Water inrush channel formation mechanism in tunnels based on coupling effect of stress-seepage-damage

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1 INTRODUCTION

During the construction process of the karst tunnel, after driving cracks to extend and interpenetrate under high water pressure, karstic water releases energy radically after pouring into the excavation free face. As a result, water inrush or mud gushing break out. The stress-seepage-damage induced by the factors of groundwater and excavation disturbance is the key problem on the formation mechanism of water inrush channel. Many researches have been devoted to this issue.

Wang and Park (2002) utilized FLAC^{3D} to describe seepage-damage evolution equation in Medium damage expansion area. Wolkersdorfer (2004) compared stress intensity factor with fracture toughness of rock to judge crack initiation. Li (2009) simulated the coupling of seepage-damage for water inrush from seam floor.

In this study the study mentioned above is improved. Coupling effect of stress-seepage-damage for the catastrophe evolution process has been analyzed, and the formation trajectory of water inrush channel has been accurately located.

2. MULTI-FIELD COUPLING

2.1 Evolution law of seepage field

$$k(\sigma, p) = \omega k_0 e^{-\beta\left(\frac{\sigma_{ii}/3-\alpha p}{H}\right)} \qquad (1)$$

where k is the permeability coefficient; p is the pore water pressure; ω is the permeability kick coefficient; β is the coupling coefficient; σ_{ii} is the average stress; H is the Biot constant; α is the pore pressure coefficient.

2.2 Evolution law of stress-seepage-damage

(1) Stress-seepage coupling equation for tensile damage evolution

$$D = \begin{cases} 0 & \varepsilon_{t0} \leqslant \varepsilon \\ 1 - \dfrac{f_{tr}}{E_0 \varepsilon} & \varepsilon_{tu} < \varepsilon < \varepsilon_{t0} \\ 1 & \varepsilon \leqslant \varepsilon_{tu} \end{cases} \qquad (2)$$

At this time, the corresponding unit permeability coefficient is as fellows.

$$k = \begin{cases} k_0 e^{-\beta(\sigma_3 - \alpha p)} & D = 0 \\ \omega k_0 e^{-\beta(\sigma_3 - \alpha p)} & 0 < D < 1 \\ \omega' k_0 e^{-\beta(\sigma_3 - p)} & D = 1 \end{cases} \qquad (3)$$

where D is the damage variable; f_{tr} is the tensile residual strength; E_0 is the elasticity modulus with no damage; ε_{t0} is the strain threshold of tensile damage; ε_{tu} is the ultimate tensile strain; ω' is the increase coefficient of permeability coefficient.

(2) Stress-seepage coupling equation for shear damage evolution

$$D = \begin{cases} 0 & \varepsilon < \varepsilon_{c0} \\ 1 - \dfrac{f_{cr}}{E_0 \varepsilon} & \varepsilon_{c0} \leqslant \varepsilon \end{cases} \qquad (4)$$

At this time, the corresponding unit permeability coefficient is as fellows.

$$k = \begin{cases} k_0 e^{-\beta(\sigma_1 - \alpha p)} & D = 0 \\ \omega k_0 e^{-\beta(\sigma_1 - \alpha p)} & D > 0 \end{cases} \qquad (5)$$

where f_{cr} is the compressive residual strength; ε_{c0} is the ultimate compressive strain.

The constitutive laws of element under uniaxial tensile and compressive stress are showed in Fig 1 respectively.

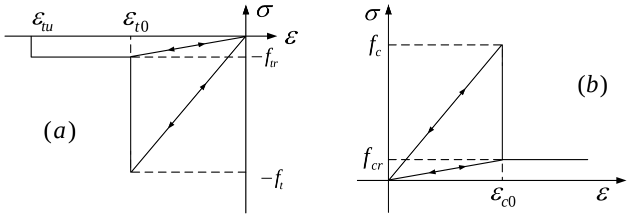

Fig. 1 Constitutive law: (a) Elastic damage constitutive law of element under uniaxial tensile stress; (b) Elastic damage constitutive law of element under uniaxial compressive stress

3. NUMERICAL SIMULATION on FORMATION PROCESS of WATER INRUSH CHANNEL

3.1 Model and parameters

The plane strain model is adopted as the numerical model. The model is homogeneous bedrock with the size of 150m*150m. The left and right boundaries are all restrained on displacement, while the bottom boundary is fixed. The in-situ stress loading on the top is 10MPa. All the boundaries are water insulating. Meanwhile, a karst cavity containing the sustained confined water with the pressure of 1MPa exists on the upper left of the tunnel. The diameters of cavity and tunnel are 12m and 6m, respectively. The model is shown as the following figure.

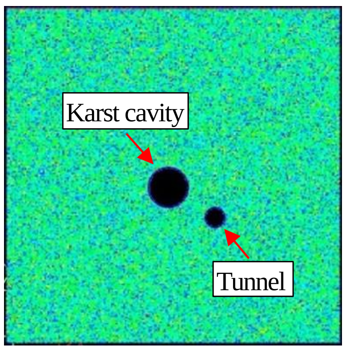

Fig. 2 Numerical model for simulation

The numerical model for calculation is divided into 48400 mesoscopic units. And the parameters of bedrock are listed in Table 1.

Table 1 Parameters employed in calculation

Compressive strength	Elasticity modulus	Poisson ratio	Frictional angle
35 MPa	7 GPa	0.27	30°
Density	Permeability coefficient	Pore water pressure coefficient	
2700 kg/m^3	0.1 m/d	0.5	

3.2 Simulation result analysis

(1) Evolution law of shear stress field

Before the tunnel excavation, there has been a stable shear stress field around the karst cavity. The rock unloading and seepage force arouse the rapid variation of shear stress field, especially in the rock mass between cavity and tunnel (Fig. 3).

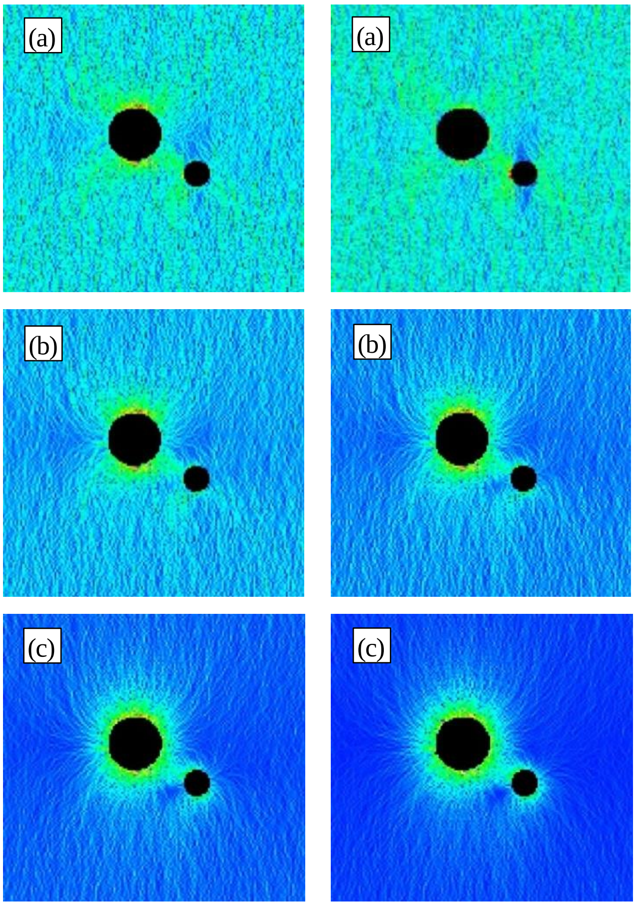

Fig. 3 Evolution law of shear stress field: (a) Stage of crack initiation; (b) Stage of crack propagation; (c) Stage of crack transfixion

(2) Formation process of water inrush channel

The formation process of water inrush channel is also the process of energy release in the rock mass. Therefore, the formation trajectory of channel can be recorded by the acoustic emission appearing when tensile failure or compression shear failure occurs, and the course is presented in Fig.4.

(3) Result analysis

Stage of crack initiation: The compression shear failure mainly influenced by rock mass unloading exists in the surrounding rock mass of tunnel and cavity. However, the crack initiation is due to the interference of excavation rather than seepage-damage.

Stage of crack propagation: On account of further the influence of surrounding rock mass unloading, the amount of cracks around the tunnel increases gradually. In addition, the cracks extend towards the karst cavity. Besides, cracks close by the cavity continue to expand.

Stage of crack transfixion: Because of continuous replenishment karstic water, an extensive damage zone gradually grows up in rock mass. A large number of cracks are yielded by tensile failure or compression shear failure on the linkage path between tunnel and cavity. Under the continuous effect of seepage-damage, adjacent cracks interpenetrate little by little. Finally, the water inrush channel is formed.

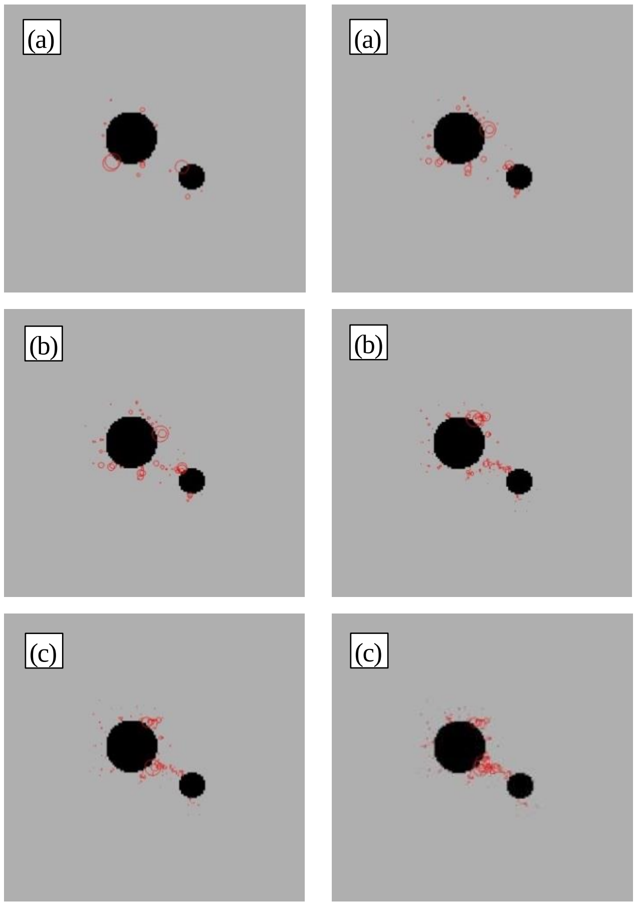

Fig. 4 Formation trajectory of water inrush channel: (a) Stage of crack initiation; (b) Stage of crack propagation; (c) Stage of crack transfixion

4 CONCLUSIONS

The ultimate formation of water inrush channel is due to strength reducing of rock mass induced by the sustained coupling effect of stress-seepage-damage, and the surrounding rock mass of water insulation experiences crack initiation, propagation and transfixion. According to the two kinds of failure situation of insulation rock, the formation trajectory of channel can be accurately and visually located.

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