Research Article

Water Inrush Mechanism of Fault Zone in Karst Tunnel under Fluid-Solid Coupling Field considering Effective Stress

Cunhan Huang,1,2 Wenhao Dong,1,2 Zhengzheng Cao,3,4 Yue Wang,3 Gangjian An,3 Huanqi Chen,3 Yunlong Jia,3 and Qiuyu Pan3

1Institute of Resources & Environment, Henan Polytechnic University, Jiaozuo, 454000 Henan, China
2Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Jiaozuo, 454000 Henan, China
3School of Civil Engineering, Henan Polytechnic University, Jiaozuo, 454000 Henan, China
4Henan Key Laboratory of Underground Engineering and Disaster Prevention, Henan Polytechnic University, Jiaozuo, 454000 Henan, China

Correspondence should be addressed to Zhengzheng Cao; caozz@hpu.edu.cn

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At present, the tunnel construction engineering is increasingly transferring to southwest mountainous areas with complex terrain and geological conditions in China and presents a trend of “large buried depth, long tunnel line, high stress, strong karst, high water pressure, complex structure and frequent disasters.” Taking water inrush disaster of karst tunnel fault zone as the research object, an evolutionary mechanical model of rock damage under the coupling action of stress-seepage is proposed in this paper. Besides, based on Comsol Multiphysics numerical software, the tunnel excavation is simulated, and the stress field, seepage field, and rock damage during the excavation are analyzed; thus, the mechanical mechanism of water inrush disaster from tunnel fault in karst area is obtained. The research results indicate that the tunnel excavation is a dynamic construction process, and the construction disturbance redistributes the original rock stress field and changes the state of seepage field. With the increase of excavation steps, the contour distribution of vertical stress ratio near the tunnel face is a circle shape, indicating that the rock mass is obviously disturbed by excavation, and the ratio of principal stress difference of rock mass at arch crown and bottom plate is large. Besides, the fault fissures expand and penetrate under the influence of tunnel excavation disturbance, increasing the permeability of fault zone in karst tunnel. In addition, the water seepage erosion takes away the granular rock mass, and the lithology becomes more weaker, which makes it possible for the occurrence of water inrush disaster in karst tunnel. Therefore, the advanced geological prediction is important in tunnel construction in karst area. The research results can be treated as an important theoretical basis for the prevention and treatment for water inrush disaster of fault zone in karst tunnel.

1. Introduction

With the rapid development of transportation infrastructural construction in China, a large number of tunnel projects are built in extremely complex mountainous and karst areas in Southwest China. Water inrush disasters occur in the construction process of tunnel excavation, resulting in large economic losses and casualties [1, 2]. For example, during the construction of the horizontal shaft of the tunnel in the Great Yao Mountain Tunnel, much mud and sand are taken out by the karst water, which leads the equipment to be submerged in the shaft and the tunnel, interrupting the regular construction for one month [3]. Besides, the water inrush disaster occurs in Nanling Tunnel of Beijing-Guangzhou Railway, which brings great inconvenience to safe construction of karst tunnel [4, 5]. Therefore, it is of
great significance to study the water inrush mechanism of karst tunnel and provide the theoretical guidance for tunnel engineering practice.

In recent years, many scholars have deeply analyzed the causes of water inrush in tunnel engineering from three aspects, namely, model test, theoretical research, and numerical simulation. Qiao Wei et al. [6] conducted an similarity material simulation of water inrush and fault activation, and the results show that fault activation was the root cause of water inrush. Li Shucai et al. [7] developed a large-scale tunnel water inrush disaster evolution simulation test system independently; besides, according to the tunnel excavation method and karst cave development size, simulation tests of evolution process of water inrush disaster in concealed cave under various working conditions were carried out. Deng Shujin et al. [8] designed and developed test devices independently and carried out water inrush simulation tests under the conditions of overburden head height, medium type, and medium particle grading characteristics of different media. Chen Guoqing et al. [9] employed the numerical software of COMSOL Multiphysics to simulate the whole process of water inrush disaster and proposed that complicated fractures tend to cause water inrush disaster due to water pressure concentration. Huang Mingli et al. [10] systematically studied the stress field, seepage field, and damage field in the process of water inrush induced by the karst cave during tunnel construction through the rock failure process analysis program (RFPA) and provided an important reference for the prediction and treatment of water inrush disaster. Wang Yuan et al. [11] employed the PFC3D and fluid mechanics finite volume method to simulate the whole process of water inrush and mud inrush. Based on the thin plate theory, Qiao Peizhen et al. [12] studied the mechanism and influencing factors of tunnel water inrush disaster, and concluded that the basic conditions of the occurrence of water inrush in karst tunnel contain the change of stress field of surrounding rock and the water pressure in surrounding rock of karst cave. Pu Hai et al. [13] established the mechanical model of deformation and failure of surrounding rock including fault and no fault. Specifically, the stress and plastic zone distribution of surrounding rock and the distribution characteristics of pore water pressure were analyzed by numerical simulation method. Parisio et al. [14] modeled the hydrodynamic effect during tunnel excavation and studied the tunnel excavation process under appropriate boundary conditions and initial conditions. Weng Xianjie et al. [15] established the calculation model of tunnel dynamic excavation across fault zone by the numerical simulation method. According to the hydraulic fracturing theory, Wang Junxi et al. [16] proposed the water inrush mechanism of deep buried tunnel under the action of hydraulic splitting. Li Xiaozhao et al. [17] proposed the stress change of fault zone under excavation disturbance and analyzed the water inrush process of fault under excavation disturbance.

It is obvious that the tunnel fault water inrush is the result of the comprehensive action of surrounding rock lithology, structure, stress field, and seepage field induced by tunnel excavation [18, 19]. Therefore, the coupling analysis of multiple physical fields is important in the water inrush mechanism of tunnel fault. In this paper, the effective stress principle is applied to the coupling analysis of multiple physical fields, and the numerical software of COMSOL Multiphysics is employed to simulate the tunnel excavation process. Therefore, the dynamic coupling process of stress and seepage during the tunnel excavation process is achieved, and the mechanism of water inrush in the fault geological zone of karst tunnel is obtained.

2. The Stress-Seepage Coupling Model considering Effective Stress

It is assumed that the surrounding rock mass of karst tunnel is the porous elastic-plastic material, and the initial pore pressure exists. Therefore, the fluid flow in the cracks of rock mass conforms to Darcy’s law in

\[ \nu = \frac{k}{\mu} (\nabla p + \rho g) \]  

(1)

where \( \nu \) is the seepage velocity, \( \mu \) is dynamic viscosity coefficient, \( k \) is the permeability of the rock, \( p \) is fluid pressure, \( \rho \) is the fluid density, and \( g \) is gravitational acceleration.

The stress of rock mass satisfies the elastic mechanics theory at the elastic stage [20, 21], and the stress field equation of porous media rock considering pore water pressure is derived in

\[ G\varepsilon_{i,j} + \frac{G}{1-2\nu} \varepsilon_{j,i} - \alpha p_i + F_i = 0 \]  

(2)

where \( G \) is the shear modulus, \( \nu \) is the Poisson’s ratio, \( p_i \) is pore water pressure, \( \alpha \) is Biot coefficient, \( \varepsilon \) is the displacement component of stress field, and \( F_i \) is the external force.

Tunnel excavation construction causes the deformation and damage of rock mass, and the important physical parameters of rock mass of karst tunnel, such as porosity shown in the following equation, are changed with the redistribution of stress.

\[ n = (n_0 - n_r) \exp \left( \alpha_n \cdot \sigma_v \right) + n_r \]  

(3)

where \( n_0 \) is the initial porosity, \( n_r \) is the porosity under high compressive stress, \( \alpha_n \) is the stress influence coefficient \( (5.8 \times 10^{-9}/\text{Pa}) \), and \( \sigma_v \) is related to the effective stress, which is calculated by

\[ \sigma_v = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3} - \alpha p \]  

(4)

The change of stress field affects the seepage field, and the permeability of rock mass changes [22]. Besides, the cubic law is employed to express the relationship between permeability and porosity as shown in

\[ \frac{k}{k_0} = \left( \frac{n}{n_0} \right)^3 \]  

(5)
where $k_0$ is the permeability under zero stress state and $k$ is the permeability in stress state.

3. Numerical Simulation of Water Inrush of Fault Zone in Karst Tunnel

3.1. Numerical Simulation Model. According to the geological characteristics of a karst tunnel fault zone, a simplified plane strain numerical simulation model is established, as shown in Figure 1. The numerical simulation model includes three types of rock strata, namely, water-bearing sandstone as aquifer, weakly permeable rock mass, and fault fracture zone, respectively. Besides, the mechanical parameters of rock mass of karst tunnel in numerical simulation model are shown in Table 1.

For the stress field, the left and right and bottom boundaries of the numerical simulation model are supported by rollers to restrict the horizontal and vertical displacement, and 5 MPa load is applied to the upper boundary. The upper and lower boundaries of the karst tunnel are free condition, while the front and back boundaries are horizontally constrained. For the seepage field, the water pressure of 4.1 MPa is applied to the left and right boundaries of water-bearing sandstone. The waterproof rock mass boundary is an impermeable boundary to maintain the water pressure of the geological environment where the karst tunnel is located, and the air pressure of the excavation face is the same as that of the atmosphere.

The excavation step of karst tunnel is set, and each excavation step is 10 m, so it is 40 m from the left to the fault. In order to research the stress characteristics of surrounding rock mass of the karst tunnel, monitoring line A-B is set at 1 m below it, and monitoring line C-D is set at the beginning of excavation location in karst tunnel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Water-bearing rock mass</th>
<th>Impermeable rock mass</th>
<th>The fault</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$</td>
<td>2670</td>
<td>2780</td>
<td>2260</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>The elastic modulus, $E$</td>
<td>7.6</td>
<td>8.3</td>
<td>1.0</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.24</td>
<td>0.22</td>
<td>0.3</td>
<td>—</td>
</tr>
<tr>
<td>Uni-axial tensile strength, $\sigma_t$</td>
<td>1.4</td>
<td>1.8</td>
<td>0.1</td>
<td>MPa</td>
</tr>
<tr>
<td>Cohesion, $c_s$</td>
<td>5.3</td>
<td>6.5</td>
<td>1.2</td>
<td>MPa</td>
</tr>
<tr>
<td>Internal friction angle, $\varphi$</td>
<td>37</td>
<td>43</td>
<td>27</td>
<td>—</td>
</tr>
<tr>
<td>Biot coefficient, $\alpha$</td>
<td>1.00</td>
<td>0.01</td>
<td>0.1</td>
<td>—</td>
</tr>
<tr>
<td>The initial porosity, $n_0$</td>
<td>0.14</td>
<td>0.27</td>
<td>0.348</td>
<td>—</td>
</tr>
<tr>
<td>The initial permeability, $k$</td>
<td>$2.3 \times 10^{-11}$</td>
<td>$5.8 \times 10^{-14}$</td>
<td>$1 \times 10^{-13}$</td>
<td>m$^2$</td>
</tr>
</tbody>
</table>

Figure 1: Numerical simulation model of tunnel excavation.

Table 1: Mechanical parameters of rock mass.
3.2. Distribution Characteristics of Stress-Seepage Field in Tunnel Excavation

3.2.1. The Stress Field. The vertical stress ratio refers to the ratio of the vertical stress of rock mass at A-B below the tunnel to the vertical stress of the original rock when the tunnel is excavated to a given location, which reflects the variation range of the stress field before and after excavation. The contour lines of vertical stress ratio distribution at $L = 10$ m and $L = 40$ m are shown in Figure 2, and the negative value represents the pressure.

With the advance of tunnel excavation, the range of vertical stress ratio increases, because the excavation surface becomes longer, and the front and rear walls of the tunnel bear the heavier rock mass. With the increase of tunnel depth, the vertical stress ratio of rock mass increases and gradually restores the original rock stress state in the surrounding rock mass of karst tunnel. Besides, the contour distribution of vertical stress ratio near the tunnel excavation location is a circle shape, and the value is obviously greater than 1, indicating that the rock mass is obviously disturbed by tunnel excavation and tends to expand in front of the tunnel excavation. Although the value decreases, it is still greater than 1, which is consistent with the actual situation that the lithology of the tunnel excavation face is weak, and the deformation and damage of rock mass occur easily.

In addition, the vertical stress ratio of the fault zone is close to 1 in the initial excavation step, indicating that it is not affected by the excavation disturbance. However, when the fourth step is excavated, the vertical stress ratio of the
fault is less than 1, because the joint fissures are developed in the fault zone and the lithology is weak. The fault fissures expand and penetrate under the influence of excavation disturbance, and the granular rock mass is taken away by the flowing water seepage erosion. Thus, the lithology becomes more weaker, inducing the occurrence of water inrush disaster. Therefore, advance geological prediction and waterproof lining structure are important in tunnel construction.

The variation of vertical stress ratio in monitoring line A-B is shown in Figure 3. The conditions in excavation distance $L = 10\, \text{m}$, $20\, \text{m}$, $30\, \text{m}$, and $40\, \text{m}$ are obtained. Specifically, the vertical stress ratio gradually reaches the peak value from the far rock strata to the beginning of the tunnel advancement location, and it decreases and maintains the lowest value at the tunnel face, increases again at the tunnel face, and decreases to a stable state in the far rock strata in front of the karst tunnel.

By comparing the four working conditions, it is obvious that the tunnel construction face is lengthened, and the range of in situ stress area is slightly smaller than the length of the tunnel construction face. Besides, the peak value of vertical stress ratio increases, and appears in the area in front of the tunnel construction face, because the tunnel construction face bears heavier upper load, and the stress field of surrounding rock mass of the karst tunnel is in a high stress state. When the excavation reaches the peak area, the elastic strain energy stored in the high stress surrounding rock is released, resulting in the development of rock mass fissures and the formation of water seepage channels. Therefore, the support and lining structures are damaged by the inverted arch subsidence, thereby causing water inrush disaster in karst tunnel. The principal stress difference ratio refers to the ratio of the principal stress difference of the initial state to the principal stress difference of a certain
excavation step \(\Delta\sigma/\Delta\sigma_0\), where \(\Delta\sigma\) and \(\Delta\sigma_0\) are obtained from the first principal stress \(\sigma_1\) and the third principal stress \(\sigma_3\) in the plane stress state.

Contour lines of principal stress difference ratio distribution in monitoring line C-D are shown in Figure 4. The ratio of principal stress difference is significantly higher than the original rock stress at the vault and inverted arch of tunnel construction face. Besides, the ratio of principal stress difference in tunnel excavation decreases compared with that of nonexcavation and gradually returns to the initial state with the increase of depth.

With the extension of the tunnel excavation face, the maximum value of the principal stress difference ratio increases, which is located at the vault and inverted arch of the tunnel face, indicating that the excavation disturbance is an important factor affecting the stress state of surrounding rock mass. At the same time, the stress state in the fault zone of karst tunnel changes in the tunnel construction process. In particular, there are dense isolines in the rock mass adjacent to the water-bearing sandstone and cement rock, indicating that the fault zone is affected by tunnel excavation disturbance, and the change of stress field creates certain
Figure 7: Continued.
conditions for water inrush disaster in the tunnel construction.

The variation trend of principal stress difference ratio of rock strata under tunnel invert with depth is shown in Figure 5. At the same depth, the ratio of principal stress difference of longer tunnel construction face is larger. Besides, the ratio of principal stress difference decreases with the increase of depth and gradually approaches the stress state of original rock. Tunnel excavation causes cracks and damage to the rock mass at a certain depth below the inverted arch, but this influence is not transmitted to the deeper rock strata, indicating that a certain thickness of water resisting layer is ensured during the tunnel construction process.

3.2.2. The Seepage Field. The excavation construction of karst tunnel is a coupling process of stress field and seepage field. The construction disturbance destroys the stable stress field in original rock mass, the development of rock fissures, and the change of pore structure. Besides, the permeability of rock strata is affected, and the seepage state of fluid in the fracture changes. The physical quantities of seepage field include water pressure, permeability, and flow rate.

It is obvious that the water pressure surrounding the karst tunnel decreases gradually and changes continuously from the aquifer to the boundary of the tunnel in Figure 6. As the tunnel excavation advances, the area of low pressure expands. At the last step, the tunnel excavation face is
connected to the fault, and the pressure at the bottom of the fault is the same as atmospheric pressure. Combined with the analysis of stress field, the fractures of rock mass are connected with the air, which forms a water seepage channel in the surrounding rock mass of the karst tunnel.

The permeability of isolated cement rock varies with excavation step as shown in Figure 7. The permeability evolution of cementing rock is low in tunnel invert and vault, but is high at the construction face of the karst tunnel. It is obvious that the plastic damage occurs in rock mass, and the fracture pores in rock mass increase. According to the cubic law, the permeability increases. The tunnel construction face becomes longer, but the permeability does not significantly increase, because the impermeability of cement rock is better, and the initial porosity and permeability are smaller than those of others.

The permeability distribution and the flow rate of seepage field when $L=40$ are shown in Figure 8. The seepage field is obtained when the karst tunnel is connected with the fault zone. Isolines are densely distributed near the karst tunnel construction face, indicating that the permeability changes obviously and decreases gradually to the distance. The contour lines at the invert and vault of the karst tunnel are sparse, close to the initial permeability of $5.8 \times 10^{-14} \text{m}^2$. Besides, the arrow length represents the flow velocity. The water flows from the left and right boundaries of the aquifer...
to the downward strata. Compared with the surrounding strata, the flow velocity in the fault zone increases slightly, and the seepage in the deep rock layer is weak. Finally, the water flows to the karst tunnel, thereby leading to the water inrush disaster in karst tunnel.

4. Conclusions

(1) Tunnel excavation is a dynamic construction process, and the construction disturbance redistributes the original rock stress field and changes the state of seepage field. Based on the numerical simulation of stress field, seepage field and damage evolution of rock mass of karst tunnel, the influence of in situ stress on surrounding rock mass of karst tunnel is analyzed, and the disaster-causing mechanism of water inrush in fault zone of karst tunnel is obtained.

(2) With the increase of excavation steps, the contour distribution of vertical stress ratio of the karst tunnel is a circle shape, and the value is obviously greater than 1, indicating that the rock mass is obviously disturbed by tunnel excavation, and the ratio of principal stress difference of rock mass at arch crown and bottom plate is large. The fault fissures expand and penetrate under the influence of tunnel excavation disturbance, increasing the permeability of fault zone in karst tunnel.

(3) The continuous extension and expansion of the damage zone affect the stability of the karst fault, where the fractured rock mass is further damaged, and the fracture development enhances the permeability. The fault zone becomes a water passage, and the groundwater flows into the karst tunnel, leading to the water inrush disaster. Therefore, the advanced geological prediction and grouting reinforcement are important in tunnel excavation construction in karst area.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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