Study on Mechanism of Water Inrush of Karst Tunnels

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Abstract: Water inrush, which is one of the challenging issues and hot topics in the tunneling industry, is very easy to occur during the construction of karst tunnels. The mechanism of water inrush of karst tunnels is discussed and analyzed in the paper: the water inrush of karst tunnels is generally divided into three steps, i.e., the forming of the hazard source, the forming of the water inrush passage and the failure of the anti-inrush rock mass. The failure of the anti-inrush rock mass of karst tunnels are classified into 5 types, i.e., the integral tensile-shear failure, the hydraulic fracturing, the infiltration-induced sliding of the filling medium, the loss of key blocks and the comprehensive water inrush mode. The failure mechanism is studied on basis of typical cases and by means of numerical simulation or theoretical analysis. Conclusion is drawn that most of the water inrushes in actual tunneling are comprehensive water inrushes, which are the comprehensive results of the interrelation and interaction of various water inrush types, and that different types of water inrushes have related continuity and progressive evolution relationships under certain conditions.

Keywords: karst tunnel; water inrush; mechanism; numerical simulation; failure mechanism

1 Introduction

Karst is well developed in Southwest China. Water inrush of karst tunnels is still a big challenge in the tunneling industry. Serious water inrush accidents occurred during the construction of many national key projects in China such as Shanghai-Kunming Railway, Chengdu-Kunming Railway, Yichang-Wanzhou Railway and Lichuan-Wanzhou Expressway. Therefore, study on the mechanism of water inrush of karst tunnels is of great significance in aspect of avoiding water inrush disaster, reducing casualties and reducing economic losses[1-2].

In view of this, many scholars in China and abroad have carried out related researches, and believe that the integrity and stability of the anti-

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(This paper is selected from *China Railway*) inrush rock mass is the key to avoiding water inrush disaster when the tunnel excavation pass by the karst body with a close distance[3-5]. According to the property and integrity of the anti-inrush rock mass, the failure of the anti-inrush rock mass is usually classified into the tensile-shear failure, the hydraulic fracturing failure, the infiltration-induced sliding of the filling medium and the loss of the key blocks[5-8]. In the paper, the mechanism of water inrush of karst tunnels is discussed and analyzed by means of numerical simulation and theoretical analysis, in order to provide theoretical support for engineering researches.

2 Mechanism of water inrush of karst tunnels

Water inrush during tunneling is a phenomenon of a large amount of water rushing into the tunnel, carrying mud, sand and gravel, along the fissures, faults, karst conduits and other paths, which is caused by the sudden change of the original groundwater circulation system and the mechanical equilibrium state of the surrounding rock due to the tunnel excavation, the forming of the dominant water passage and the release of the energy stored in the water and the surrounding rock instantaneously[1].

The occurring of the disaster is closely related to the geological structures of the tunnel. According to the hazard sources, the water inrush of karst tunnels can be classified into the water-rich fault type, the karst cave (cavity) type, the fissure type, the underground river type and the conduit type. According to the anti-inrush structures, the water inrush of karst tunnels can be classified into the complete rock mass type, the fissured rock mass type and the filling medium type etc. From the perspective of the systems theory, the occurring of any disaster includes the forming of the hazard source, the forming of disaster path and the failure of the protection structure (see Figure 1). Similarly, the occurring of the water inrush disaster in tunneling includes three aspects[1]: the karst water, the forming of the water inrush passage and the failure of the anti-inrush rock mass.

2.1 Hazard source

The hazard source is the source and primary factor of the water inrush in tunneling. The hazard source is usually the geological body with water, deposits and cavities in the surrounding rock, which has obvious characteristics of energy storage. Karst tunnels with large cover depth are often located in an environment with high ground stress and high water pressure, therefore the rock mass often store strong elastic strain energy and the water has large potential energy and kinetic energy. Once the high-pressure water is revealed during tunneling, great geological hazards are often caused.

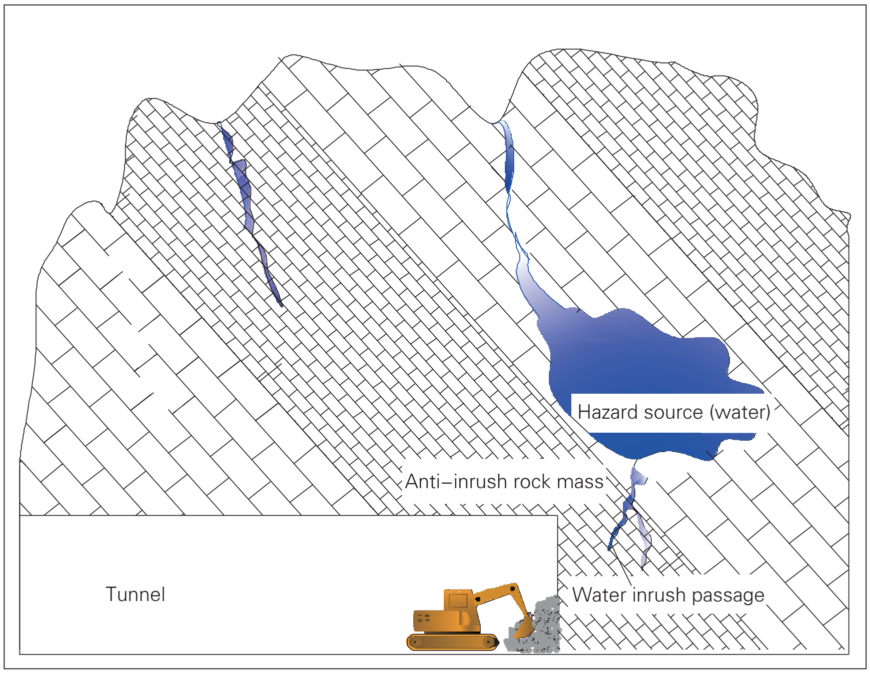


Figure 1 Sketch of mechanism of water inrush of karst tunnel

2.2 Water inrush passage

Water inrush passage is the dominant path of the water when disaster occurs, and is one of the necessary conditions of disaster. When the hazard water enters the water inrush passage, the water, mud and sand have complicated coupling action with the passage and the surrounding rock, including complex mechanical and chemical erosion actions. The composition and property of the filling medium in the water inrush passage determine whether the water inrush occurs instantaneously or is delayed and whether the water inrush is intermittent or continuous.

2.3 Anti-inrush rock mass

Anti-inrush rock mass is the rock mass between the free face and the hazard water source, and is the last barrier to prevent the hazard water from entering the tunnel. The water inrush of karst tunnel is a process of destruction and evolution of the rock mass induced by water movement and construction disturbance. The safe thickness of the anti-inrush rock mass is closely related to the surrounding rock properties, the tunnel cross-section, the cover depth and the water source characteristics[3]. The anti-inrush rock mass can usually be classified into complete rock mass, fissured rock mass and cementitious filling medium. Different anti-inrush rock masses often have different water insulation properties and different failure mechanisms, for example, the complete limestone with several meters of thickness can withstand the water head with tens of meters height.

3 Type and mechanism of failure of anti-inrush rock mass

Different karst tunnels have different water inrush mechanisms, however, the failure of the anti-inrush rock mass of karst tunnels is usually classified into the tensile-shear failure, the hydraulic fracturing failure, the infiltration-induced sliding of the filling medium and the loss of the key blocks, and these failure types are interactive and correlated.

3.1 Overall tensile-shear failure

The surrounding rock close to large karst caves is mainly of Grade II and Grade III complete limestone. When the karst tunnel is excavated near the karst cave with rich high-pressure water, due to the insufficient thickness of the anti-inrush rock mass, the tensile stress or the shear stress on the anti-inrush rock mass is greater than the allowable stress thereof, which results in the failure of the anti-inrush rock mass. For example, in the construction of Xiejiadong Tunnel on Hechi-Du'an Expressway, a large soil-filled karst cave with a size of about 52 m (long) × 70 m (wide) ×48 m (high) was revealed, and the 6m-thick roof above the tunnel collapsed as a whole[9]. The analysis shows that this accident is a typical overall tensile-shear failure of the anti-inrush rock mass.

The integral anti-inrush rock mass is generally simplified as the simple supported beam, the cantilever beam, the fixed supported beam or the plates with fixed supports around under the action of uniform water pressure, and the safe thickness of the anti-inrush rock mass is determined by calculating the tensile stress and the shear stress at the critical sections. When the stress at the critical sections exceeds the allowable strength of the anti-inrush rock mass, local failure occurs, and the tunnel becomes connected with the karst structure, resulting in water pressure transfer and karst water inrush[1, 2, 10]. An example of numerical analysis is illustrated here for further analysis and discussion and the calculation model is shown in Figure 2.

It is assumed that the cover depth of the tunnel is 100 m, there is a karst cave filled with high-pressure water above the tunnel, and the water pressure is 1.0 MPa. Here, the water pressure is simplified as uniform load acting on the anti-inrush rock mass, and the longitudinal thickness of the anti-inrush rock mass is 1 m. The calculation parameters of the surrounding rock are shown in Table 1.

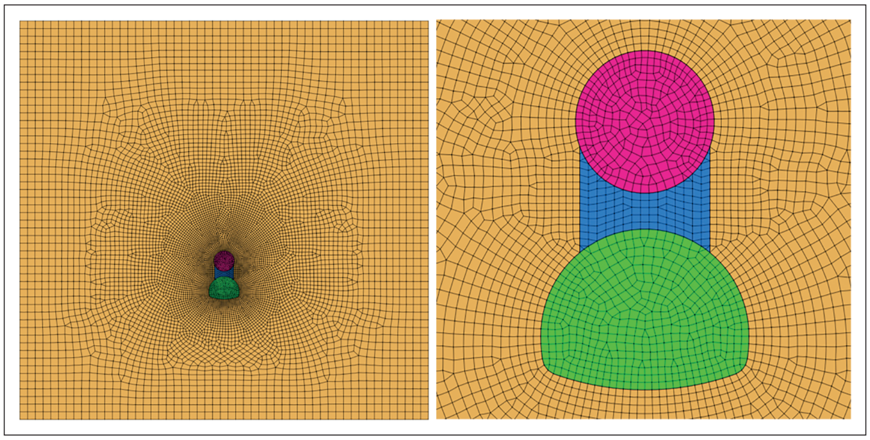


Figure 2 Numerical calculation model

Table 1 Calculation parameters of surrounding rock

Elastic modulus E/ GPa	Bulk density γ/ (kN·m^{-3})	Poisson's ratio μ	Friction angle φ/ (°)	Shear strength τ/ MPa	Coefficient of lateral pressure of ground λ
5.0	25.0	0.3	35	0.5	1.0

The distribution of the shear stress when the distance between the tunnel and the karst cave is 5 m and 2 m is shown in Figure 3. Here, the shear stress on the end of the anti-inrush rock mass is analyzed. It can be seen that when the thickness of the anti-inrush rock mass decreases from 5 m to 2 m, the shear stress on the end of the anti-inrush rock mass increases significantly, and the shear stress on some elements even increases by more than 1 time. When the shear stress on the elements obviously exceeds the shear strength of the rock mass, the end of the anti-inrush rock mass is prone to shear failure. It can be seen that the insufficient thickness of the anti-inrush rock mass will lead to the increase of the stress on the rock mass, Therefore, reasonable thickness of the anti-inrush rock mass plays a major role in preventing karst water inrush in tunnel construction.

3.2 Hydraulic fracturing failure

Hydraulic fracturing mostly occurs to deep rock mass. Under the action of the high-pressure water, the fissures in the rock mass are penetrated through, which significantly improves the permeability of the rock mass. Meanwhile, along with the effects of erosion and argillation, the increase of the permeability enhances the infiltration effect, and in turn enhances the hydraulic fracturing effect[10-11]. The hydraulic fracturing generally causes the inrush of the fissure water at some position around the tunnel. Under such circumstance, clear water ejects out, with less impurities. In addition, crisp rock splitting sound usually occurs before the water inrush, accompanied by the spraying of water mist.

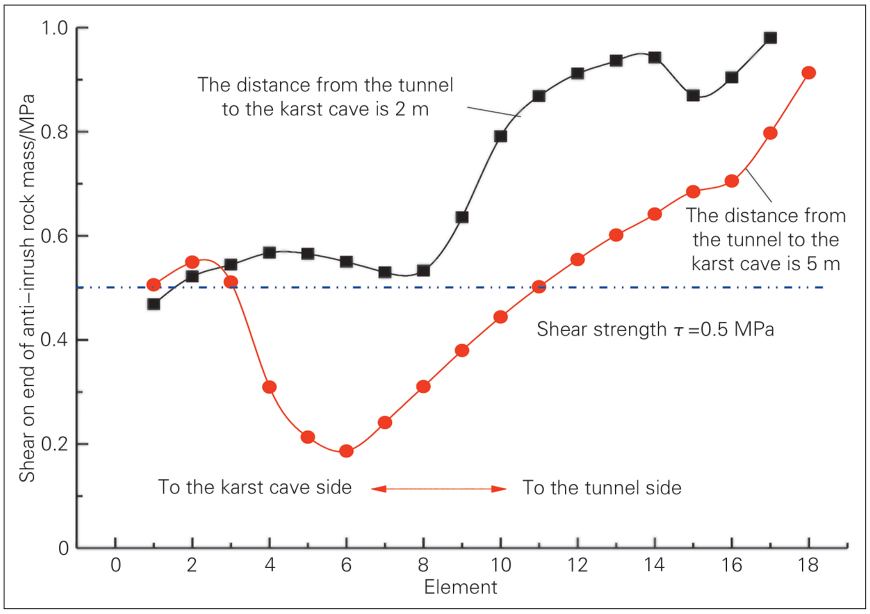


Figure 3 Stress on anti-inrush rock mass

For example, the maximum cover depth of the tunnels of Jinping Phase II Project is more than 2000 m, and the surrounding rock of the tunnels is mainly of brittle hard rock. The traces of tawny rust are observed in the deep exploration of the water-transferring cracks; however, no traces of rust are found at the end of the water-transferring cracks near the large water inrush points at 2 848.5 m and 3 580.0 m in PD1 adit. This is because the original cracks are expanded due to the hydraulic fracturing effect of the groundwater after tunnel excavation. The cracks are concentrated near the water inrush points and are inter-connected each other. Among the water inrushes with more than 1 000 L/s rate in the study area, nearly 35% of the water inrushes are of hydraulic fracturing type[12].

The key of the study on the hydraulic fracturing failure is the determination of the critical water pressure.

The ideal calculation model for the fracturing of an individual crack is shown in Figure 4. As shown in Figure 4, the crack is subject to the vertical stress σ_1 and the horizontal stress σ_3, the angle between the crack and the vertical direction is α, and the pore water pressure is p_w. Assuming that the water pressure exerts the same force along all directions of the crack and the rock mass is brittle elastic, the normal stress on the crack surface σ_α and the shear stress on the crack surface τ_α are calculated as follows:

$$\begin{cases} \sigma_\alpha = -\left[\dfrac{\sigma_1 + \sigma_3}{2} - \dfrac{\sigma_1 - \sigma_3}{2}\cos 2\alpha - p_w\right] \\ \tau_\alpha = -\dfrac{\sigma_1 - \sigma_3}{2}\sin 2\alpha \end{cases} \tag{1}$$

According to Literature [13], the critical water pressure in the case of tensile-shear failure type is calculated as follows:

$$p_w = \frac{K_{\mathrm{Ic}}}{\sqrt{\pi a}} + \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2}\sin 2\alpha - \frac{\sigma_1 - \sigma_3}{2}\cos 2\alpha \tag{2}$$

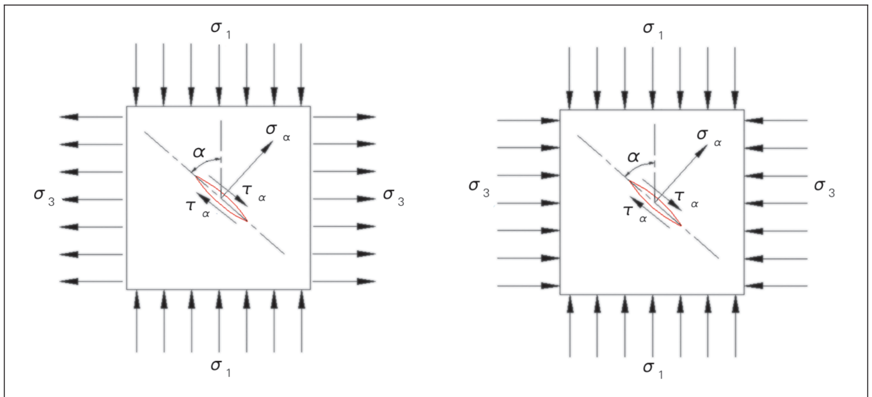
The critical water pressure in the case of compressive-shear failure type is calculated as follows:

$$p_w = \frac{\sigma_1 + \sigma_3}{2} - \frac{\sigma_1 - \sigma_3}{2}\cos 2\alpha - \frac{1}{\tan\varphi}\left(\frac{K_{\mathrm{IIc}}}{\sqrt{\pi a}} + \frac{\sigma_1 - \sigma_3}{2}\sin 2\alpha\right) \tag{3}$$

Where: K_{Ic} is Type I fracture toughness; K_{IIc} is Type II fracture toughness; a is the half-length of the crack.

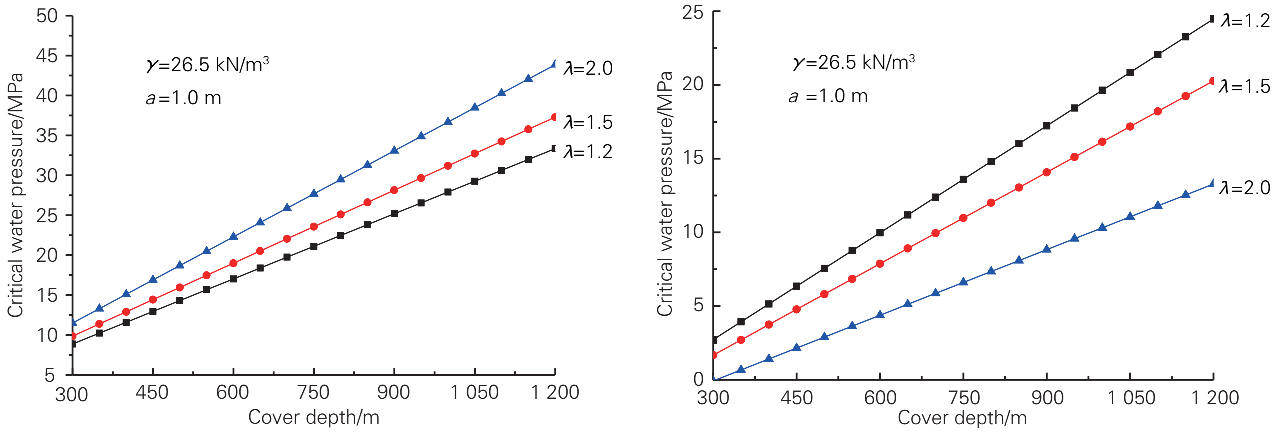
The following parameters[10]are selected in order to better understand the crack propagation modes of Type I hydraulic fracturing and Type II hydraulic fracturing: the length of the crack in the rock mass $2a = 2.0$ m, the maximum principal stress $\sigma_1 = \lambda\gamma h$, the minimum principal stress $\sigma_3 = \gamma h$, the coefficient of the lateral pressure of the ground λ=1.5, the bulk density γ = 26.5 kN /m^3, angle α=20°, the friction angle of the crack φ =30°, the fracture toughness K_{Ic} = 1.26 MN/m$^{3/2}$, K_{IIc} = 4.63 MN/m$^{3/2}$. The calculation results of the critical water pressure for the two fracture modes are shown in Figure 5.

Under the same cover depth and the same ground pressure, the critical water pressure in the case of the compressive-shear failure mode is significantly lower than that in the case of tensile-shear failure mode. From the viewpoint of the fracture mechanics, the main difference between the two failure modes of the hydraulic fracturing of fissured rock mass is the difference between the tension state on the crack surface and the compression state on the crack surface. In fact, the bulk density of the ground is greater



(a) Tensile-shear failure (b) Compressive-shear failure

Figure 4 Ideal calculation model for fracturing of individual crack



(a) Tensile-shear failure mode

(b) Compressive-shear failure mode

Figure 5 Critical water pressures under 2 fracture modes

than the volume weight of the groundwater, and the groundwater level is generally below the ground surface, and there is no possibility of tension on the water-bearing fracture surface of underground rock mass. In engineering practice, therefore, the hydraulic fracturing of the fissured rock mass is of compressive-shear failure mode.

Due to the unloading action, the excavation of deep karst tunnels causes damage to the surrounding rock, which weakens the constraining on the surrounding rock. Furthermore, due to the expansion and even penetration of the cracks in the rock mass, the strength of the rock mass decreases to certain extent, which significantly reduces the critical water pressure required for the hydraulic fracturing of the surrounding rock and may eventually lead to water inrush at certain location of the surrounding rock. The minimum safe thickness of the anti-inrush rock mass at the face of karst tunnel is shown in Figure 6.

The mechanism of water inrush in the case of the jointed anti-inrush rock mass in the construction of karst tunnels can be summarized as follows[3, 13-14]: (1) The complex mechanical and chemical effects in the development of the high-pressure water-rich karst in front of or around the tunnel lead to the formation of a certain range of initial fissure zones in the surrounding rock. The initial fissure zones have strong permeability, are easy to form infiltration passages and therefore have no resistance to the high-pressure karst water; (2) The mechanical disturbance and unloading effect in the tunnel excavation change the karst between the original initial fissure zones, affect the stress state of the weak rock mass and the internal cracks in the rock mass, weaken the friction factor of the crack surface, and thus reduce the critical water pressure of the hydraulic fracturing, resulting in the expansion and penetration of the cracks until the forming of the water inrush passage and water inrushing. As can be seen from Figure 6, the minimum safe thickness of the rock mass between the free tunnel face and the high-pressure water includes two parts: the thickness of the initial fissure zone S_c and the thickness of the hydraulic fracturing zone S_f. The thickness of the initial fissure zone S_c generally ranges from 1 m to 2 m[15], and the calculation formula for the thickness of the hydraulic fracturing zone S_f of the anti-inrush rock mass is as follows[3]:

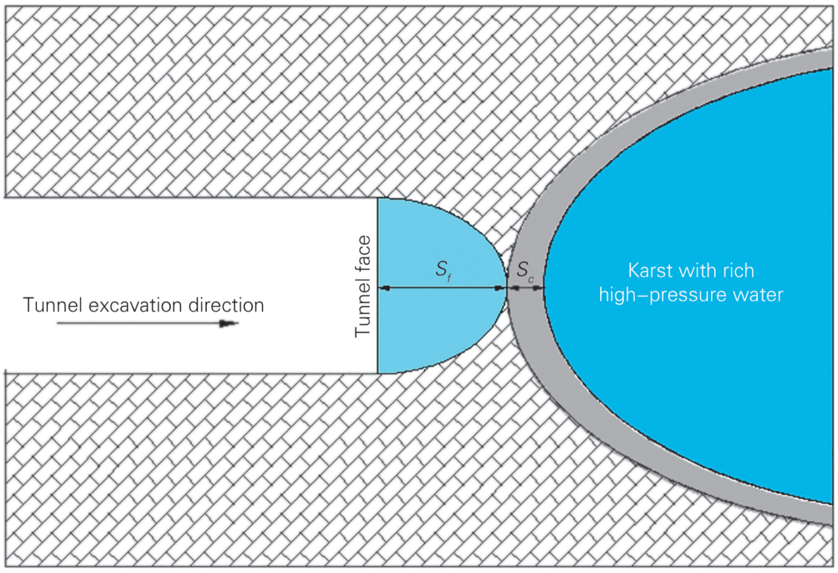


Figure 6 Schematic diagram of minimum safe thickness of anti-inrush rock mass at face of karst tunnel

$$S_{\mathrm{f}}=\frac{11R}{17}\left\{\ln\lambda-\ln\left(\lambda-\frac{a(\sin(2\Psi)-f(1-\cos(2\Psi))\cos(\Psi)}{a(\sin(2\Psi)+f(1+\cos(2\Psi)\cos(\Psi)+\pi l_{\mathrm{c}}}-\frac{2\,000p_{\mathrm{w}}af\cos(\Psi)-1\,000K_{IC}\sqrt{\pi l_{\mathrm{c}}}}{\gamma Ha\left[(\sin(2\Psi)+f(1+\cos(2\Psi)\cos(\Psi)+\gamma H\pi l_{\mathrm{c}}\right]}\right)\right\} \tag{4}$$

For details of the calculation formula, please refer to Literature [3]. The minimum safe thickness of the anti-inrush rock mass is $S_{\mathrm{min}}=S_{\mathrm{c}}+S_{\mathrm{f}}$, that is, when the thickness of the anti-inrush rock mass is lower than S_{min}, water inrushing will occur.

3.3 Loss of stability of filling medium

When the tunnel excavation reveals the filled karst, whether water inrush occurs or not is closely related to the property and stability of the filling medium. According to the difference in the permeability of the filling medium, the loss of the stability of the filling medium is usually classified into two failure types: the integral sliding type and the infiltration-induced stability loss type.

3.3.1 Integral sliding of filling medium

When the filling medium has compact structure, high cementation degree, good integrity and low permeability, it is generally difficult to form a complete water passage in the filling medium, Under such circumstance, the filling medium can even be regarded as an integral water insulation layer. The free face formed by the tunnel excavation provides the condition for the integral sliding of the dense filling medium. Under the combined action of the continuous blasting vibration and the hydrostatic pressure of the karst water during construction, shear failure occurs to the filling medium at the inner wall of the karst conduit, resulting in the loss of the stability of the filling medium due to sliding and eventually resulting in water inrush and mud inrush. According to Literature [7], the critical length of the sliding of the filling medium L_0 is calculated as follows:

$$L_0=\frac{(\gamma D\sin\alpha-2c)+\sqrt{(2c-\gamma D\sin\alpha)^2+4\lambda\gamma p_{\mathrm{w}}D\tan\varphi}}{2\lambda\gamma\tan\varphi} \tag{5}$$

Where: D is the width of the karst conduit; γ is the bulk weight of the filling medium; p_{w} is the uniform water pressure on the filling medium; λ is the coefficient of the lateral pressure of the surrounding rock; α is the inclination angle of the filling medium; c *and* φ are the cohesion and internal friction angle of the filling medium respectively.

3.3.2 Loss of stability due to water infiltration into filling medium

If the filling body is rich in mud and sand, with obvious granular characteristics and certain permeability, it can block and slow down the infiltration of karst water to some extent. The blasting vibration in the tunnel construction disturbs the original state of the filling medium, resulting in the strengthening of the karst movement and the loss of the fine particles in the filling medium, and thus gradually forming a microscopic infiltration passage. Due to the enhancement of water infiltration and erosion, the expanding action continues and reciprocates, making the microscopic infiltration passage gradually evolve into a macroscopic water inrush passage, and eventually resulting in large-scale water inrush disaster in the tunnel. In actual construction practice, such water inrush is often manifested as lagging water inrush[8].

The evolution of the loss of stability caused by water infiltration into the permeable medium filled in the karst conduits can be divided into three stages[8]:

(1) In the initial compact stage, the unit drag force generated by the filling medium on the wall of the karst conduit is calculated as follows:

$$f_{\mathrm{w}}=\frac{n\rho_{\mathrm{w}}gDJ}{2} \tag{6}$$

(2) In the infiltration stage, the unit drag force generated by high-density sediment on the wall of the karst conduit is calculated as follows:

$$f_{\mathrm{w}}=\frac{n\rho_{\mathrm{s}}gDJ}{2} \tag{7}$$

(3) In the penetration stage, the unit drag force generated by the mixed fluid on the wall of the karst conduit is calculated as follows:

$$f_{\mathrm{w}}=\frac{\rho_{\mathrm{s}}gDJ}{2} \tag{8}$$

Where: J is the longitudinal hydraulic gradient along the karst conduit; D is the diameter of the karst conduit; n is the porosity of the filling medium, generally $n\leqslant 1$, or $n=1$ in the penetration stage; ρ_{w} is the density of the water flow; ρ_{s} is the density of the mixed mud/sand fluid.

Therefore, the drag force generated by the mixed mud/sand fluid on the wall of the karst conduit is greater than that generated by the karst water, and thus the expanding effect of the mixed mud/sand fluid on the karst conduit is more obvious.

3.4 Loss of key blocks

The key block of the rock mass usually refers to the body subject to collapse, which may be caused by cutting along the structural plane or the free face after tunnel excavation (see Figure 7).

In the study on the key block of rock mass, it is usually assumed that

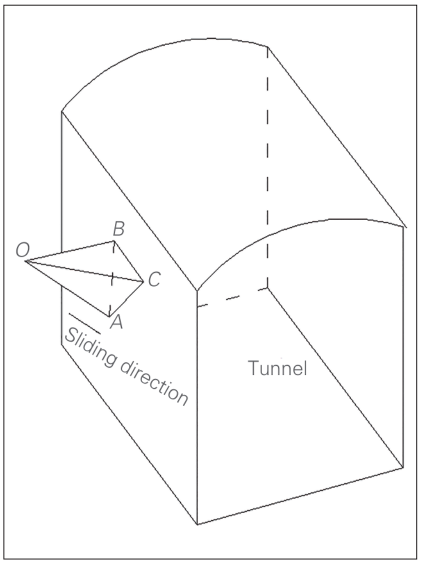


Figure 7 WSchematic diagram of ultimate equilibrium with key block sliding

the block is a rigid structure. Stress-induced yield failure does not occur to the key block, and the deformation strain of the key block is not considered. The failure that occurred to the key block is the sliding-shear failure along the structural plane. The absence of the key block of the rock mass often leads to the instability and failure of other blocks controlled by the key block. The key block of the rock mass is usually determined by the stereographic projection method. The mechanical constraints and working conditions of the key block, as well as the dynamic characteristics, failure modes and safety factors of the key block, are analyzed by the ultimate equilibrium method or the comprehensive analysis method[17].

In the water-rich karst ground, the surrounding rock is divided into many mutually embedded blocks by the joints and fractures of the ground. Before tunnel excavation, these blocks are in a state of equilibrium. The tunnel excavation causes the release of the original stress and energy of the surrounding rock, resulting in free faces and disturbed areas. Furthermore, the capability of the embedment between the shear structural planes of the blocks decreases under the action of the fissure water, which leads to the instability of the key blocks and further causes more blocks to slide and become unstable. The loss of the stability of large area of rock blocks will inevitably lead to significant reduction of the water-insulating capacity of the anti-inrush rock mass, resulting in water inrush accidents in the tunnel. For example, the joints and fissures of the surrounding rock of Jiudingshan Tunnel on Chuxiong-Dali Expressway are developed, and the surrounding rock is fractured. In July 2017, the crown of the tunnel collapsed, an many mud/water inrushes occurred. The analysis shows that karst develops above the tunnel, with high infiltration pressure and fractured surrounding rock. Under continuous karst water infiltration and construction disturbance, spalling occurs the tunnel crown gradually, resulting in crown collapse and water inrushing. Therefore, the evolution of the water inrush disaster is definitely accompanied by the softening and loss of the key blocks[18].

When the normal vector of the free face of the surrounding rock is consistent with the direction of the gravity or at a small angle with the direction of the gravity, the stability of the surrounding rock is poor. The stress redistribution or stress concentration of the surrounding rock will cause some rock blocks to slide along the structural plane, resulting in the loosening of the entire rock mass structure and in the end resulting in the loss of the stability of the rock mass[19]. Therefore, when the tunnel passes through fractured ground or ground with the joints and fissures intersecting each other, attention should be paid to prevent the chain of failures of the rock mass due to the loss of the stability of the key block or the loss of the key block. The key block can be confirmed according to the stereographic projection method. Grouting reinforcement, as well as anchor bolting and shotcreting if necessary, can be conducted. For the analysis on the stability of the key block under water pressure, please refer to Literature [16]:

$$k = \frac{\dfrac{Q\cos\gamma + PS_1\cos(\alpha_1 + \gamma)}{\sin\beta_{23}}(\cos\beta_3\tan\varphi_2 + \cos\beta_2\tan\varphi_3) - P(S_2\tan\varphi_2 + S_3\tan\varphi_3) + c_2S_2 + c_3S_3}{Q\sin\gamma + PS_1\sin(\alpha_1 + \gamma)} \tag{9}$$

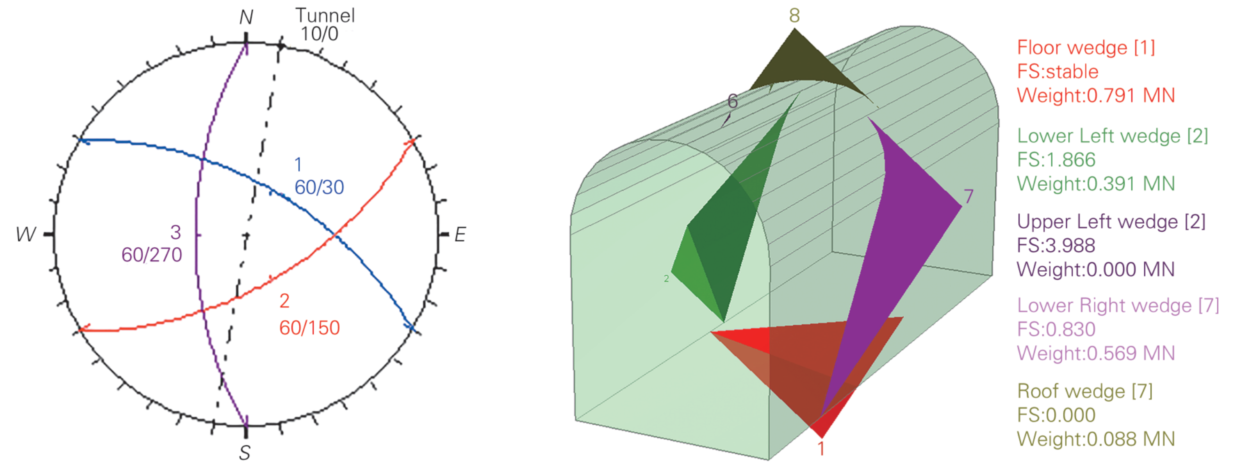
Where: k is the safety factor of the block; Q is the gravity of the block; P is the water pressure; γ is the dip angle of Line OA; S_1, S_2 and S_3 is the area of the structural plane; α_1 *is* the inclination angle of OBC; β_{23} is the angle between OAC and OAB; β_2 and β_3 are the angle between OAC and OA and that between OAB and OA respectively; c_2 and c_3 are the cohesions of OAC and OAB respectively; φ_2 and φ_3 are the friction angles of OAC and OAB respectively.

Here, the key block formed by the tunnel excavation is analyzed by means of a block analysis software. The software is suitable for the analysis on the stability of the 3D wedge formed by discontinuous structures and underground excavation. The safety factor of the potentially unstable blocks under various types of support modes can be calculated, and the influence of the supporting system on the stability of the wedge can be analyzed.

The density of the surrounding rock γ=26.5 kN/m^3. The excavation of the tunnel is affected by the joint surface. The angle between the tunneling direction and the joint surface is shown in Figure 8 (a). The friction angle of the joint surface φ=35°, the cohesion c= 0.01 MPa, and the design coefficient is taken as 1.5. After analysis, the key blocks formed by the tunnel excavation are obtained, as shown in Figure 8 (b). It can be seen that Block 8 above the crown may fall off, while Block 7 on the right side, with a safety factor of 0.83, is also in an unstable state. If there is a hidden water-filled karst cave above the crown or on the right side, the combined action of the construction disturbance and the karst water will easily lead to local or even overall damage of the anti-inrush rock mass, resulting in water inrush disaster. Therefore, Block 7 and Block 8 should be reinforced by advance grouting or shotcreting and anchor bolting, so as to improve the overall stability of the surrounding rock.

3.5 Comprehensive destructive water inrush

The evolution of the water inrush of karst tunnels, which has the micro-characteristics and macro-characteristics of the coupling of the stress field and the infiltration field of the surrounding rock, is very complicated. Therefore, in actual tunneling, multiple water inrush modes are interrelated and interact with each other. According to the geological characteristics, the water inrush characteristics and the actual tunneling conditions, it



(a) Angle between the tunneling direction and the joint surface

(b) Key blocks and their safety factors

Figure 8 Key blocks formed by tunnel excavation

can be judged that certain water inrush mode is the main mode. For example, after local fissures have been formed in the anti-inrush rock mass, the tensile-shear water inrush may develop into the hydraulic fracturing water inrush or shear-failure water inrush. Another example, when the surrounding rock of the karst tunnel has discontinuous joints and the pressure of the karst water is high, the tunnel excavation will induce cracking, expanding and penetrating of the fissures in the anti-inrush rock mass, forming hydraulic fracturing water inrush. With the continuous soaking and erosion of the filling medium in the cracks by the karst water, large shear deformation and displacement occur at the structural surface, resulting in shear-failure water inrush[3, 5, 14, 20, 21].

Different modes of water inrushes of karst tunnels show a certain continuity and progressive relationship under certain conditions. For example, tensile-shear water inrush generally occurs to the complete anti-inrush rock mass; in the case of incomplete anti-inrush rock mass, when there are many non-through fissures in the anti-inrush rock mass, hydraulic fracturing water inrush is easy to occur at the end of the fissures, while when the weak structural plane is connected with the karst water, shear failure occurs; when there are many fissures in the anti-inrush rock mass, the anti-inrush rock mass becomes more broken and fractured, the key block disappears and water inrush occurs[3, 5, 14].

4 Conclusion

In the paper, the mechanism of the water inrush of karst tunnels is summarized. The failure of the anti-inrush rock mass is classified into four types: the tensile-shear failure, the hydraulic fracturing failure, the sliding of the filling medium due to infiltration, and the loss of key blocks. The mechanism of the water inrush of karst tunnels is analyzed by means of theoretical analysis and calculation examples, and the following conclusions are drawn:

(1) The tensile-shear failure of the anti-inrush rock mass of the complete surrounding rock is analyzed by numerical simulation. The results show that the decrease of the thickness of the anti-inrush rock mass will cause a significant increase in the shear stress at the end. When the shear stress at the end is less than the shear strength of the rock mass, the loss of the overall stability of the anti-inrush rock mass occurs. In actual tunneling, the overall collapse of the anti-inrush rock mass above the crown of the karst tunnel is of such failure.

(2) The theoretical analysis shows that the hydraulic fracturing of the fractured rock mass in underground works is of compressive-shear failure. In actually tunneling, the excavation of the deep karst tunnels often causes damage to the surrounding rock due to the unloading action, which weakens the constraining force on the surrounding rock. In addition, due to the expansion and even penetration of the fissures in the rock mass, the strength of the surrounding rock is also weakened to some certain extent, which significantly reduces the critical water pressure required for the hydraulic fracturing of the surrounding rock and finally leads to fissure water inrush around the tunnel.

(3) The loss of the stability of the filling medium is classified into two types: loss of stability due to sliding and loss of stability due to infiltration. Under the combined action of the continuous blasting vibration and the hydrostatic pressure of the karst water during construction, shear failure occurs to the filling medium at the inner wall of the karst conduit, resulting in the loss of the stability of the filling medium due to its sliding. The process of infiltration failure is divided into three stages: the initial compact stage, the infiltration stage and the conduit penetration stage. In addition, the drag force of the mud/sand mixed fluid on the conduit wall

is big and the effect of expanding the conduit diameter is obvious.

(4) The loss of the key blocks is analyzed by means of block analysis software. The analysis results show that the key blocks are formed under the combined action of the free face in tunnel excavation and the original joint surface of the rock mass, and the safety factor of the key blocks is generally small. The loss and instability of the key blocks under the action of the karst water and the construction disturbance can easily lead to the local or even overall failure of the anti-inrush rock mass, resulting in water inrush disaster.

(5) The evolution process of the water inrush of karst tunnels is very complicated. The water inrush in actual tunneling is often the comprehensive result of the interrelation and interaction of multiple types of water inrushes, and different types of water inrushes have related continuity and progressive evolution relationships under certain conditions.

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