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Research Article

Evolution Characteristics Analysis of Displacement and Seepage Pressure of Water Inrush in Karst Tunnel Face with Layered Structure

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Abstract

To study the disaster process of water and mud resistant rock mass with layered structure and the accompanying catastrophe information of water inrush in karst tunnel, a new method based on the discrete element method and fictitious joint technology was adopted to really simulate the evolution process of water inrush process in karst tunnel face and study the evolutionary characteristics of displacement and seepage pressure of water and mud resistant rock mass with different layered structure. Results show that as the excavation of the karst tunnel progresses, the extrusion displacement of the water and mud resistant rock mass transitions from single unloading to the joint influence of unloading and karst water pressure, and the displacement of each measuring point on the karst tunnel face increases. As the water in the cavity continues to pour into the joints and fissures, the water pressure continues to rise. When the water inrush channel of tunnel face is formed, the karst water flow rate rises sharply, which provides significant water inrush precursor information. With the continuous increase of the inclination angle of the layered structure, the maximum lateral displacement of the face moves downward from the front, and the water pressure at each position of the water and mud resistant rock mass shows a trend of first increasing and then decreasing. The conclusions obtained in this study have a great significance to early warning and prevention of water inrush in karst tunnels.

Keywords: Karst tunnel, Tunnel face, Layered structure, Water inrush

1. Introduction

As an important part of the traffic road network, tunnel projects often encounter various karst geological disasters during the construction of karst areas due to complex engineering geology and hydrogeology, development of karst disaster-causing structures, and active groundwater. The water inrush is one of the most common and extremely destructive geological disasters [1-5]. Without pre-support and pre-reinforcement, if the water and mud resistant rock mass cannot withstand the combined action of karst water pressure, excavation disturbance and external factors, the cracks will rapidly generate, expand, and penetrate each other, eventually causing water inrush disaster. In recent years, hundreds of water inrush accidents have occurred in China, causing serious economic losses, engineering casualties and environmental damage [6, 7]. At present, the technology of building tunnels in karst areas is still immature, and the research on the mechanism of water inrush disasters 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 disaster in karst tunnels and the evolution characteristics of the accompanying disaster information.

Water inrush of karst tunnel face is a system imbalance process in the form of water and mud resistant rock mass rupture and the formation of water inrush channels under the combined action of excavation disturbance and karst water pressure [8]. The water inrush mechanism of the water and mud resistant rock mass with different structures of the karst tunnel face is obviously different. The common water and mud resistant rock mass structures of karst tunnel face include complete structure, massive fracture structure, discontinuous structure and layered structure. In the limestone strata, joints and fissures connecting the hazard-causing structures and tunnels often develop inside the water and mud resistant rock mass with layered structure, which constitute the weak structural surface of the water and mud resistant rock mass [9].

There are many joints and fissures in the water and mud resistant rock mass with layered structure. When the tunnel excavation approaches but does not expose the water and mud resistant rock mass, the natural equilibrium conditions of the original groundwater have been changed, the joints and fissures continue to expand and penetrate, forming water inrush channels, and the water and mud resistant rock mass is split and damaged, karst water pours into the tunnel, resulting in water inrush disasters. Therefore, the structure characteristics of the water and mud resistant rock mass and water-rock interaction in the rock mass with layered structure play the important role in the disaster process of water inrush and evolutionary characteristics of displacement and seepage pressure.

2. State of the art

Many scholars have done a lot of researches on the disaster mechanism of water inrush and the catastrophe information

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characteristics of water inrush through theoretical analysis, model tests and numerical simulation [10]. Xu et al. deduced the minimum safe thickness formula of water and mud resistant rock mass by using section synthesis and elastic mechanics theory [11]. Fu et al. deduced the formula for calculating the minimum safe thickness of the karst cave below the excavation tunnel [12]. Guo et al. studied the stability of water and mud resistant rock mass between the tunnel and karst cave [13]. Based on Hoek-Brown failure criterion and considering the adverse effect of infiltration force on karst tunnel face, Wu et al. deduced the formula of critical safety thickness for tunnel face instability [14]. Huang et al. established a mathematical calculation model for the safe thickness of hidden karst cave and tunnel face based on mathematical theory [15]. The instability criterion based on theoretical analysis can only be used to judge the overall instability of the system at the final stage of water inrush process in karst tunnel [16]. Water inrush of karst tunnel involves the process of crack initiation, expansion and penetration of the fissures in the water and mud resistant rock mass. Therefore, it is difficult to theoretically describe the whole process of the water inrush disaster caused by the failure of the water and mud resistant rock mass.

The model tests can accurately simulate the rupture and instability process of the water and mud resistant rock mass when the tunnel face is close to the high-pressure karst structure. Idinger et al. studied the stability of tunnel face through physical model tests [17, 18]. Huang et al. used acoustic emission devices to study the development characteristics of fractures on the tunnel face and the formation of water inrush channels in the process of tunnel excavation [19]. Yang et al. studied the evolution law of water pressure in karst cave during tunnel excavation and revealed the evolution mechanism of water inrush through the physical model test [20]. Liang et al. studied the evolution law of surrounding rock stress, displacement and water pressure through the physical model experiment of water inrush [21]. Due to the limited number of monitoring components and the limitations of the monitoring instrument's own functions [22], it is impossible to obtain enough macro information about water inrush [23]. However, the numerical simulation method can solve the above problems, and it has the function of visualizing the dynamic water inrush rupture process of the water and mud resistant rock mass [24]. In the field of numerical simulation, Zhao et al. proposed the converted permeability coefficient of water inrush pipe flow in confined karst cave and constructed the whole process analysis model of water inrush in karst cave [25]. Pan et al. studied the mechanism of water inrush caused by the proximity of karst caves during tunnel construction through numerical simulation [26]. Lai et al. used numerical simulation method to study the evolution characteristics of seepage pressure, displacement and other catastrophe information in the process of water inrush disaster under different conditions of karst water pressure, tunnel depth and lateral pressure coefficient [27]. Qin et al. used FLAC3D to analyse the distribution of releasable elastic strain energy and failure zone under different hidden caves widths [28]. Wang et al. used three-dimensional finite difference program to simulate and analyze the influence of water-filled cave in front of the tunnel face on the stability of surrounding rock of the tunnel, and established a mathematical model of the minimum safe thickness between the cave in front and the tunnel through multiple regression analysis [29].

The previous researches and achievements as above for the stability and disaster process of the water and mud resistant rock mass promoted the advancement in this field and provided a solid foundation for further study in this study. However, there are some shortcomings about numerical calculations. For example, most of the above researches are based on the finite element method or finite difference method, which regard the water and mud resistant rock mass as a porous continuous medium. It cannot truly reflect the dynamic evolution process of the surrounding rock such as slump and seepage after karst tunnel excavation. Moreover, the studies on the hydraulic failure mechanism of the water and mud resistant rock mass are less involved, and it also can't accurately describe the evolution process of water inrush and the evolution characteristics of water inrush disaster.

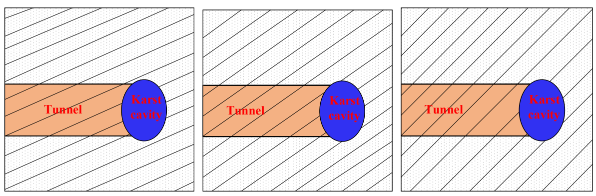
In view of this, this study uses a new method based on the UDEC and fictitious joint technology to conduct a series of simulation, studies the dynamic evolution characteristics of water inrush in water and mud resistant rock mass with layered structure, analyses the influence of layered joints on the water inrush and instability failure process of the water and mud resistant rock mass, and the evolution characteristics of displacement and seepage pressure of water and mud resistant rock mass in the process of water inrush in karst tunnels under different joint inclinations is revealed. The research results can be of great significance to the early warning and prevention of water inrush in karst tunnels.

The rest of this study is organized as follows. Section 3 gives the numerical simulation scheme. Section 4 describes the simulation results and analysis, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Numerical calculation model

In order to improve the efficiency of calculation, the model size is 80 m × 80 m, and the cross section of the tunnel adopts the three-centred circle drawing method, the radius is 4.97 m, 9.58 m, and 6.3 m, respectively [30, 31]. The span of tunnel is 10 m and the height is 12 m. The buried depth of the tunnel is 500 m. According to the depth of the tunnel, the weight of the rock and soil above is converted into an equivalent load and added to the upper boundary of the model. The upper boundary is set as a free boundary, and the other boundaries are set as fixed boundaries. The model grid adopts layered shape to simulate the structure type of water and mud resistant rock mass. In this model, the karst cavity with high-pressure model is simplified, an ellipse model with a long axis of 15 m and a short axis of 10 m was used for the karst cavity in front of the tunnel, and the water pressure of the karst cavity in front of the tunnel is 2 MPa, the inclination angles of rock stratum are 15°, 45° and 60°, respectively (Fig. 1).



(a) θ=15° (b) θ=45° (c) θ=60°

Fig. 1. Numerical calculation model.

3.2 Measuring points layout and mechanical parameters

To study the evolution characteristics of catastrophic information when water inrush occurs during the excavation process of water and mud resistant rock mass in the karst tunnel face, the karst tunnel construction excavation has been simplified to a certain extent. The excavation method is full-section excavation. The footage of the first excavation is 10 m, and the second excavation is 6 m. The third and fourth excavations are 3 m each time, and then 1 m each time until the tunnel face is damaged by water inrush. During the sequential excavation of the tunnel and gradually approaching the water-soluble cavity in front of the tunnel, the monitoring points were set up within 2 m of the cavity (Fig. 2), which monitor the evolution characteristics of catastrophic information during the water inrush process of water and mud resistant rock mass.

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 joints. The mechanical parameters of rock block mechanics and layered joints of water and mud resistant rock mass are shown in Tables 1 and 2.

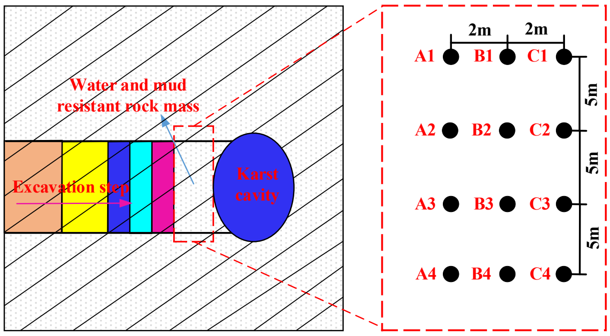


Fig. 2. Measuring points layout.

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 (kN/m^3)
30	22.60	11.10	0.25	0.86	42	26.60

Table 2. Mechanical parameters of layered joints.

Normal stiffness (GPa)	Tangential stiffness (GPa)	Internal friction angle (GPa)	Cohesion (MPa)
30	22.60	11.10	0.25

4. Results analysis and discussion

4.1 Evolution characteristics of displacement under different inclinations of rock stratum

In the process of karst tunnel excavation, the evolution characteristics of the displacement field of the water and mud resistant rock mass in the karst tunnel face under different inclinations of rock stratum are shown in Fig. 2. The displacement cloud diagram shown in Fig. 3 is the displacement state when the model is calculated and balanced after each tunnel excavation.

As seen from Fig. 3, with the further excavation of the karst tunnel, the extruded displacement of the water and mud resistant rock mass in the karst tunnel face gradually increases, and the increase is larger and larger. It shows that in the continuous excavation of the karst tunnel to the side of the high-pressure cavity, the lateral displacement of the water and mud resistant rock mass in the tunnel face gradually transitions from a single unloading to the combined influence of unloading and high-pressure cavities. The influence of the karst cavity in front of the karst tunnel in the stability of the water and mud resistant rock mass is increasing.

After the excavation in the early stage, the lateral displacement in front of the water and mud resistant rock mass in the karst tunnel face is almost symmetrically distributed up and down, and migrates in the direction of the bedding joints. It shows that the unloading effect of excavation is transitioning to the influence of the original inclination joint of the outburst prevention body.

After the seventh excavation, the horizontal displacement of the water and mud resistant rock mass in the tunnel face increased sharply. At this time, under the comprehensive influence of factors such as excavation unloading, karst water pressure, and the inclination of rock stratum, the water and mud resistant rock mass is split along the direction of the bedding joints, and an obvious failure zone is formed in the tunnel face.

Comparing the results after the seventh excavation under different joint inclinations, it can be seen that with the continuous increase of the rock stratum inclination, the maximum lateral displacement of the tunnel face moves downward from the front of the tunnel face, and the position where the water and mud resistant rock mass of the tunnel face is first broken through keeps moving downward. In the end, the water and mud resistant rock mass is split and damaged, forming an obvious damage zone in the tunnel face.

It can be seen from the Fig. 4 that with the further excavation of the karst tunnel, the extruded displacement of the water and mud resistant rock mass in the karst tunnel face gradually increases, and the increase is larger and larger. It shows that in the continuous excavation of the karst tunnel to the side of the high-pressure cavity, the lateral displacement of the water and mud resistant rock mass in the tunnel face gradually transitions from a single unloading to the combined influence of unloading and high-pressure cavities. The influence of the karst cavity in front of the karst tunnel in the stability of the water and mud resistant rock mass is increasing.

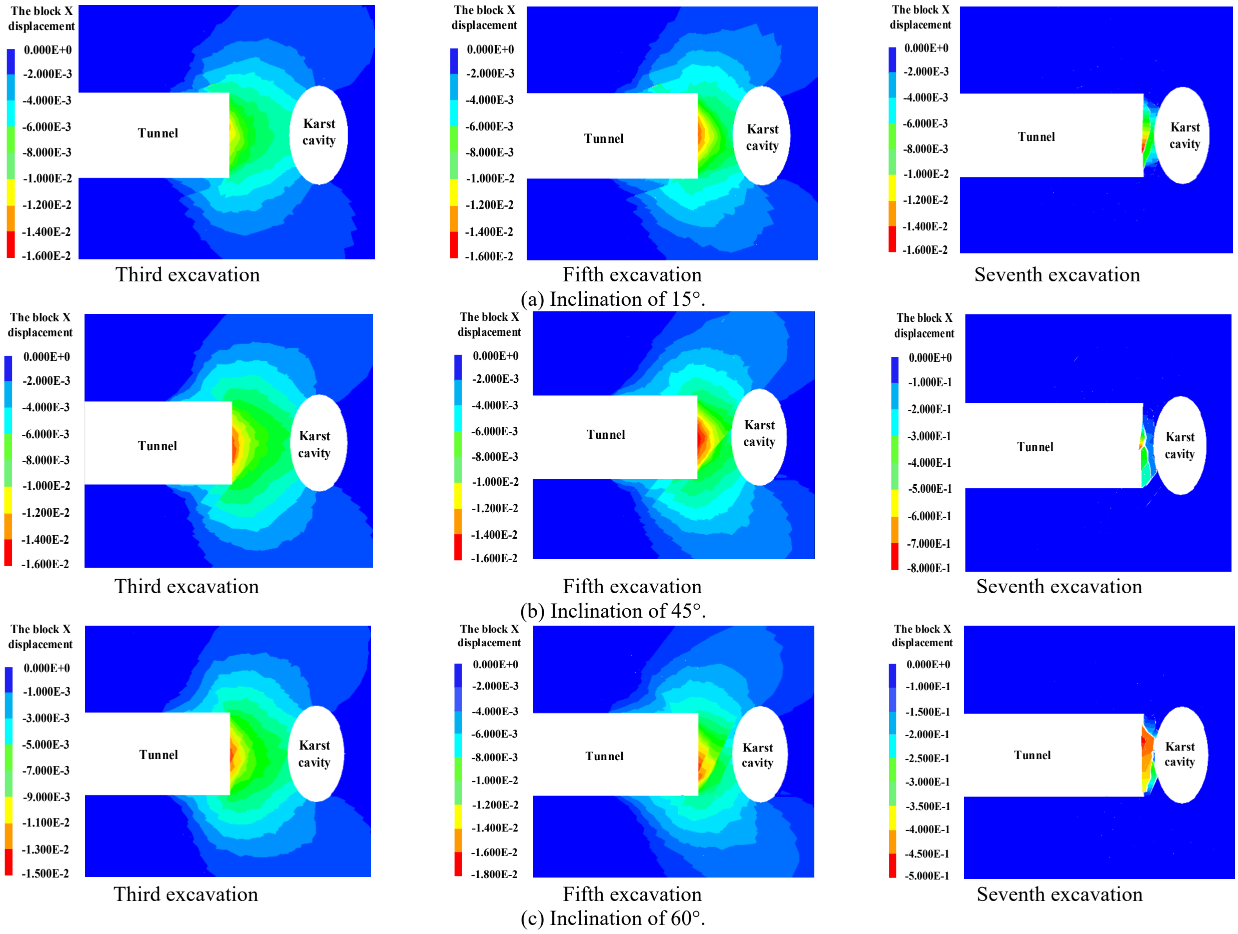


Fig. 3. Evolution process of displacement under the different inclinations of rock stratum (unit: m).

After the excavation in the early stage, the lateral displacement in front of the water and mud resistant rock mass in the karst tunnel face is almost symmetrically distributed up and down, and migrates in the direction of the bedding joints. It shows that the unloading effect of excavation is transitioning to the influence of the original inclination joint of the outburst prevention body.

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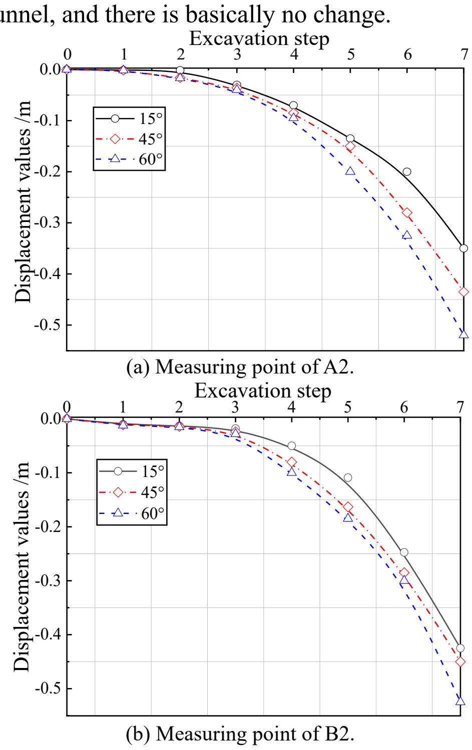
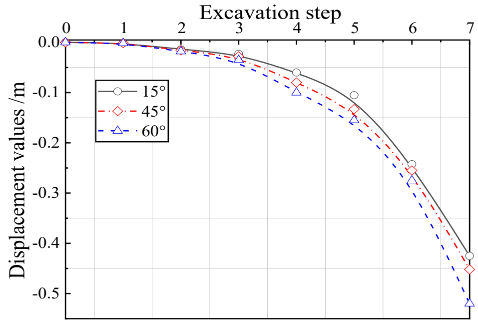
When the tunnel face is damaged, take the sudden deformation of the center points as the displacement change values of the tunnel face. In order to further study the evolution characteristics of the displacement under different inclinations of rock stratum. In this study, according to the lateral displacement of each measuring point on the monitoring level 2, draw the displacement change characteristics of the mearing points under different inclinations of rock stratum (Fig. 4). With the continuous excavation of the tunnel along the tunnel face, the variation trend of the lateral displacement of the water and mud resistant rock mass in the tunnel face under different inclinations of rock stratum is basically the same. The three steps of excavation have little effect on the lateral displacement of the water and mud resistant rock mass in the karst tunnel, and there is basically no change.





(c) Measuring point of C2.

Fig. 4. Evolution characteristics of displacement.

With the further excavation of the tunnel, the lateral displacement and deformation of the water and mud resistant rock mass in the tunnel face gradually increases. The more times of excavation, the smaller the thickness of the water and mud resistant rock mass, and its stability gradually decreases under the action of karst water pressure and excavation disturbance. It can also be seen from the above the Fig. 6 that with the continuous increase of the inclination of the rock stratum, the displacement of the water and mud resistant rock mass in the tunnel face continues to increase. It shows that the increase of the inclination of the rock stratum reduces the stability of the water and mud resistant rock mass, and its anti-outburst ability gradually decreases. Under the same karst water pressure, the minimum safe thickness required for the karst tunnel continues to increase.

4.2 Evolution characteristics of seepage pressure under different inclinations of rock stratum

In the process of karst tunnel excavation, the evolution process of the seepage field of the water and mud resistant rock mass in the tunnel face under different inclinations of rock stratum is shown in Fig. 5.

In the process of karst tunnel excavation, the formation and evolution of the water inrush channel in the water and mud resistant rock mass under different inclinations of rock stratum is shown in Fig. 5. It can be seen from the Fig. 6 that after the third excavation, the karst water in front of the tunnel entered the layered joints connected with the cavern. At this time, the karst water is basically maintained in the water and mud resistant rock mass in the influence area of the rightmost row of layered joints connected to the cavity. Moreover, the seepage of the water and mud resistant rock mass in the tunnel face is not obvious after three excavations, indicating that the excavation disturbance has limited influence on the seepage stability of the water and mud resistant rock mass in the tunnel face. After the fifth excavation, with the further reduction of the distance between the tunnel face and the high-pressure cavity in front of the tunnel, the excavation disturbance began to appear. The water pressure of the layered joint on the far right further increased, the karst water continued to infiltrate along the layered joint to the tunnel face direction, and the karst tunnel face began to seepage of karst water. This phenomenon can be regarded as a precursor feature of water inrush in the tunnel face. After the seventh excavation, many cracks were formed between the middle and upper part of the tunnel face and the layered joints. The water and mud resistant rock mass in the tunnel face could no longer resist the water pressure of the former cavern. Under the combined action of excavation disturbance and water pressure, the overall instability and failure occurred, and then a stable water inrush channel was formed.

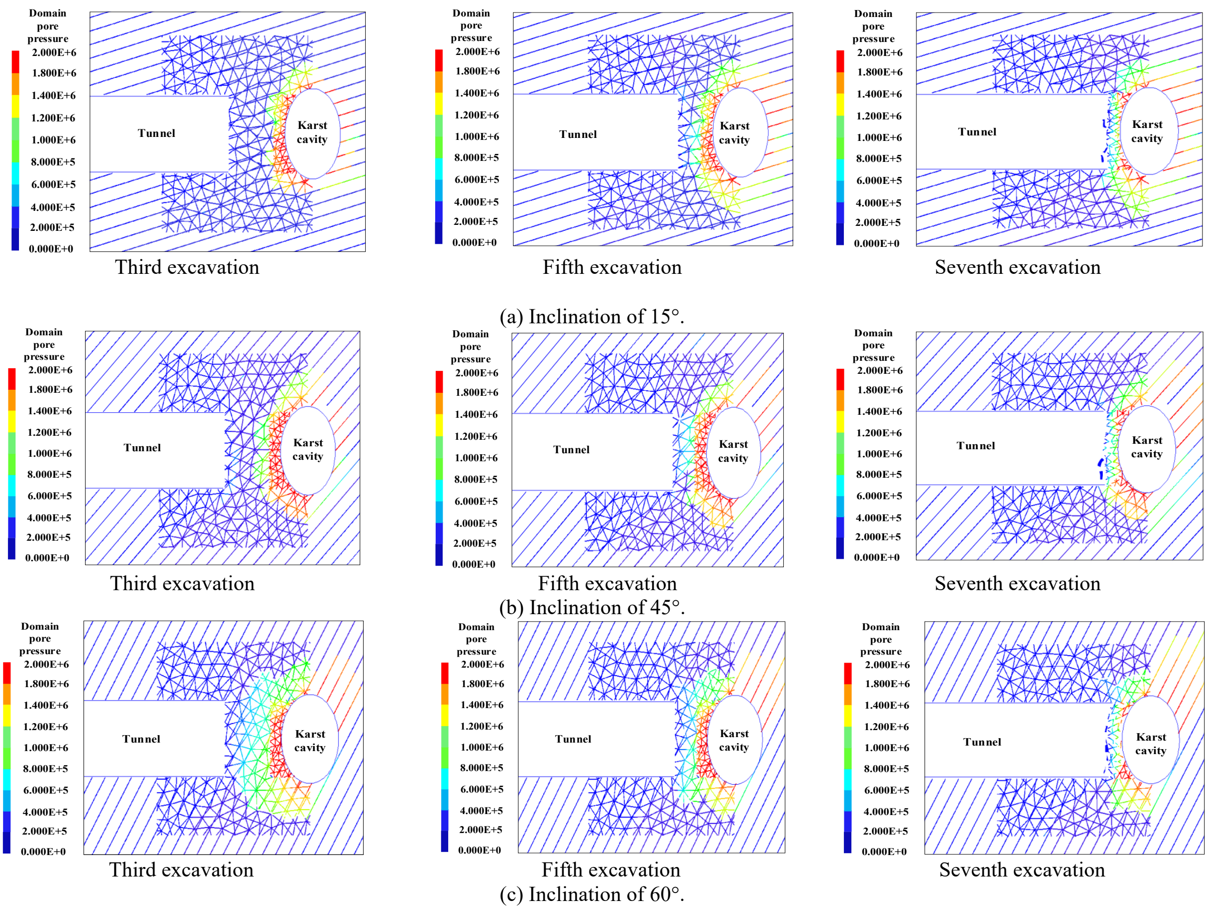
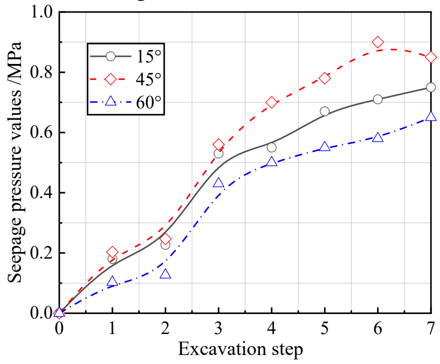
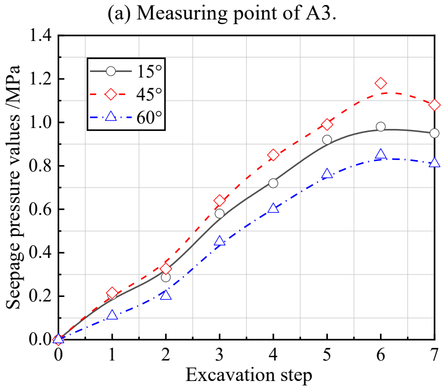


Fig. 5. Evolution process of seepage pressure under different inclinations of rock stratum (unit: Pa).

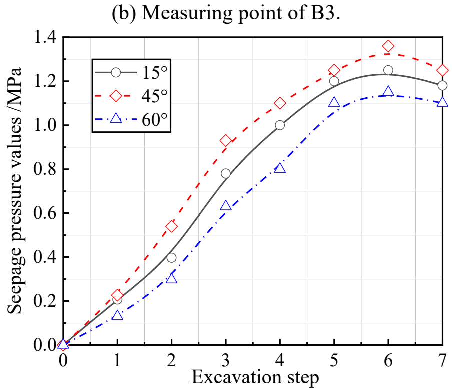
In order to further study the evolution characteristics of seepage pressure when the tunnel face fails under different inclinations of rock stratum. In this study, according to the seepage pressure of each measuring point on the monitoring level 3, the seepage pressure change relationship of the tunnel face under different inclinations of rock stratum is drawn, as shown in Fig. 6.



(a) Measuring point of A3.



(b) Measuring point of B3.



(c) Measuring point of C3.

Fig. 6. Evolution characteristics of seepage pressure.

It can be seen from Fig. 7 that with the continuous excavation of the karst tunnel, the water in karst cavity continues to pour into the joints and fissures, resulting in the continuous increase of water pressure. When the tunnel face is close to the cavity, the joint fissure is connected with tunnel face, causing water to flow out from tunnel face, and the water pressure gradually decreases. Under the combined action of disturbance stress and water pressure, the water and mud resistant rock mass is greatly deformed, part of the blocks are close to each other and overlap, and the joint water pressure between the two blocks will increase sharply at this time. When the inclination of rock stratum increases from 15° to 45°, the water pressure at the same point basically increases continuously within the same time. In the fourth step, the water pressure increased from 0.58 MPa to 0.64 MPa after the excavation was balanced. When the inclination of joint increases from 45° to 60°, the water pressure at each point decreases continuously, and the water pressure decreases from 0.64 MPa to 0.45 MPa.

5. Conclusions

A new method based on the DEM and fictitious joint technology was adopted to dynamically study on evolution characteristics of the displacement and seepage pressure in the water inrush process on karst tunnel face with the layered structure during sequential excavation of karst tunnel. The main results are as follows:

(1) As the tunnel face approaches the cavity with high-pressure in front of the tunnel, the extrusion displacement of the water and mud resistant rock mass in the tunnel face is initially caused by a single unloading, then it gradually transitioned to the joint effect of unloading and fore-burdened karst water pressure, and the displacement of each measuring point in the tunnel face increased greatly.

(2) With the continuous excavation of the karst tunnel, the water in the karst cavity continues to pour into the joints and fissures, resulting in a continuous increase in water pressure. When the tunnel face approaches the karst cavity, the water inrush channel in the tunnel face is formed instantaneously, the flow rate of karst water in the karst tunnel face increased sharply, which can provide significant water inrush precursor information.

(3) With the continuous increase of the inclination of rock stratum, the maximum lateral displacement of the tunnel face moves downward from the front, and the position where the water and mud resistant rock mass is first broken through keeps moving downward; When the inclination of rock stratum increases from 15° to 45°, the water pressure at each position of the water and mud resistant rock mass increases continuously. When the inclination of rock stratum increases from 45° to 60°, the water pressure at the tunnel face begins to decrease gradually.

The excavation of tunnels generally adopts the drilling and blasting method, and the influences of blasting load on the structural stability of the karst tunnel face with layered structure cannot be ignored. In the next step, the evolution characteristics of displacement and seepage pressure during the water inrush process of the water and mud resistant rock mass in the karst tunnel face with layered structure under the disturbance of blasting and excavation should be carried out.

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