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Analysis on Stress and Stability of Lining in Partially-blocked Tunnel Drainage System

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Abstract

Drainage systems are important in tunnel projects. The condition of a drainage system has an impact on the stress condition and stability of the tunnel lining. To further reveal the difference between the stress condition and the stability of the tunnel lining of the drainage system under two block patterns, Zhongliangshan Tunnel was selected for field tests. On the basis of the tests, the stress on various parts of the tunnel lining and its variation trend were studied. Then, the numerical model of the tunnel was established with the finite element method and the numerical simulation results were compared with the field test results. On this basis, the stability of the tunnel when the drainage system was partially blocked was analyzed. Test results indicate a huge difference between the two block patterns of the drainage system in how they influence the lining stress. The finite element analysis confirms the reliability of the numerical model. The tunnel stability analysis shows that when the blocked lengths are 16 and 24 m, the reduction factors are approximately 10.3 and 9.7, respectively, and the tunnel stability is controlled by the symmetric block pattern of the drainage system. When the blocked lengths increase to 32 and 40 m, the reduction factors are reduced to 9.0 and 8.7, respectively, and the tunnel stability is controlled by the asymmetric block pattern. The length of the blocked part determines which block pattern controls the tunnel stability. In the case of asymmetric block, vault limit displacement is not recommended as an instability criterion.

Keywords: tunnel project, drainage system, partial block, stress condition of lining, stability

1. Introduction

With the rapid development of China's transportation infrastructure, building tunnels in groundwater-rich areas has become unavoidable. As an important part of a tunnel, a drainage system that works well is the premise of a properly working tunnel. Partial block is likely to occur in tunnel drainage systems in groundwater-rich areas due to various reasons, such as significant presence of easy-to-precipitate substances in groundwater, microorganisms that breed and scale in the drainage pipes, and concrete leakage and lack of standardization during construction [1, 2]. Predicting whether the block is symmetric on both sides of the tunnel cross-section or not is difficult when the drainage system of the tunnel is blocked due to the reasons above. Symmetric block in this study refers to the situation where the drainage system is blocked the same way on both sides of the tunnel cross-section, while asymmetric block refers to the situation where the drainage system is blocked only on one side of the tunnel cross-section. These are the two partial block patterns in tunnel drainage systems, where partial block is defined as the symmetric or asymmetric block of different lengths of the drainage system along the tunnel.

Scholars at home and abroad have focused on the symmetric block of drainage systems when studying the influence of partial block on tunnels. They conducted extensive research on symmetric block [3–7] and believed that the symmetric block of drainage systems seriously affects the normal service capacity of tunnels. However, the situation is complex and full of uncertainties in actual projects, because drainage systems are not always blocked symmetrically. Therefore, the asymmetric block pattern should be studied.

In view of the above, field tests and numerical analysis were conducted to study and compare the stress conditions and overall stability of the tunnel lining under the two block patterns. The goal is to improve the safety of tunnel structures when drainage systems are partially blocked and provide reference for tunnel design.

2. State of the Art

The effect of the tunnel drainage system's working state on the stress and stability of the lining is complicated. Consequently, numerous studies have been conducted.

Alija et al. [8] studied the Gavarres Tunnel in Spain, which is in the karst area where crystallization is likely to occur. They proposed a suitable supporting structure, but they failed to explore the stress characteristics of the drainage system further when it is partially blocked. Zou et al. [9, 10] conducted extensive statistical studies on the water leakages in tunnels in karst areas and found that they

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are mainly caused by groundwater corrosiveness and blocked of drainage facilities. However, they failed to propose a calculation method for tunnel stability in case of drainage system blocked.

Yu et al. [11] established a test model for the tunnel drainage system and conducted tests on its crystallization rate at various water qualities, flow rates, and water pressure conditions. They found that the tunnel drainage system was blocked for a variety of reasons. The speed of block varied in different parts of the drainage system, indicating the possibility of asymmetric block. Unfortunately, the stress condition of the tunnel after the blocking of the drainage system was not analyzed. Zhou et al. [12] conducted a model test to study the rules of crystallization block in the drainage system under the effect of pipeline arrangement, flow rate, and the concentration of easy-to-crystallize ions in the tunnel drainage system. This test provides a reference for dealing with drainage system blocks, but cannot to tell the difference between the two block patterns.

In computational theory, El Tani [13–15] did a lot of calculations and improved the formula for the calculation of tunnel drainage volume. However, the role of drainage system in tunnel engineering was simplified in the calculation process. Lee et al. [16] studied the effect of penetration on the tunnel in different situations, including whether there were drainage pipes, when tunnels were shallow buried or built underwater. They carried out several studies on the stability of and external water pressure on the tunnel lining. In the case of continuous drainage, the water pressure that the support structure of the tunnel can bear was greatly reduced. Nam et al. [17] studied the factors that made the tunnel lining vulnerable to groundwater, and considered the permeability of the whole tunnel structure and the deterioration degree of the drainage system as the main factors. The load curve for calculating the external water pressure of the tunnel lining was put forward. However, in their research, the block of the drainage system was assumed to be always symmetric. Therefore, the calculation method of the external water pressure on the lining under the two block patterns was difficult to obtain. Bouvard et al. [18] deduced the seepage field formula based on the assumption that groundwater flew radially to the tunnel. However, for the block issue of the drainage system, only the equivalent permeability coefficient method can be used. This formula is neither able to identify the stress characteristics of the tunnel under symmetric block of its drainage system nor able to compare the two block patterns.

Many studies have been conducted on the stress state of the tunnel when the drainage system is symmetrically blocked, while few have been conducted on asymmetric block. Studies regarding the difference between the two block patterns on how they influence the stress and stability of the tunnel are even less. Based on this situation, a field test on the partial block of the drainage system was carried out to test the stress condition of the tunnel lining. Then, the finite element analysis method was used to study the effect of partial block length of the drainage system on the stress condition of the tunnel lining and verify the test conclusions. Subsequently, the safety factor of the overall tunnel stability was calculated with the strength reduction method, and the two block patterns of the drainage system were further compared regarding their influence on tunnel stability.

The rest of this study is organized as follows. The field test and the finite element modeling method are described in the third section. In the fifth section, the test results of the lining stress with different partial block lengths are analyzed. The influence of the two block patterns on tunnel lining is discussed from two aspects: the size and the location of stress. The finite element analysis method is used to verify the test results. On this basis, the stability of the tunnel under the two block patterns of the drainage system is analyzed. In the final section, this study is summarized and relevant conclusions are provided.

3. Methodology

3.1 Field test on partial block of drainage system

3.1.1 Hydrogeology and tunnel overview

A typical case study of the Zhongliangshan Tunnel in Chongqing was conducted. The tunnel is in a trough valley area eroded by geological structures. Joint fissures and beddings develop in the rock stratum, with the moderate to good interlayer bonding. Karst zones, karst flutes, and underground rivers also develop. The tunnel passes under a large reservoir with abundant water supply. The rock is mainly composed of limestone and marl, and occasional mudstone.

The tunnel section is straight and between 200 and 220 m deep. The maximum width inside the tunnel is 12.24 m and the maximum height inside is 10.23 m. The cross-section of the tunnel is a five-circle section. The primary support is a spray anchor network bracing that is 250-mm thick. The second lining is a reinforced concrete structure that is 1000-mm thick. The tunnel is protected by grouting reinforcement, which is 3 m thick.

3.1.2 Monitoring of lining stress

A vibrating-wire strain sensor and the frequency measuring system were used to measure the change of the concrete stress in the second lining. The measuring points at the measuring section are shown in Fig. 1.

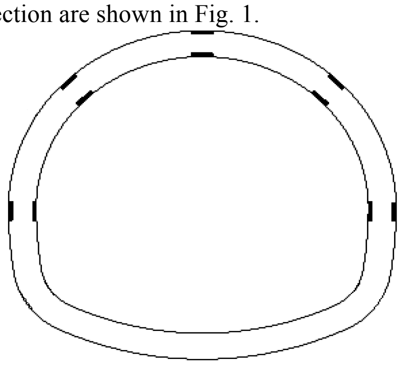

Fig. 1 The monitoring point of the tunnel lining

Ten sensors were placed at each measuring section. The vibrating-wire strain sensor and the frequency measuring system are shown in Fig. 2.

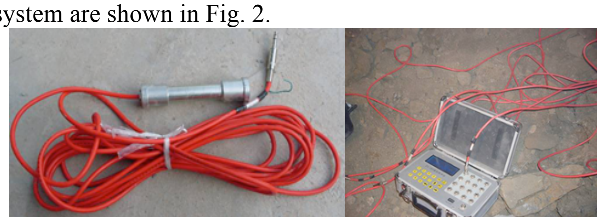

Fig. 2 Vibrating-wire strain sensor and frequency measuring system

The concrete stress test section is the section at coordinate 0 in Fig. 3.

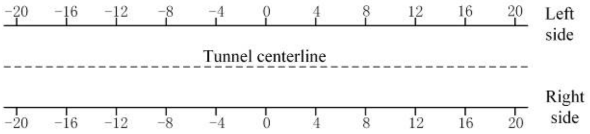

Fig. 3 The arrangement of water pressure test section

3.1.3 Partial block of drainage system

Before the construction of the second lining, steel pipes were connected to the transverse drainage pipeline. These pipes stretched out of the second lining and were opened and closed by a flange. After the drainage pipeline was closed, the frequency measuring system was read to obtain the concrete stress, that is, the internal force of the lining. Details of the test plan are shown in Tab. 1.

Table 1. The scheme of drainage pipe blocking location

Block pattern	Block position		Block length
Asymmetric block	Left side	-8 m~8 m	16 m
		-12 m~12 m	24 m
		-16 m~16 m	32 m
		-20 m~20 m	40 m
	Right side	-8 m~8 m	16 m
		-12 m~12 m	24 m
		-16 m~16 m	32 m
		-20 m~20 m	40 m
Symmetric block	Both side	-8 m~8 m	16 m
		-12 m~12 m	24 m
		-16 m~16 m	32 m
		-20 m~20 m	40 m

Table 1 shows that the tests were conducted at three occasions: the drainage system was blocked on the left, the drainage system was blocked on the right, and the drainage system was blocked on both sides. In each occasion, the individual tests were based on different lengths of block. The test plan is shown in Fig. 4.

After each test, the drainage pipelines should be opened. Only when the pipelines are working properly can the next test be started. The tests should be conducted during the period with no rain to eliminate the interference of rainfall during the test. When the readings of the water pressure gradually increase, seepage might be found in the second lining. If the seepage is serious, the test should be suspended immediately.

Fig. 4 Field test of the blocked drainage system

3.2 Finite element analysis

3.2.1 Establishment of calculation model

The calculation model of the tunnel and drainage system was established using FLAC3D. To minimize the interference from factors other than the partial block length and block pattern, the drainage system was modeled according to the actual conditions, while the surrounding rock of the tunnel was simplified to highlight the drainage system. The surrounding rock, grouting circle, and support structure were modeled using solid elements. According to actual conditions, the project design, and geological data, the buried depth of the tunnel model was set to 212.5 m. The upper rock mass pressure was modeled by the load applied to the surface of the model. The dimensions of the tunnel model were consistent with the real tunnel. Its longitudinal depth was 88 m, which mitigated the influence of boundary conditions on the calculation results. Considering the Saint-Venant's principle and previous studies, the lower boundary of the tunnel was 40 m from the lower boundary of the model, and the left and right boundaries of the tunnel are 40 m from the corresponding boundaries of the model. The grouting circle was 3-m thick. The groundwater supply was sufficient because the tunnel runs beneath the reservoir. The water level was set to 200 m. The calculation model is shown in Fig. 5.

The Mohr–Coulomb yield criterion is expressed as

$$\tau_n = \sigma_n \tan\varphi + c \tag{1}$$

The yield criterion expressed by the principal stress is

$$\sigma_1 - \sigma_3 = (\sigma_1 + \sigma_3)\sin\varphi + 2\cos\varphi \tag{2}$$

The yield criterion can also be expressed by stress invariant as

$$f = \frac{1}{2} I_1 \sin\varphi + (\cos\theta_\sigma - \frac{1}{\sqrt{3}}\sin\theta_\sigma)\sqrt{J_2} - c\cos\varphi = 0 \tag{3}$$

where $-\pi/6 \le \theta_\sigma \le \pi/6$.

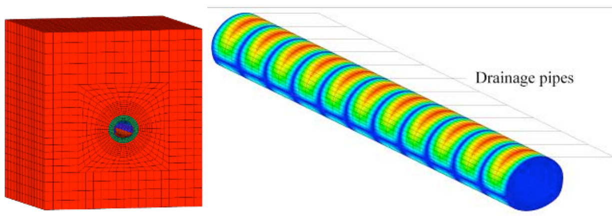

Fig. 5 Three dimensional model of tunnel and drain-pipe schematic

Table. 2 Material parameters

Parameters	Surrounding rock	Primary support	Second lining	Grouting reinforced region
Volumetric weight (kg/m^3)	2260	2500	3000	2370
Elastic modulus (GPa)	10.7	28	30	15
Poisson's ratio	0.4	0.21	0.19	0.38
Cohesion (MPa)	0.7	1.08	3.1	0.9
Internal friction angle (°)	17	26.6	52.1	22.1
Permeability coefficient (m/d)	1.23	6.336×10^{-4}	—	2.45×10^{-3}
Void ratio	0.5	0.25	—	0.3

A longitudinal drain was arranged inside the tunnel, annular drainage pipes were arranged at the corresponding nodes on the outer surface of the second lining, and longitudinal drainage pipes were arranged at the foot of the wall. The water pressure of the nodes on the outer surface of the second lining that are part of the drainage system was fixed at 0, and the water pressure of those that are not part of the drainage system was in a free state. The second lining was considered impermeable. The drainage pipes are shown in Fig. 5, where the blue part is the drainage system in the model.

Parameters of the surrounding rock and tunnel support structure are shown in Tab. 2.

The governing equations in FLAC3D are equilibrium equation, equation of motion, constitutive equation, and compatibility equation.

If large deformation is not considered, the equilibrium equation for a particle in the fluid is

$$-v_{i,j} + q_v = \frac{\partial V}{\partial t} \tag{4}$$

where q_v is the fluid source strength (L/s), $v_{i,j}$ is the seepage velocity (m/s), and $\frac{\partial V}{\partial t}$ is the change of fluid volume per unit volume of the porous media.

The movement of fluid is described by Darcy's law. For homogeneous, isotropic solids and constant-density fluids, the equation of motion is expressed by

$$v = \frac{Q}{A} = K\frac{h_1 - h_2}{l} \tag{5}$$

Where Q is the fluid volume, A is flow area, K is the permeability coefficient, $h_1 - h_2$ is the liquid level height difference, and l is the flow path length.

The fluid satisfies the law of mass conservation, and the mass balance is established as

$$-\frac{\partial q_i}{\partial x_i} + q_v = \frac{\partial V}{\partial t} \tag{6}$$

Where $\frac{\partial q_i}{\partial x_i}$ is fluid velocity vector.

The change in volume strain causes a change in fluid pore pressure due to the coupling effect. The constitutive equation is

$$\Delta\tilde{\sigma}_{ij} + a\Delta p\delta_{ij} = \dot{H}_{ij}(\sigma_{ij}, \Delta\varepsilon_{ij}) \tag{7}$$

where $\Delta\tilde{\sigma}_{ij}$ is the change of stress in the rock and soil masses, $\dot{H}_{ij}$ is a given function, and ε_{ij} is the total volume strain of the rock and soil masses.

The compatibility equation between the strain rate and the velocity gradient is

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial \dot{u}_i}{\partial x_j} + \frac{\partial \dot{u}_j}{\partial x_i}\right) \tag{8}$$

where u is the change of stress in the rock and soil masses.

The numerical simulation is based on the following basic assumptions:

(1) With the M-C yield criterion as prerequisite, the rock mass is assumed an isotropic, continuous, and homogenous medium;

(2) The rock and soil masses within a certain area around the tunnel are assumed a homogeneous and isotropic fluid;

(3) Given that the tunnel is in an area with few geological structures and is buried deeply, only the influence of gravity stress is considered.

(4) The top of the tunnel is a stable head boundary. The ground surface is a free border. The left and right boundaries of the model are constrained by the displacement in the X direction. The bottom boundary of the model is constrained by the displacement in the Z direction. The front and back boundaries of the model along the Y axis are constrained by the displacement in the Y direction.

3.2.2 Numerical analysis methods

The drainage system was tested under three working conditions: normal, asymmetric, and symmetric blocking. In the latter two cases, finite element analysis was performed at block lengths of 16, 24, 32, and 40 m, respectively. Finite element analysis was conducted after the excavation of the tunnel and the construction of the supporting structure and drainage system. During calculation, the change of the second lining stress with the increase of the block length was measured, and the influence of the two block patterns of the drainage system on the tunnel lining was examined.

4 Result Analysis and Discussion

4.1 Test results for asymmetric block of drainage system

After the second lining construction, the stress value of the lining concrete was monitored before the field test. After more than 60 days of testing, the concrete stress was basically stable and the drainage system was unblocked (the block length was 0).

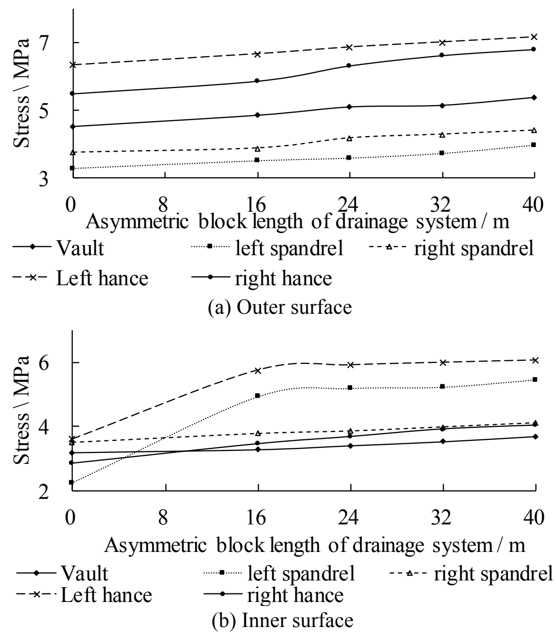

Fig. 1 Stress of the second lining after the left side of the drainage system is blocked

Then, asymmetric block test of the drainage system was carried out by blocking the drainage system on the left and right sides. On this basis, the variation of the internal force of the concrete in the second lining was obtained. The test results for the drainage system blocked on the left are summarized in Fig. 6. The test results for the drainage system blocked on the right are summarized in Fig. 7. Figs. 6 and 7 show that as the length of the asymmetric block of the tunnel drainage system increases, the stress of the second lining increases, but the increase rate varies in the different positions of the second lining. For the spandrel and hance on the blocked side, the concrete stress changes significantly before and after blocking. However, as the block length increases from 16 m to 40 m, the increase of the concrete stress slows down. For the other measuring points, the asymmetric block of the drainage system also causes an increase in concrete stress, but in a gentler manner.

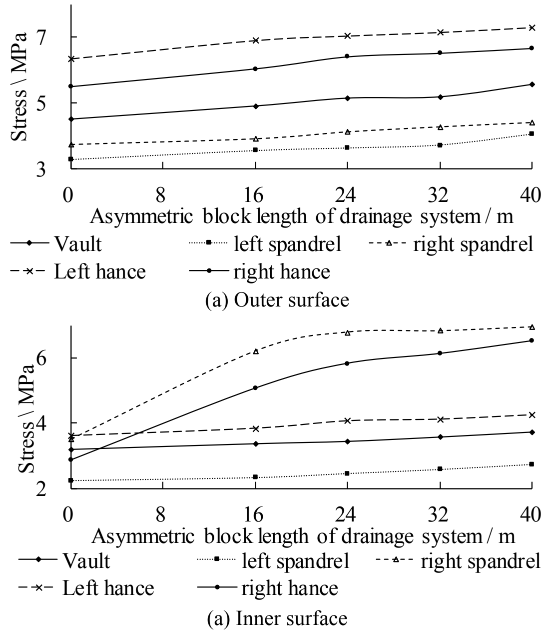

Fig. 2 Stress of the second lining after the left side of the drainage system is blocked

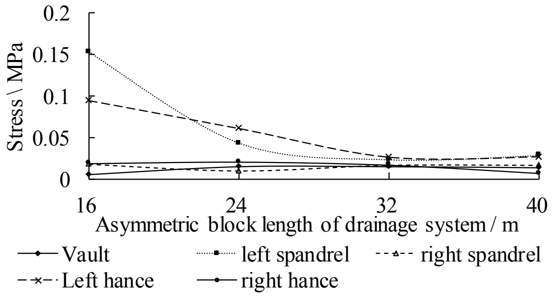

Fig. 3 The increment stress of the second lining per meter after the left side of the drainage system is blocked

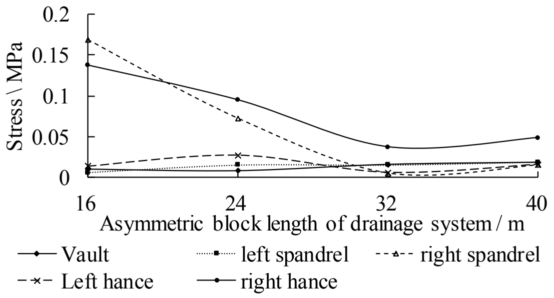

Fig. 4 The increment stress of the second lining per meter after the right side of the drainage system is blocked

Based on the concrete stress values in Figs. 6 (b) and 7 (b), the increase of concrete stress per unit length (1 m) can be derived. The data are summarized in Figs. 8 and 9. When the block length of the tunnel drainage system is increased from 0 m to 16 m, the concrete stress increment per meter is much higher at the spandrel and hance on the blocked side than that at the other locations of the same section. When the asymmetric block length of the drainage system gradually increases from 16 m to 40 m, the concrete stress increment per meter at the spandrel and hance on the blocked side is reduced to approximately the same value as, but still slightly higher than that at the other positions of the same cross-section. Figs. 6 and 7, the concrete stress at the spandrel and hance on the blocked side of the drainage system is still significantly greater than that at the other locations of the same cross-section. This indicates that the asymmetric block of the tunnel drainage system has a greater impact on the second lining concrete on the blocked side.

4.2 Test results for symmetric block of drainage system

After the above tests, symmetric block tests were conducted by blocking both sides of the drainage system. The variation of the concrete stress in the second lining was obtained. The test data are shown in Fig. 10.

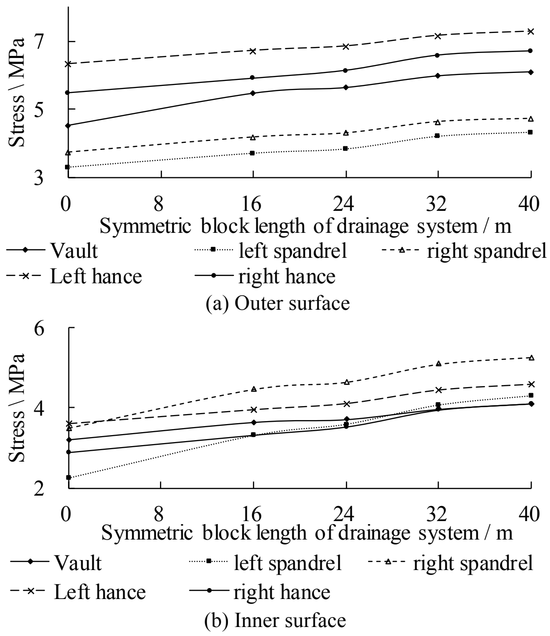

Fig. 10 Stress of the second lining after the drainage system is blocked

According to Fig. 10, when the tunnel drainage system is symmetrically blocked, the external water pressure on the lining increases, driving the stress of the concrete at various parts of the lining to increase as well. With the increase of symmetric block length, the concrete stress increases. However, unlike in asymmetric blocking, the stress increase of concrete at various parts of the lining no longer shows a significant asymmetry. Instead, the stress increases at the lining parts are similar.

The test results above indicate that the partial blocking of the drainage system for the tunnel subjected to significant groundwater pressure significantly affects the stress of the lining. The longer the block, the greater the stress on the lining. However, the tunnel drainage system may be blocked in different patterns and may have different effects on lining stress. Asymmetric blocking causes the asymmetric distribution of stress on the lining. Similarly, symmetric blocking causes a relatively symmetric distribution of stress on the lining.

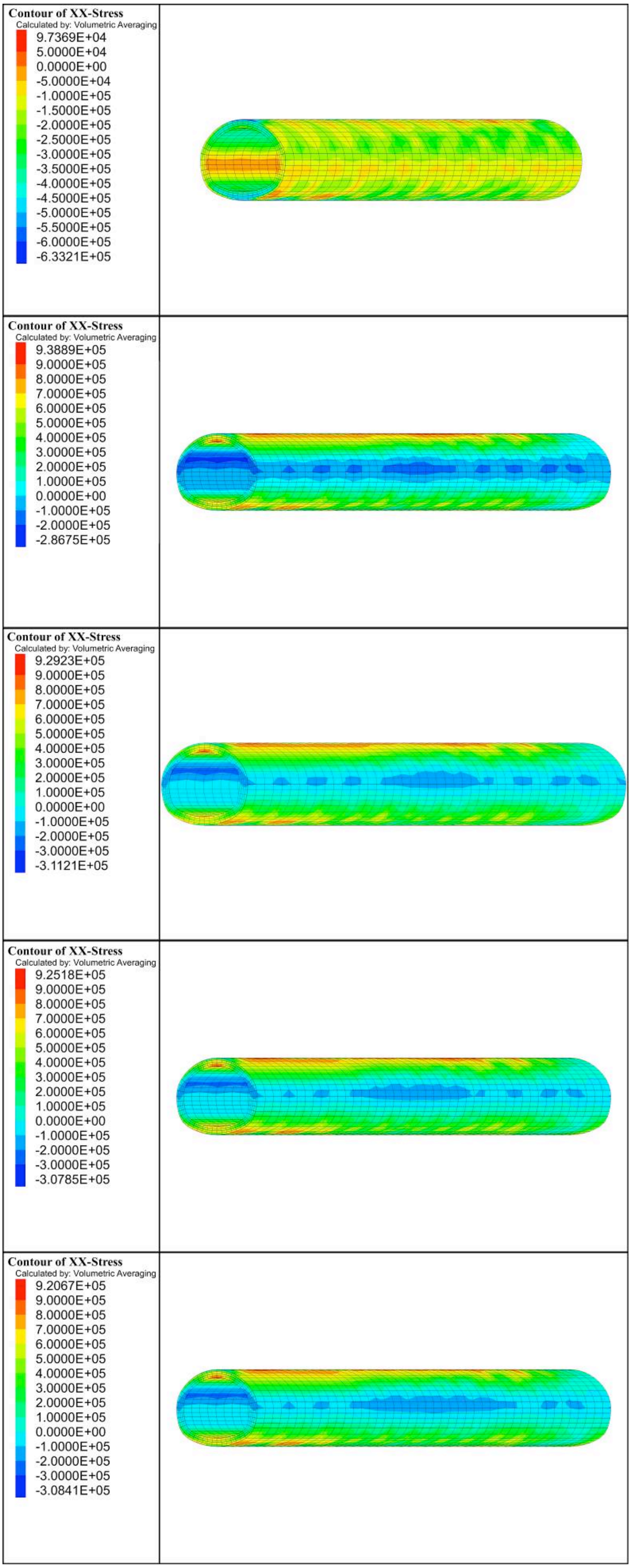

Fig. 11 X-direction stress of the secondary lining while the drainage system blocked length is 0 m, 16 m, 24 m, 32 m, 40 m

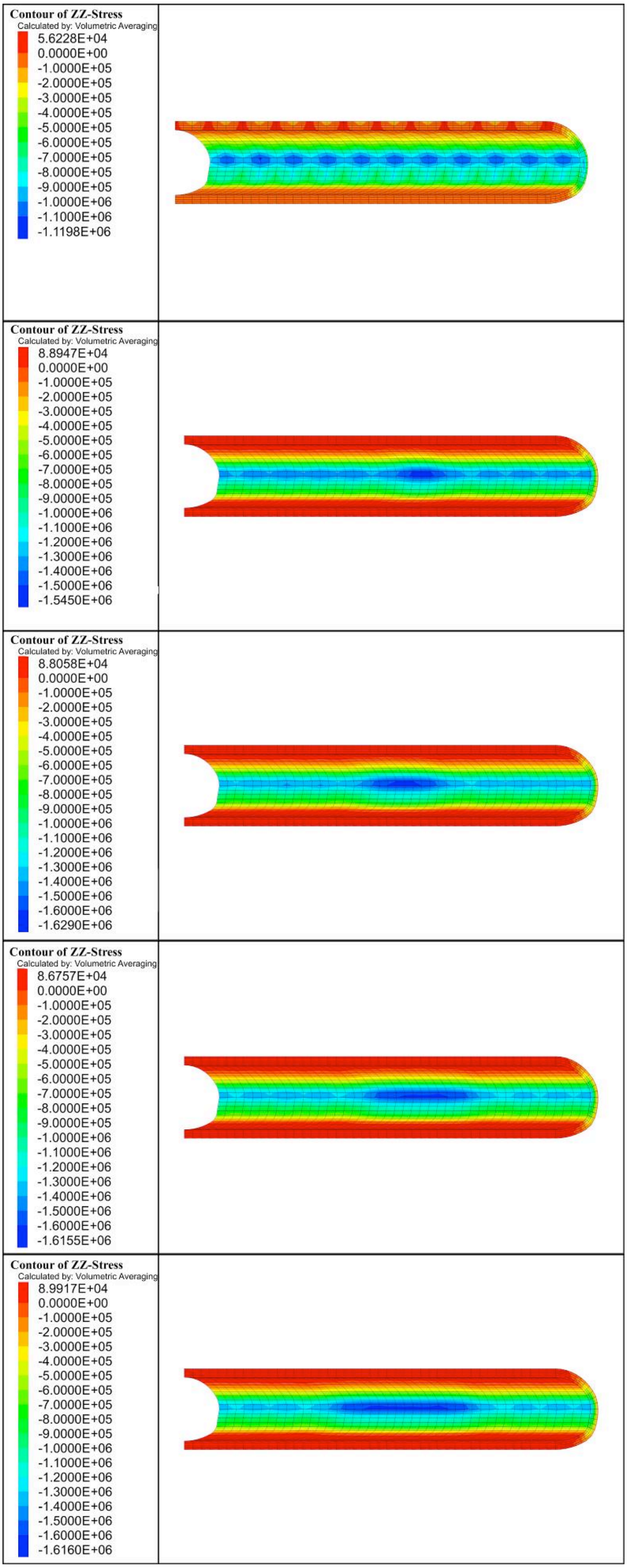

Fig. 12 Z-direction stress of the secondary lining while the drainage system blocked length is 0 m, 16 m, 24 m, 32 m, 40 m

4.3 Finite element verification

4.3.1 Variation of second lining stress with different lengths of asymmetric block

The stress contours of the second lining in the X and Z directions are calculated at different block lengths of the drainage system, as shown in Figs. 11 and 12.

Fig. 11 shows that the asymmetric block of the drainage systems at different lengths directly affects the distribution of stress in the X direction. The asymmetrically blocked area of the drainage system corresponds to the position in the X direction where the stress is large. When the asymmetric block lengths of the drainage system are 16, 24, 32, and 40 m, the lengths of the second lining with a large stress in the X direction are approximately 14, 22, 28, and 36 m, respectively. A very strong correlation exists between the lengths.

Fig. 12 shows that the stress of the lining in the Z direction is also affected by the asymmetric block of the drainage system. When the drainage system is not blocked, the stress of the second lining in the Z direction is uniformly distributed. After the drainage system is asymmetrically blocked, a significantly different stress distribution is observed at the blocked tunnel section in the Z direction. On one hand, an area with a large compressive stress in the Z direction forms at the hance of the second lining. On the other hand, the tensile stress areas at the vault and the arch bottom retreat and move backward, respectively. In the non-blocked section of the drainage system, the stress distribution in the Z direction is minimally affected.

The spandrel to hance area of the second lining is most affected by the asymmetric block in terms of the stresses in the X and Z directions, which is consistent with the test results.

The analysis of the data above shows that the length of the asymmetric block of the drainage system has little influence on the X-direction stress of the second lining of the tunnel. The Z-direction stress near the hance is shown in Fig. 13.

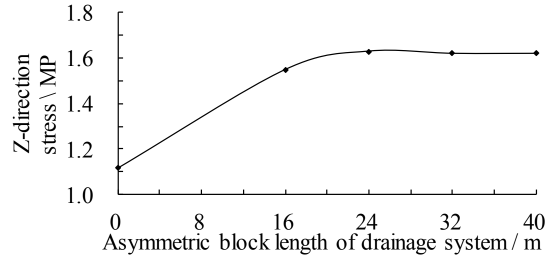

Fig. 13 Z-direction stress of the secondary lining while drainage system asymmetric blocked

When the asymmetric block lengths of the drainage system are 0, 16, 24, 32, and 40 m, the Z-direction stresses of the second lining are 1.12, 1.55, 1.63, 1.62, and 1.62 MPa, respectively. The stress in Z direction increases by 38% when the tunnel drainage system is asymmetrically blocked. However, as the block length continues to increase, the Z-direction stress does not increase significantly. The result of the numerical method and the field test data follow a similar growth trend.

4.3.2 Variation of second lining stress with different lengths of symmetric block

After the drainage system is symmetrically blocked, the lining stress varies symmetrically, and the position with a large stress change is affected by the block length. To avoid repetition, only the stress conditions with block lengths of 16 and 24 m are provided here. In this case, the stress distributions of the second lining in the X and Z directions are shown in Figs. 14 and 16, respectively.

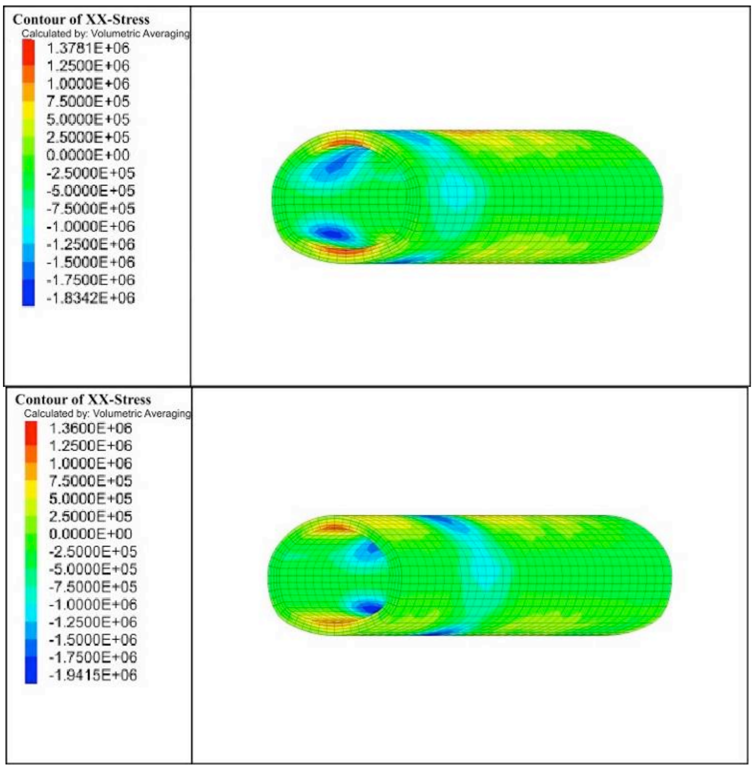

Fig. 14 X-direction stress of the secondary lining while the drainage system blocked length is 16 m, 24 m

Fig. 14 shows that the stress distribution of the lining in the X direction is directly affected by the block length. However, the stress distribution of the second lining in the X direction under a symmetric block of the drainage system is different from that under an asymmetric block. In the case of a symmetric block, a large stress is generated at the vault and at the inverted arch area. This change is mainly caused by the shift from the asymmetric stress mode of the lining to symmetric stress mode.

The maximum stress values of the second lining in the X direction are summarized in Fig. 15.

As indicated in Fig. 15, when the drainage system is symmetrically blocked, the X-direction stress of the second lining increases rapidly. Then, as the block length increases, the X-direction stress grows uniformly, which is consistent with the test results.

Fig. 16 indicates a strong correlation between the Z-direction stress distribution of the second lining when the drainage system is symmetrically blocked and the block length. With the increase of the block length, the Z-direction stress of the second lining at the vault and inverted arch rises slowly. In addition, the Z-direction stress at the hance is greater than that at the vault and inverted arch, and it grows at a greater rate.

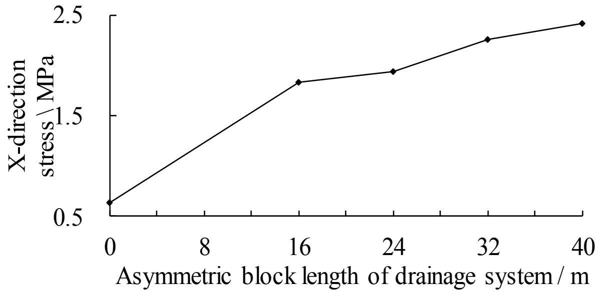

Fig. 15 X-direction stress of the secondary lining while drainage system symmetric blocked

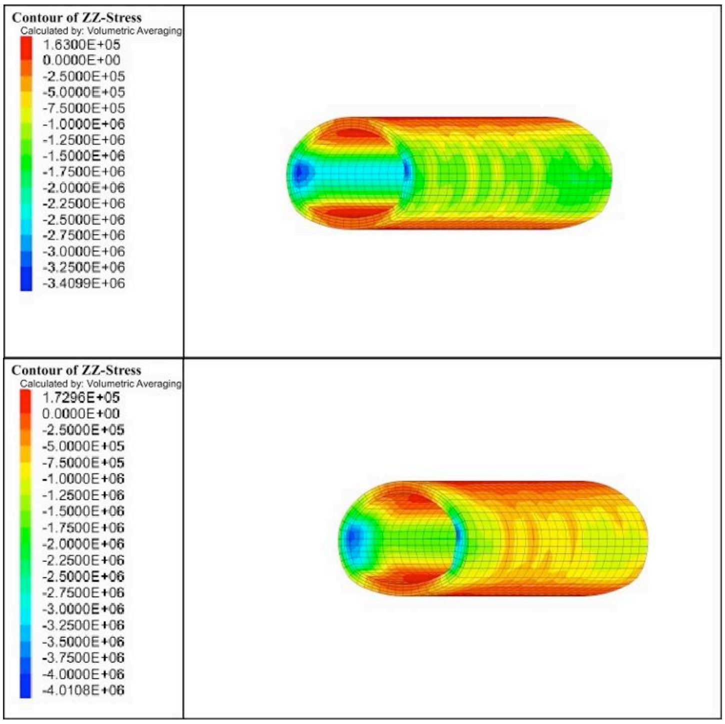

Fig. 16 Z-direction stress of the secondary lining while the drainage system blocked length is 16 m, 24 m

The maximum stress values of the second lining in the Z direction are summarized in Fig. 17.

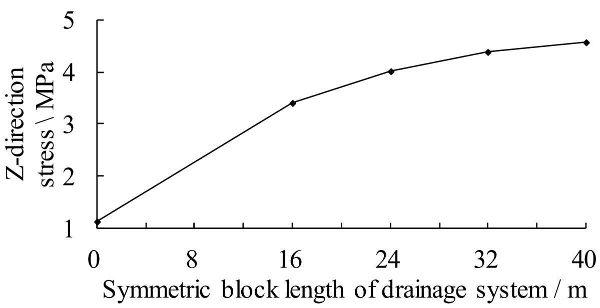

Fig. 17 Z-direction stress of the secondary lining while drainage system symmetric blocked

As indicated in Fig. 17, when the tunnel drainage system is symmetrically blocked, the Z-direction stress of the second lining increases rapidly. As the block length increases, the Z-direction stress grows uniformly, which is consistent with the test results.

Given the above findings, the stress of the second lining is greatly affected by the partial blocking of the tunnel drainage system. The longer the partial block, the stronger the effect. The numerical simulation results, which demonstrate where and how the stress of the second lining is affected by the partial block, are consistent with the test results. Therefore, the numerical simulation and test results are considered to match and confirm each other.

In tunnels under large groundwater pressure, the block pattern of the drainage system plays a major role in the stress condition of the lining and makes a big difference in the location of stress increase. Further contrastive analysis on the influence of the two block patterns of the drainage system on the stability of the tunnel is necessary.

4.4 Analysis of tunnel stability

4.4.1 Instability criterion

When using the finite element strength reduction method to study the stability of the tunnel, the reduction factor represents the tunnel stability. The selection of instability criterion is important. In this study, the stability of the tunnel is discussed based on the occurrence of sudden or limit displacement of the lining structure.

At some reduction factors, sudden displacement increase may occur in some locations of the tunnel structure. These reduction factors are considered as the safety factor of the tunnel. The Railway Tunnel Design Code offers a method to determine the stability of the tunnel through the relative limit displacement of the vault of the primary support. It includes specifications on the relative limit displacement of the vault and defines the relative subsidence value of the vault as the ratio of the vault subsidence value after subtracting the overall subsidence value of the tunnel to the original height of the tunnel. The surrounding rocks of the tunnel are mostly limestone and marlstone, which fall between hard and soft rocks according to the Handbook of Engineering Geology. The surrounding rocks are mainly classified as Grades IV and V. The buried depth of the tunnel is $50 < h \leq 300$. For greater safety, the limit value for relative subsidence of the vault is set to 0.10%. If the relative displacement of the primary support vault exceeds this value, the tunnel is no longer stable.

4.4.2 Tunnel stability with partial block of the drainage system at different lengths

Fig. 18 shows the curve of the variation of the second lining's maximum displacement with the reduction factor at different lengths of asymmetric block.

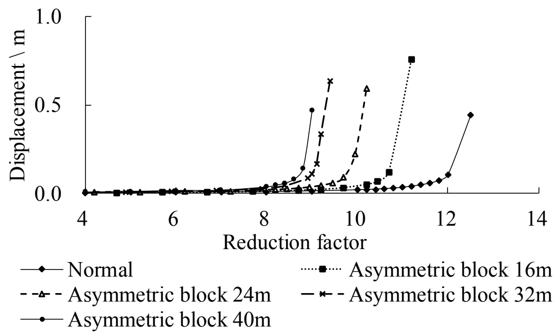

Fig. 18 Maximum displacement curve of secondary lining

When the reduction factor is less than 8, the maximum displacement of the second lining remains small and barely changes with the reduction factor. When the reduction factor is greater than 8, the maximum displacement of the second lining increases sharply after the reduction factor exceeds a certain interval, indicating a sudden change in the displacement of the tunnel structure. In this case, the tunnel has lost its stability. The same trend is observed in the maximum displacement of the second lining in symmetric blocking.

Fig. 18 shows that the abrupt change in the maximum displacement of the second lining does not occur before or after the reduction factor reaches a certain value, but rather when the reduction factor falls into a value interval. Therefore, a reduction factor interval is obtained from Fig. 18. The reduction factors of the asymmetric and symmetric blocks of the tunnel drainage system are summarized in Tab. 3.

Tab. 3 The Reduction factor area while the displacement of secondary lining suddenly changed

Block length		0 m	16 m	24 m	32 m	40 m
Reduction factor	Asymmetric block	11.8~12	10.5~10.7	9.7~9.9	8.9~9.1	8.6~8.8
	Symmetric block		10.2~10.4	9.6~9.8	9.2~9.4	8.8~9.0

According to Tab. 3, the reduction factor is largest when the drainage system works normally. This indicates that the currently tunnel has the largest strength margin, that is, the highest overall stability. The larger the partial block length of the drainage system, the smaller the reduction factor, indicating that partial blocking significantly affects the stability of the tunnel.

As the partial block lengthens, the reduction factors in the two block patterns cross over each other. When the block lengths are 16 and 24 m, the reduction factor in a symmetric block is smaller than that of asymmetric block, indicating that symmetric blocking plays a dominant role in tunnel stability. When the block lengths are 32 and 40 m, the reduction factor in an asymmetric block is smaller, indicating that asymmetric block plays a dominant role in tunnel stability. In this case, the asymmetric block is more detrimental to tunnel stability. Studies suggest that tunnel stability is not always controlled by symmetric blocking. It may also be controlled by the asymmetric blocking of the drainage system, depending on the length of the block. Therefore, in the tunnel design, calculating only the symmetric block of the drainage system is insufficient.

The reduction factors of the tunnel are calculated using the relative limit displacement of the primary support vault as the instability criterion. See Table 4.

Table 4 The vault crown settlement and reduction factors

Block length		0 m	16 m	24 m	32 m	40 m
Reduction factor	**Asymmetric block**	7.9	7.1	6.6	6.1	5.5
	Symmetric block		6.5	5.9	5.2	4.5

According to Tab. 4, under the two block patterns, the increase of the block length leads to the decrease of the reduction factor, suggesting that when the relative displacement of the vault is used as the instability criterion, the same conclusion can be reached—the increase in the partial block length of the drainage system affects the stability of the tunnel.

The comparison of Tab. 3 and 4 show that all the reduction factors for the symmetric block pattern in Tab. 3 are not lower than those for the asymmetric block pattern, while all the reduction factors for the symmetric block pattern in Tab. 4 are lower. The two instability criteria produce contradictory results. The instability criterion used in Tab. 3 is the sudden change in the maximum displacement of the lining, while the instability criterion used in Tab. 4 is the relative subsidence of the vault. Obviously, the vault of the lining is no longer the position with the largest displacement due to the asymmetric block of the drainage system that causes asymmetric stress on the tunnel lining. Thus, the use of the vault alone as the instability criterion may lead to errors in judgment. Therefore, the selection of instability criterion is very important in studying the influence of the two block patterns on the stability of the tunnel.

5. Conclusions

To explore the influence of the two partial block patterns of drainage systems on the stress and stability of tunnels, Zhongliangshan Tunnel was selected for field tests. The variation of stress at various parts of the lining was discussed based on the symmetric and asymmetric blocks of the drainage system at four lengths. Then, the reliability of the numerical model was verified through finite element analysis. On this basis, the effects of the two block patterns on the stability of the tunnel were compared and analyzed, from which the following conclusions are drawn:

(1) When the block pattern of the tunnel drainage system changes, the position of the lining where stress is greatly affected changes. In the asymmetric block pattern, the lining stress shows significant asymmetry.

(2) Tunnel stability is not always controlled under a symmetric block. It may also be controlled under an asymmetric block, depending on the length of the block. Therefore, during tunnel design, if it is necessary to check the partial block of the drainage system, checking the symmetric block alone will leave open the possibility of risk.

(3) The selection of instability criterion is very important when the strength reduction method is used to discuss the stability of the tunnel when the drainage system is partially blocked. Under the asymmetric block pattern, if the block length changes, the position of the maximum displacement on the lining structure may change as well. Using only the displacement value of some special positions as instability criterion may lead to errors in judgment and compromise tunnel safety in the design.

In this study, the influence of the two block patterns on the stress and stability of tunnels was studied. The control factor of tunnel stability changes with the length of the block. This finding should provide useful reference for the design of tunnels against possible blocks in the drainage system. In future studies, the model can be modified by considering the influence of special geological structures. In this way, this model is made more widely applicable, thereby improving tunnel safety in the design.

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