The Evolution Process of Water Inrush Near High Pressure Water-Rich Cavity in Karst Tunnel Excavation with Layered Structure

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Abstract

In order to explore the damage of water and mud resistant rock mass and the evolution law of displacement and seepage pressure in the process of excavation in karst tunnel, when the excavation is faced with high pressure and water-rich cavity, the discrete element software is used to construct the water inrush calculation model in karst tunnel face with layered structure, and the evolution process of multi-physical disaster information of water and mud resistant rock mass in the process of excavation of tunnel is analyzed. The results show that: (1) With the excavation of karst tunnel, the extrusion displacement of water and mud resistant rock mass changes from single unloading to the combined influence of unloading and karst water pressure, and the displacement of each measuring point in the tunnel face increases. (2) The lateral displacement of water and mud resistant rock mass shows an increasing trend with the excavation, and a certain range of damage in front of the tunnel face is more obvious and the first damage occurs during the excavation of the tunnel. (3) The water pressure in the joint fissure of water and mud resistant rock mass in the karst tunnel face increases first and then decreases with the increase of the number of excavation steps. The closer to the cavity, the greater the water pressure, and the water pressure in water and mud resistant rock mass decreases from right to left. The research results can provide guidance for the prevention and control of water inrush in karst tunnels.

Keywords

Karst tunnel; Excavation unloading; Tunnel face; Disaster information; Discrete element.

1. INTRODUCTION

With the continuous advancement of the" Belt and Road "initiative and the implementation of the " transportation power " strategy, China 's transportation infrastructure construction has ushered in a golden period of development, and the transportation network is gradually expanding to the western mountainous and karst areas with extremely complex terrain and geological conditions[1]. As an important part of the traffic network, tunnel engineering often has various types of karst geological disasters due to complex engineering geology and hydrogeology, karst development, and abundant groundwater during the construction of karst areas. Among them, water and mud inrush is the most common and most harmful type[2,3]. In recent years, hundreds of water inrush accidents have occurred in China, causing serious economic losses, engineering casualties and environmental damage[4-10]. There have been 19 serious water and mud inrush disasters in the construction of Maluqing tunnel of Yiwan railway, and the instantaneous water inrush is the highest in the world's railway construction. Only two major outburst disasters occurred on January 21,2006 and April 11,2008, resulting in 15 deaths[11].When the Te'ermo tunnel of the Chengdu-Kunming Railway expansion project was constructed to the mileage DK274+580, multiple water inrush disasters occurred on the tunnel face. The maximum water pressure was1~1.2MPa, and the water inflow was 9000m^3/d, resulting in project shutdown and delay[12]. During the construction of the Yesanguan tunnel, water and mud burst suddenly, and the water inflow was about 40,000~50,000m^3/h, resulting in 52 construction personnel trapped and multiple equipment destroyed, eventually leading to 10 deaths[13]. At present, the technology of constructing tunnels in karst areas is not yet mature, and the research on the mechanism of water inrush disaster in karst tunnels lags far behind the development of production practice. Therefore, it is of great significance for the prevention and control of water inrush in karst tunnels to carry out relevant research on the evolution process of water inrush in karst tunnels and the evolution characteristics of accompanying disaster information.

In this paper, a series of simulation studies on the dynamic evolution law of water inrush in layered water and mud resistant rock mass are carried out by discrete element method. The evolution process of water inrush in layered rock mass is analyzed when the karst tunnel face is close to the front high-pressure water-rich cavity during the excavation. In the process of excavation of karst tunnel, the evolution process of displacement and seepage pressure of water and mud resistant rock mass in tunnel face with layered structure is studied under the condition that the internal water pressure of the front karst cavity is 1MPa. The evolution law of displacement and seepage pressure of water and mud resistant rock mass in the process in karst tunnel with layered structure is revealed under the condition that the internal water pressure of the front karst cavity is 1MPa. The research results are of great significance to the early warning and prevention of water inrush in karst tunnels.

2. METHODOLOGY

2.1. Numerical calculation model

In order to improve the efficiency of calculation, the model size is 80m×80m, and the cross section of the tunnel adopts the three-center circle method, which is 4.97m, 9.58m and 6.3m, respectively[14,15]. The span of tunnel is 10m and the height is 12m. The buried depth of the tunnel is 500m.According to the buried depth of the tunnel, the weight of the rock and soil mass above it is converted into equivalent load and added to the upper boundary of the model. The upper boundary is set as the free boundary, and the other boundaries are set as the fixed boundary. The layered model grid is used to simulate the structure type of layered water and mud resistant rock mass. In this model, the high-pressure water-rich cavity model is simplified. The water-containing cavity in front of the tunnel adopts an elliptical model with a long axis of 15m and a short axis of 10m. The water pressure of the cavity in front of the tunnel face is 1MPa, and the dip angle of the rock joint is 30°.

2.2. Measuring points layout and mechanical parameters

In order to study the evolution law of disaster information when water inrush occurs in the excavation process of water and mud resistant rock mass in karst tunnel face with layered structure, the construction and excavation of karst tunnel is simplified to a certain extent. The excavation method is full-section excavation. The first excavation footage is 18m, the second excavation is 10m, the third and fourth excavations are 6m each time, the fifth excavation is 3m, and the subsequent excavation is 1m each time until the tunnel face was damaged. In the process of sequential excavation of the tunnel adjacent to the water-rich karst cavity in front of the tunnel face, the monitoring points are set within 2m near the karst cavity (Figure 1). The evolution characteristics of disaster information in the process of water inrush are monitored.

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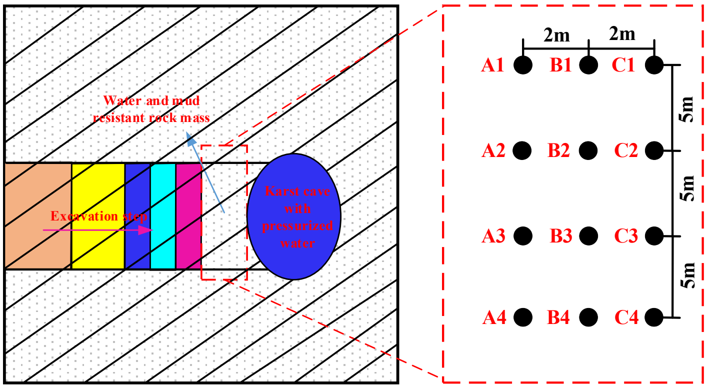


Figure 1. Monitoring station layout and number

The Mohr-Coulomb model (The cons=2) is used for the water and mud resistant rock mass in the tunnel face. The Coulomb sliding model (The jcons=1) is used for the layered joint. The mechanical parameters of rock block mechanics and layered joints of water and mud resistant rock mass are shown in Table 1 and 2.

Table 1. Mechanical parameters of surrounding rock mass

Elastic modulus (GPa)	Bulk modulus (GPa)	Shear modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Internal friction angle (°)	Unit weight (kg/m^3)
30	22.6	11.1	0.25	0.86	42	26.6

Table 2. Mechanical parameters of layered joints

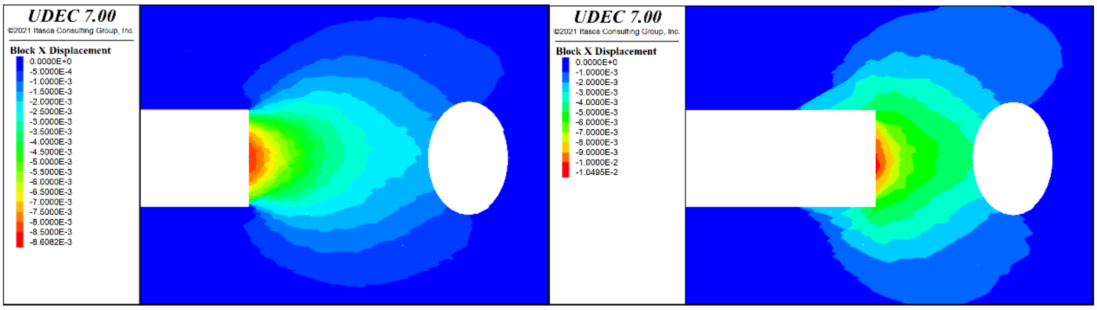
Normal stiffness (GPa/m)	Tangential stiffness (GPa/m)	Internal friction angle (°)	Cohesion (MPa)
18.6	6.2	30	0.5

3. RESULTS ANALYSIS AND DISCUSSION

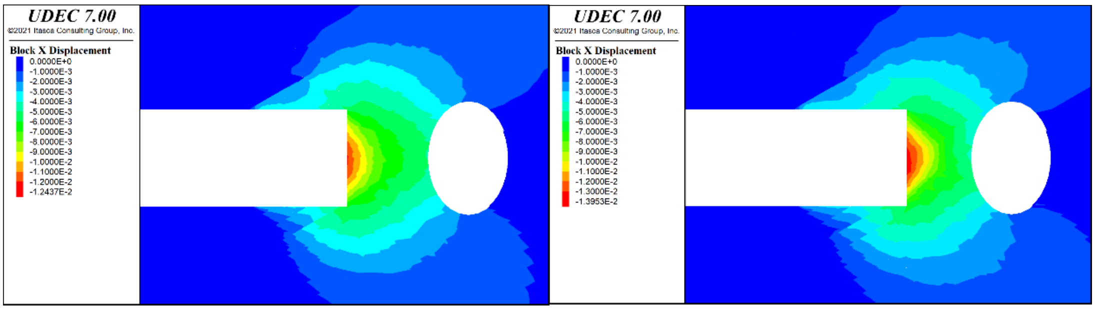
3.1. Displacement evolution characteristics of water and mud resistant rock mass under excavation disturbance

In the process of karst tunnel excavation, when the water pressure of the current karst cavity is 1MPa, the displacement of water and mud resistant rock mass with layered structure is shown in Figure 2. The Figure 2 shows the displacement state when the model is calculated to be balanced after each excavation:

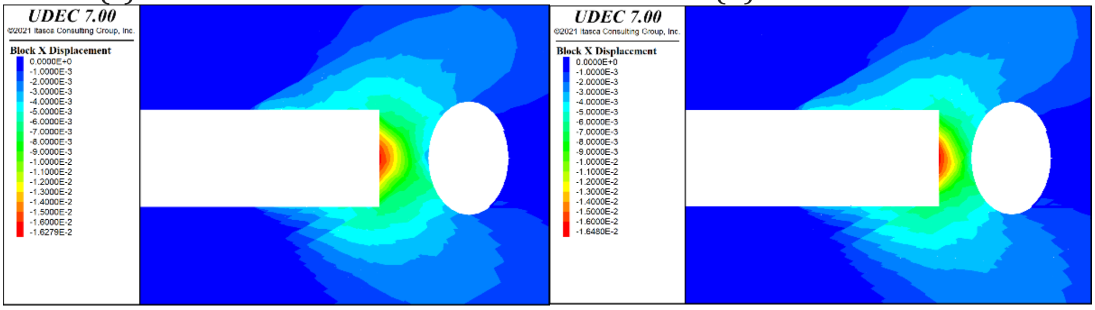
From Figure 2, it can be seen that: (1) The maximum extrusion lateral displacement of the tunnel face in the first four steps is small and equivalent. The lateral displacement of the tunnel face in the fifth step is 40% higher than that in the fourth step. At this time, the extrusion displacement of water and mud resistant rock mass in the tunnel face transits from unloading to unloading and karst water pressure. (2) During the early stage of excavation, due to the large thickness of water and mud resistant rock mass, the karst water pressure in the front cavity has little effect on water and mud resistant rock mass under the action of single excavation unloading. At this time, water and mud resistant rock mass is relatively stable. When the transition from single excavation unloading to unloading and karst water pressure is completed, the instability state of water and mud resistant rock mass is gradually reflected. (3) After the seventh excavation, the displacement of the tunnel face increases sharply, and the maximum displacement is more than 1.6m. At this time, the thickness of water and mud resistant rock mass is less than the minimum safe thickness of the tunnel face, and the water and mud resistant rock mass is split. It can be seen from the seventh step excavation that some of the rock mass has fallen out of water and mud resistant rock mass and fallen into the tunnel free surface, and the water and mud resistant rock mass is completely destroyed.



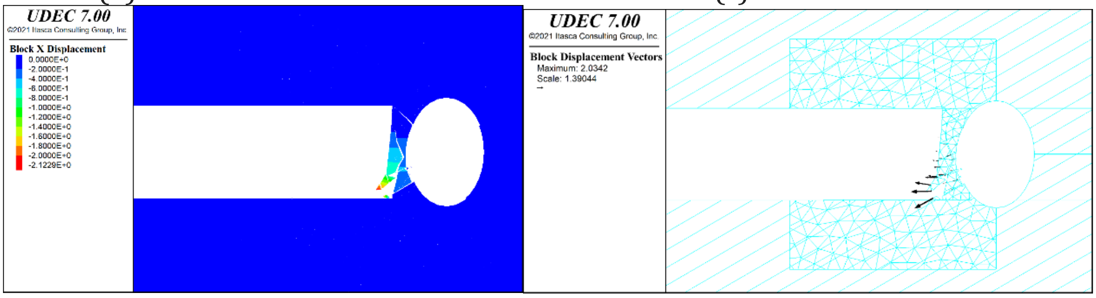
(a) First excavation (b) Second excavation



(c) Third excavation (d) Fourth excavation



(e) Fifth excavation (f) Sixth excavation



(g) Seventh excavation (h) Seventh excavation displacement vector

Figure 2. Displacement field evolution process

In order to further study the relationship between the lateral displacement of each monitoring surface of water and mud resistant rock mass when the cavity water pressure is 1MPa, the displacement relationship between the monitoring surface 1,3 and the monitoring surface 2,4 is drawn as shown in Figure 3.

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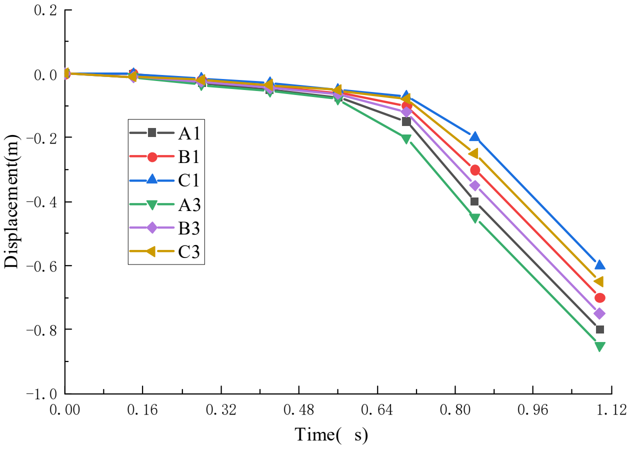
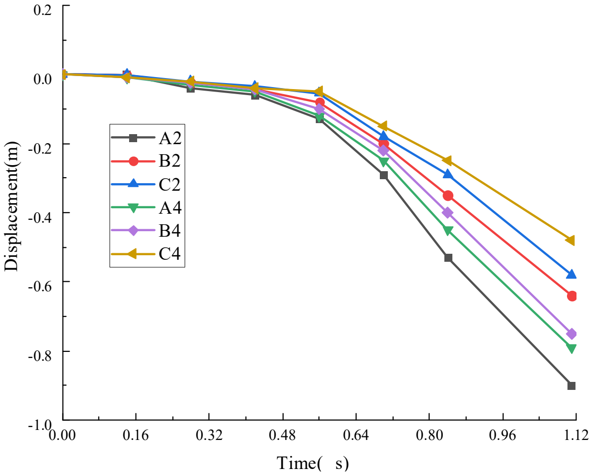


(a) The lateral displacement of 1 and 3



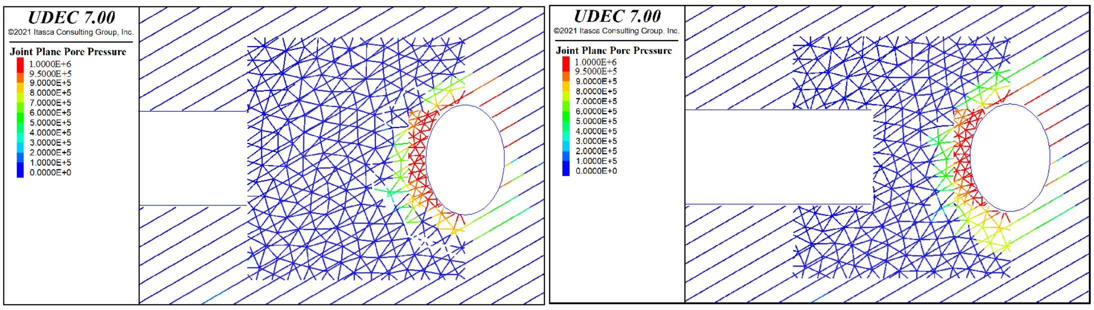
(b) The lateral displacement of 2 and 4

Figure 3. Lateral displacement of the monitoring site

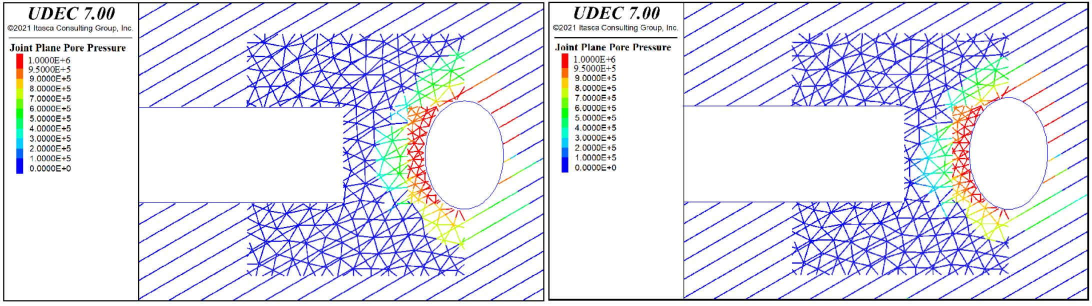
According to the displacement monitoring line chart 4, it can be seen that when the water pressure in the cavity is 1MPa. (1) The lateral displacement of the monitoring points on the monitoring surface of water and mud resistant rock mass increases with the increase of the calculated excavation time. When the tunnel excavation face is far away from the front cavity, the thickness of the water and mud resistant rock mass is larger, and the lateral displacement value of the water and mud resistant rock mass in the tunnel face is smaller. With the excavation of the tunnel face, the extrusion displacement response of different monitoring points is gradually obvious, and the change law is basically the same. (2) When the water pressure in the cavity is 1MPa, the lateral displacement of the monitoring points on the monitoring surface of the water and mud resistant rock mass increases with the increase of the calculated excavation time. (3) For the monitoring points of the same vertical monitoring surface, the displacement of monitoring point A3 is greater than that of A1, and the displacement of monitoring point A2 is greater than that of A4, which indicates that the damage in a certain range in front of the tunnel face is more obvious and the damage is the first to occur during tunnel excavation.

3.2. Hydraulic pressure evolution characteristics of water and mud resistant rock mass under excavation disturbance

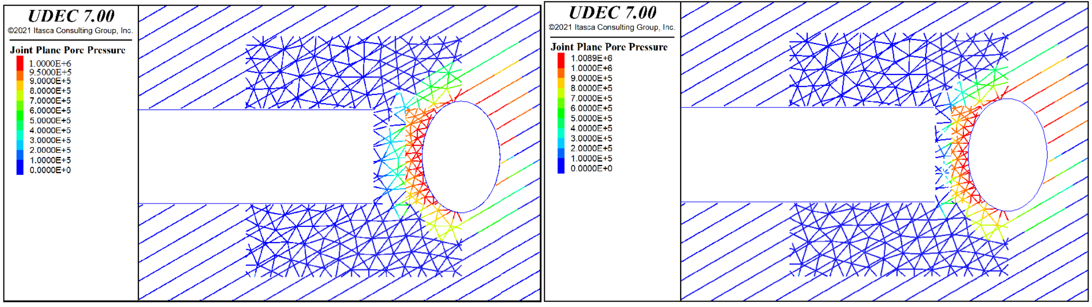
In the process of karst tunnel excavation, when the water pressure of the current karst cavity is 1MPa, the seepage pressure distribution of water and mud resistant rock mass is shown in Figure.4.



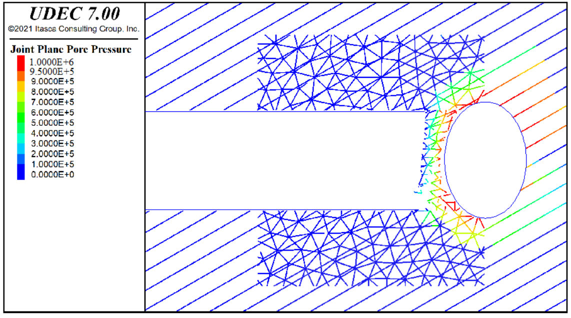
(a) First excavation (b) Second excavation



(c) Third excavation (d) Fourth excavation



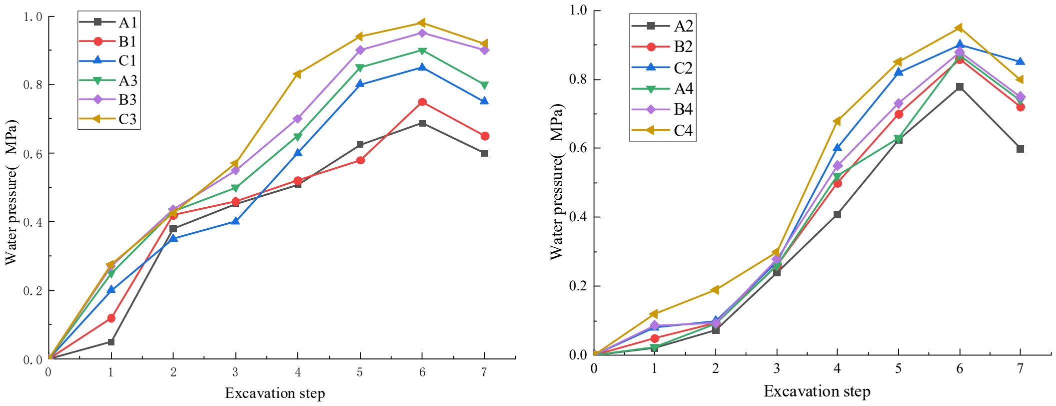
(e) Fifth excavation (f) Sixth excavation



(g) Seventh excavation

Figure 4. Evolution process of seepage field

When the water pressure of the cavity is 1MPa, the water pressure change relationship of each monitoring surface of water and mud resistant rock mass is shown in Figure.5.



(a) The lateral displacement of 1 and 3 (b)The lateral displacement of 2 and 4

Figure 5. Monitoring point water pressure

It can be seen from Figure.4 and Figure.5: (1) When the water pressure of the cavity is 1MPa, the water pressure in the joint fissure of water and mud resistant rock mass in the tunnel face increases first and then decreases with the increase of the number of excavation steps. When the tunnel face is far away from the front cavity, the water pressure distribution of the monitoring points shows a trend of gradual increase and is more regular, and the expansion and migration of fissure water in water and mud resistant rock mass is not obvious. With the advancement of the tunnel face, when the excavation is to the fifth and sixth steps, the increase of the water pressure of the same vertical monitoring surface is greater than that of the first four excavation steps, and shows an increasing trend. After the seventh step of excavation, under the action of fluid-solid coupling effect and unloading, the joint fissure expands and penetrates, forming a water inrush channel in water and mud resistant rock mass. The fissure water flows into the tunnel and the water pressure of the joint fissure decreases. (2) It can be seen from Figure.3 that the water pressure at the monitoring point near the cavity is greater than that at the monitoring point near the tunnel face, indicating that the water pressure at the monitoring point near the cavity is greater than that at the monitoring point away from the cavity. (3) As the karst tunnel face continues to close to the karst cavity, the water pressure of the monitoring point C3 and C4 is always greater than the water pressure of the monitoring point at the same level monitoring surface, indicating that the water pressure in water and mud resistant rock mass is decreasing from right to left.

4. CONCLUSIONS

In this paper, the discrete element method is used to dynamically simulate the evolution characteristics of the displacement and seepage pressure in the water inrush process in karst tunnel face with the layered structure during sequential excavation of karst tunnel. The main results are as follows:

(1) As the tunnel face is close to the pre-existing high-pressure water-rich cavity, the extrusion displacement of the water and mud resistant rock mass in the tunnel face is initially caused by a single unloading, and then gradually transitions to the combined effect of unloading and pre-existing karst water pressure.

(2) In the process of tunnel excavation, the lateral displacement of the water and mud resistant rock mass shows an increasing trend with the excavation, and a certain range of damage in front of the tunnel face is more obvious and the first damage occurs during the excavation of the tunnel.

(3) The process of tunnel excavation, the water pressure in the joint fissure of water and mud resistant rock mass in the karst tunnel face increases first and then decreases with the increase of the number of excavation steps, and the water pressure near the karst cavity is greater than that far away from the karst cavity. As the karst tunnel face continues to approach the karst cavity, the water pressure in the water and mud resistant rock mass is increasing.

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REFERENCES

[1] S.C. Li, Z.H Xu, X. Huang, et al: Classification, geological identification, hazard mode and typical case studies of hazard-causing structures for water and mud inrush in tunnels. Chinese Journal of Rock Mechanics and Engineering, Vol. 37 (2018), No.5, p.1041-1069.

[2] S.C. Li, K. Wang, L.P. Li, et al: Mechanical mechanism and development trend of water-inrush disasters in karst tunnels. Chinese Journal of Theoretical and Applied Mechanics, Vol.49 (2017), No.1, p.22-30.

[3] Y.Y. Jiao, W.S. Zhang, G.S. Ou, et al: Review of the evolution and mitigation of the water-inrush disaster in drilling-and-blasting excavated deep-buried tunnels. Hazard Control in Tunneling and Underground Engineering, Vol. 1 (2019), No.1, p.36-46.

[4] Y.X. Lv, Y.J. Jiang, H. Wei, et al: A review of the effects of tunnel excavation on the hydrology, ecology, and environment in karst areas: current status, challenges, and perspectives. Journal of Hydrology, (2020), p.586.

[5] S.C. Li, Z.Q. Zhou, L.P. Li, et al: Risk assessment of water inrush in karst tunnels based on attribute synthetic evaluation system. Tunneling and Underground Space Technology incorporating Trenchless Technology Research, Vol. 38 (2013), p.50–58.

[6] Jeannin P, Yves A, Malard D. Assessing karst-hydraulic hazards in tunneling—the Brunnmühle spring system—Bernese Jura Switzerland [J]. Environmental Earth Sciences, Vol. 74 (2015), p.7655–7670.

[7] Y.G. Xue, F.M. Kong, D.H. Qiu, et al: The classifications of water and mud/rock inrush hazard: a review and update. Bulletin of Engineering Geology and the Environment, Vol. 80 (2021), p.1907–1925.

[8] X.X. Liu, S.L. Shen, Y.S Xu, et al: Analytical approach for time-dependent groundwater inflow into shield tunnel face in confined aquifer. International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 42 (2018), p.655–673.

[9] Y.J. Zhao, F.G. Wang, C.S. Li, et al: Study of the corrosion characteristics of tunnel fissures in a karst area in southwest China. Geofluids, Vol. 7 (2018), p.1-19.

[10] Z. Huang, W. Zeng, Y. Wu, et al: Experimental investigation of fracture propagation and inrush characteristics in tunnel construction. Natural Hazards, Vol. 97 (2019), p.193-210.

[11] W.L. Wu. Catastrophic Mechanism and Risk Assessment on Water Inrush of Karst Tunnel Working Face (Ph.D., Henan Polytechnic University, China 2022), p.2.

[12] C.H. Bai. Research on Intelligent Prediction Method of Hazard Risk of Water and Mud inrush in Karst Tunnel Based on Machine Learning (Ph.D., Shandong University, China 2021), p.30.

[13] L.P. Li, W.F. Tu, S.S. Shi, et al: Mechanism of water inrush in tunnel construction in karst area. Geomatics, Natural Hazards and Risk, Vol. 7 (2016), p.35-46.

[14] Hršak, B., Čikić, A., Šeketa, T: Dimensioning and 3D modeling of a swing check valve with lever and weight. Technical Journal, Vol. 9 (2015), p.6-11.

[15] S.R. Wang, D.J. Li, C.L. Li, et al: Thermal radiation characteristics of stress evolution of a circular tunnel excavation under different confining pressures. Tunnelling and Underground Space Technology, Vol. 78 (2018), p.76-83.