.

As shown in Figure 4(b), The strain response of the inner lining is mainly compressive strain except tensile strain of the arch. In addition, the strain of arch foot and invert increases steadily before 300kPa load, and then increases rapidly, especially the strain at right arch foot changes from tensile strain to compressive strain, it shows that the mechanical response of invert and arch foot is more obvious than that of arch top and arch waist under the action of basement expansion.

3.2 Internal Force Analysis Of Lining

The peak values of the inner and outer strains of the lining structure are ε_1 and ε_2 respectively. According to the constitutive relationship of the material, the calculation formula of the section bending moment per unit length of the lining can be obtained as follows:

$$M = \frac{1}{12} E(\varepsilon_1 - \varepsilon_2) b h^2 \tag{1}$$

In the formula:

E—is the lining elastic modulus, which is 0.77 GPa according to the design value;

b—is the unit length, which is 1 m;

h—is the lining thickness, according to the design value of 0.6cm.

As shown in the figure 5, the bending moment of the tunnel section is negative at the arch top and arch bottom, and the bending moment at the arch waist and arch foot is positive as a whole, where the bending moment is positive, indicating the outer tension of the lining, that is, under the action of the expansion load of the surrounding rock below, the outer tension and inner tension of the arch top and arch bottom, while the arch waist and arch foot are the outer tension and inner pressure. With the increase of loading value, the positive and negative bending moments of each measuring point show an increasing trend.

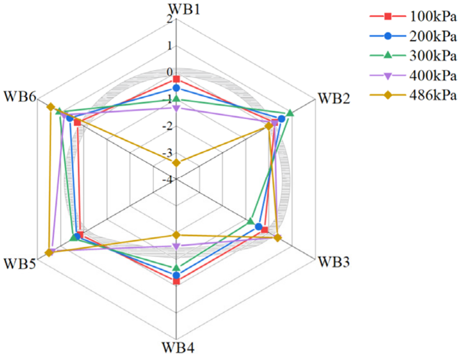


Fig. 5. Tunnel bending moment distribution diagram

As a pressure bearing member, the tensile strength of the concrete material cast in the lining is far less than the compressive strength, that is, the tension part is the weak position of the entire lining. The bending moment of the left side of the secondary lining is larger and bends outwards when the model is damaged. As the left and right invert arch feet bend outwards, the invert arch bottom rises upward, and the invert arch bottom heave occurs when the model is damaged.

3.3 Analysis of Soil Pressure Results of Surrounding Rock

The distribution diagram of surrounding rock pressure around the tunnel is obtained by monitoring the soil pressure sensor. As shown in the figure 6, under the action of basement expansion load, the pressure of surrounding rock across the tunnel is in the order of invert center > arch foot > arch waist > arch top. The maximum soil pressure at the invert center is 110.16kPa, while that at the arch top is -10.5kPa under the same load. This indicates that although the tunnel is subjected to cooperative forces in the ring direction, the pressure on the invert of the tunnel is much greater than that on the superstructure under the expansion load of the base, which further explains why the mechanical response of the invert and the arch foot is more obvious than that of the arch and the waist invert. Under the action of basement expansion force, the tunnel as a whole has vertical flattening deformation, and the surrounding rock on both sides of the tunnel and the tunnel arch are susceptible to failure, which weakens the bearing arch effect of the tunnel in the soil, and further aggravates the deformation and failure of the lining.

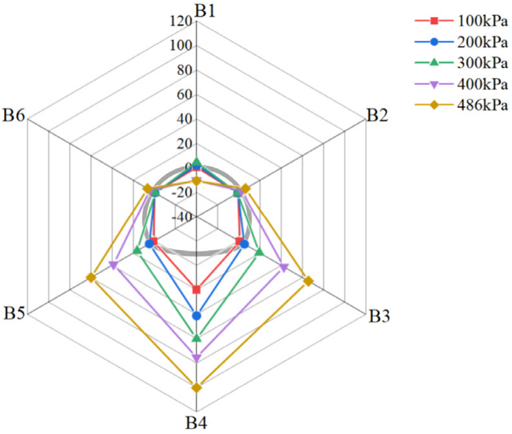


Fig. 6. Soil pressure distribution in tunnel.

4 CONCLUSION

Through the tunnel floor heave loading test device, simulated the working conditions of the tunnel invert under various expansion forces, and the deformation rule and failure mechanism of the railway tunnel invert under the expansion force of the bottom expansive surrounding rock were investigated. The research results show that:

(1) Under the action of basement expansion, the circumferential stress on the outside of the arch foot and the inside of the invert is tensile stress, and the inside of the arch foot and the outside of the invert is compressive stress, and its maximum value is at the arch foot. The arch foot and the invert are more sensitive to the action of basement expansion, and are prone to failure. It is recommended to implement measures such as increasing the quantity of foot anchors and rock bolts at the springing and invert of the tunnel lining in order to improve the overall stability of the lining structure by anchoring and reinforcing the surrounding rock.

(2) After the invert bottom is bulging, the inner side of the invert and the outer side of the arch foot are strained. For the concrete lining, the tensile strength is far less than the compressive strength, that is, these parts are prone to tensile damage, so they are the weak positions of the entire lining. It is recommended to properly strengthen the position in the actual project.

(3) Under the action of basement expansion of the tunnel, the surrounding rock at both sides of the tunnel and the position of the arch top is easy to destroy and weaken the bearing arch effect, thus aggravating the deformation and failure of the lining. Therefore, appropriate measures need to be taken during the design and construction stages of the expansive soil tunnel to reduce the impact of base expansion, such as improving the mechanical characteristics of the expansive soil, optimizing the tunnel structure, or using special structural designs.

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