Analysis of Water Inrush Displacement and Water Pressure Evolution Characteristics of Karst Tunnel Face During Excavation Process

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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

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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 3MPa. 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 3MPa. 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 3MPa, 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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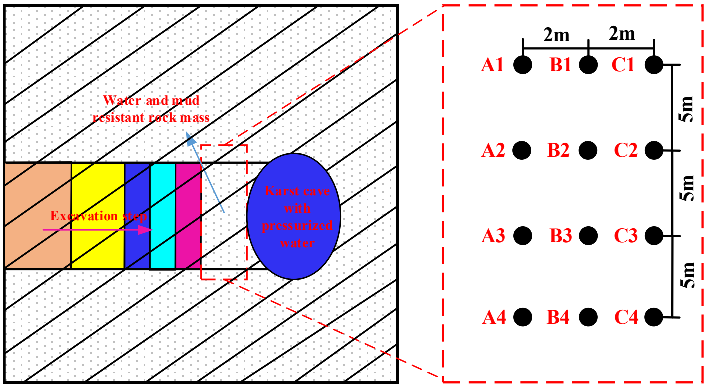

Figure 1. Monitoring station layout and number

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 3MPa, 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) In the first five steps of excavation, the horizontal lateral extrusion displacement of the tunnel face increases slightly, and the maximum horizontal lateral extrusion displacement of the water and mud resistant rock mass basically appears in the front position of the tunnel face. (2) According to the results of the sixth step of excavation, the maximum horizontal lateral extrusion displacement of the tunnel face appears in the front position of the tunnel face, and the displacement value decreases in the upper and lower directions. Compared with the cavity water pressure of 1MPa and the water pressure of 2MPa, the larger the water pressure, the position of the first failure of the tunnel face moves from the front to the front along the layered joint, and the failure zone is formed within a certain range.

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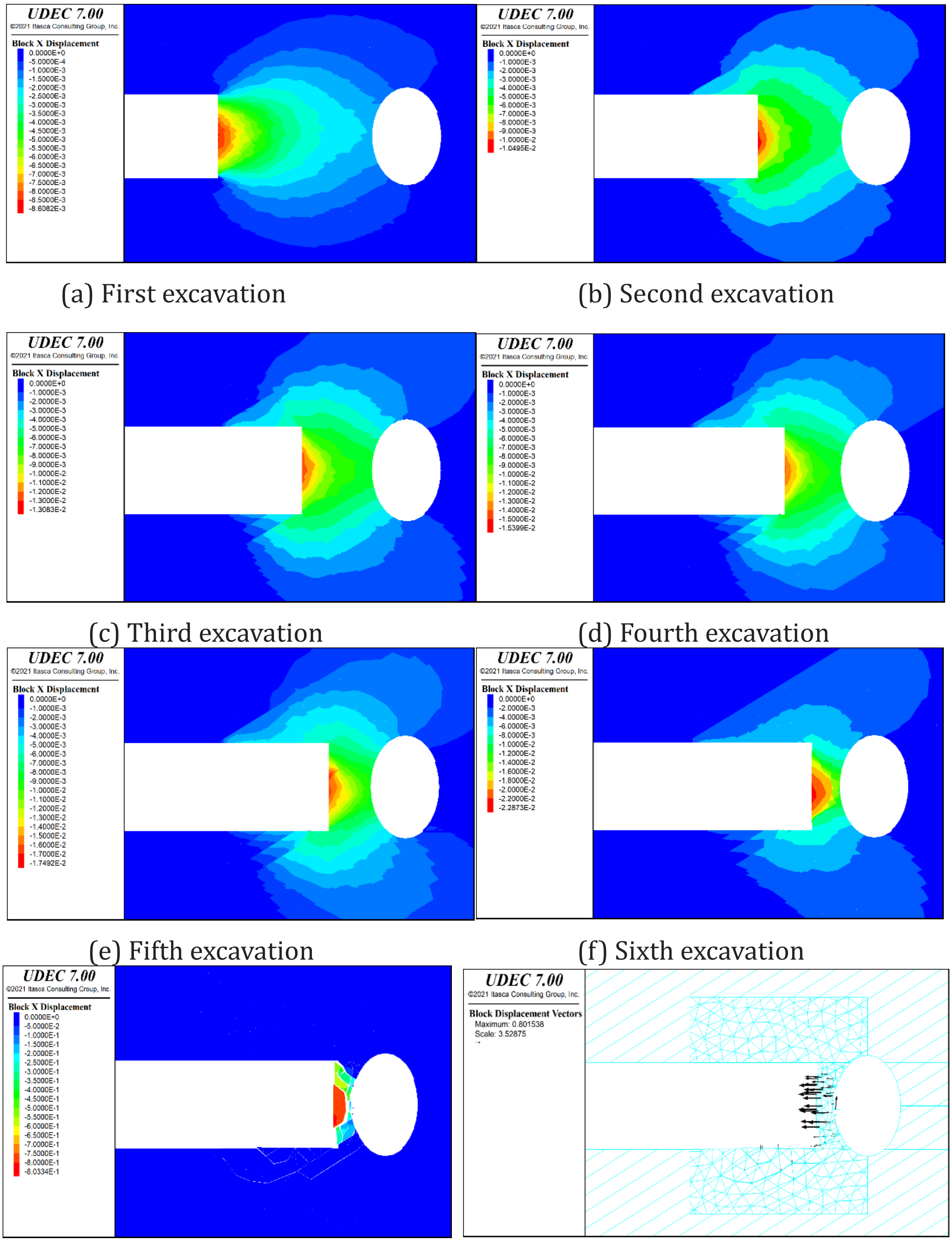
(3) After the seventh step excavation, the water and mud resistant rock mass has been destroyed, and the maximum horizontal extrusion lateral displacement of the water and mud resistant rock mass reaches 0.8m.According to the displacement vector diagram of the seventh step excavation, part of the rock mass moves laterally to the free surface of the tunnel. The water and mud resistant rock mass between the cavity and the tunnel face has experienced macroscopic splitting failure and high-pressure karst water pours into the free surface of the tunnel.



(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

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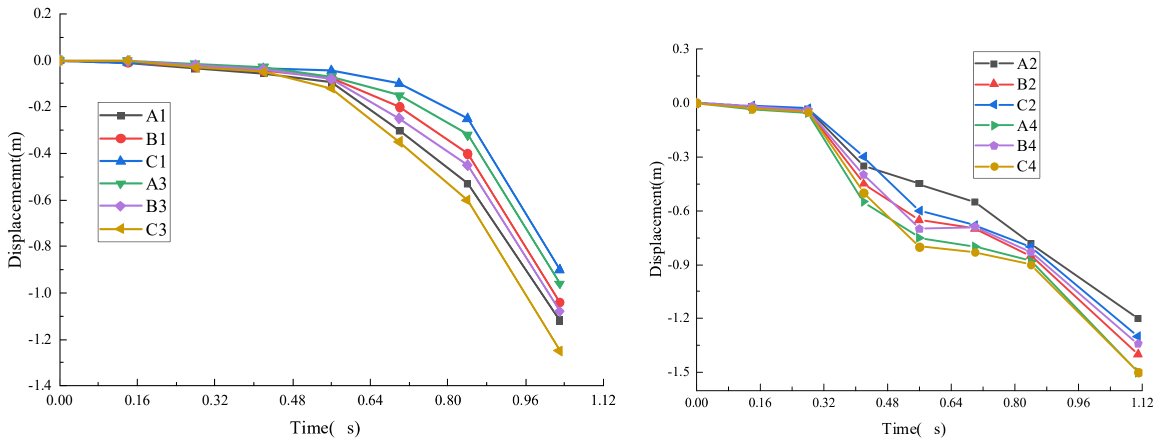
In order to further study the relationship between the lateral displacement of each monitoring surface of water and mud resistant rock mass when the cavity water pressure is 3MPa, the displacement relationship between the monitoring surface 1,3 and the monitoring surface 2,4 is drawn as shown in Figure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



(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 3MPa. (1) When the tunnel face is far away from the front cavity, the lateral extrusion displacement of the monitoring point of the same vertical monitoring surface in the first four steps of excavation is equivalent, which has little impact on the excavation environment. After the fifth step, the increase of lateral extrusion displacement after excavation is larger and the unstable state of the water and mud resistant rock mass is significantly increased. (2) After the sixth step of excavation, the lateral extrusion displacement in front of the tunnel face increases by 0.8m.Compared with the displacement after the sixth step of excavation in the first scheme, it shows that the greater the karst water pressure, the greater the influence on the lateral extrusion displacement in front of the tunnel face. (3) Under the influence of gravity, karst water pressure, excavation unloading and other comprehensive influencing factors, the failure zone in front of the tunnel face develops from the front to the front. After the sixth step of excavation, the displacement of the monitoring point A-2 of the water and mud resistant rock mass is greater than the displacement of the point A-1 and A-4. The extrusion displacement in front of the tunnel face is greater than the displacement of the vault and the arch bottom, and the failure zone is formed first at the front down position.

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 3MPa, the seepage pressure distribution of water and mud resistant rock mass is shown in Figure.4.

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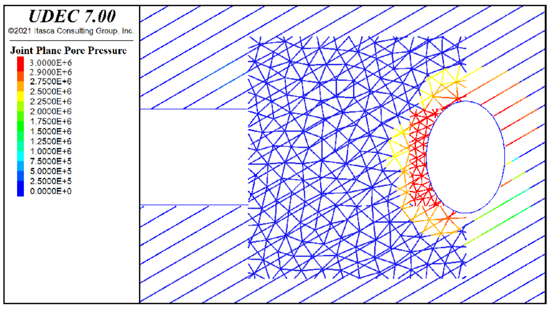
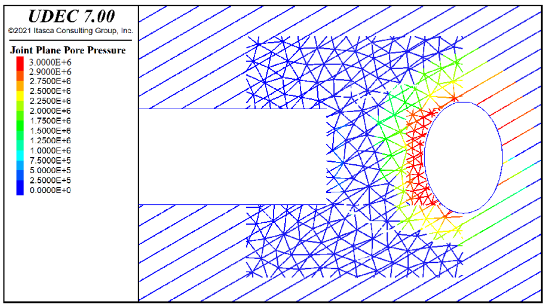
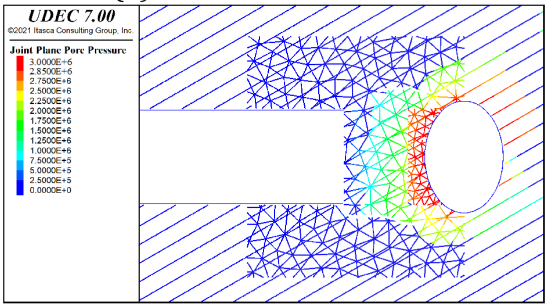


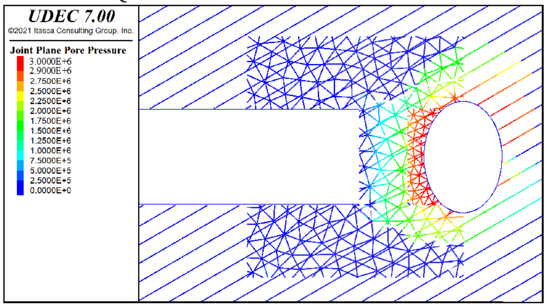
(a) First excavation



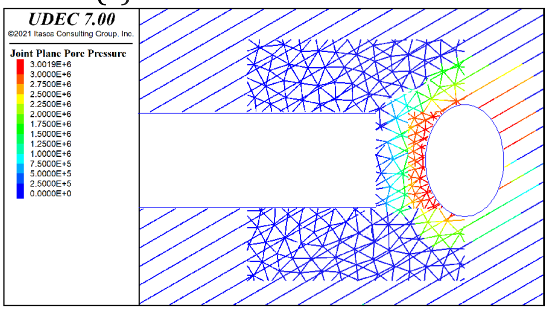
(bSecond excavation



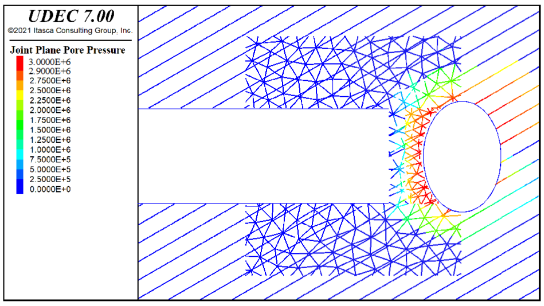
(c) Third excavation



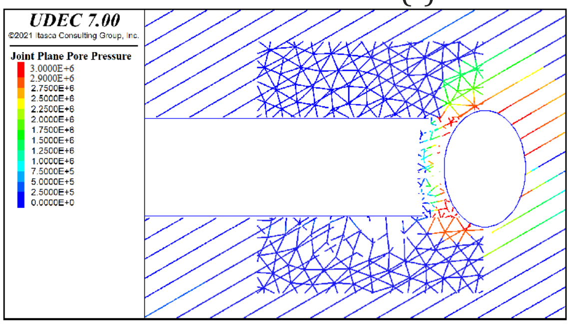
(d) Fourth excavation



(e) Fifth excavation



(f) Sixth excavation



(g) Seventh excavation

Figure 4. Evolution process of seepage field

When the water pressure of the cavity is 3MPa, the water pressure change relationship of each monitoring surface of water and mud resistant rock mass is shown in Figure.5.

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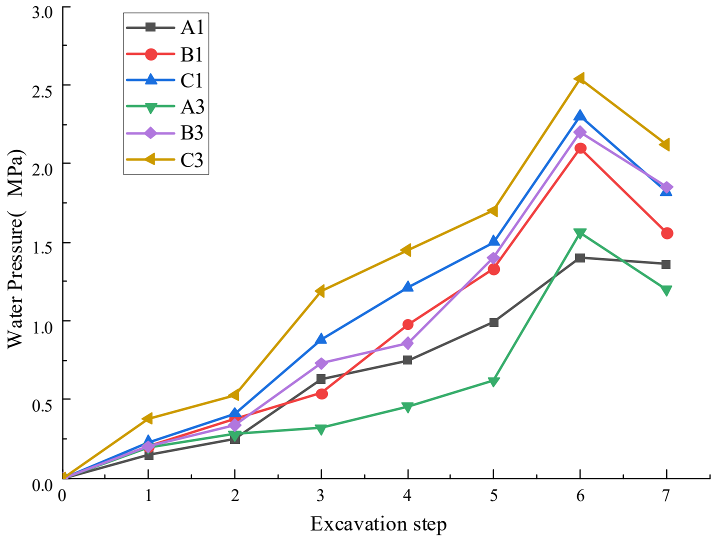
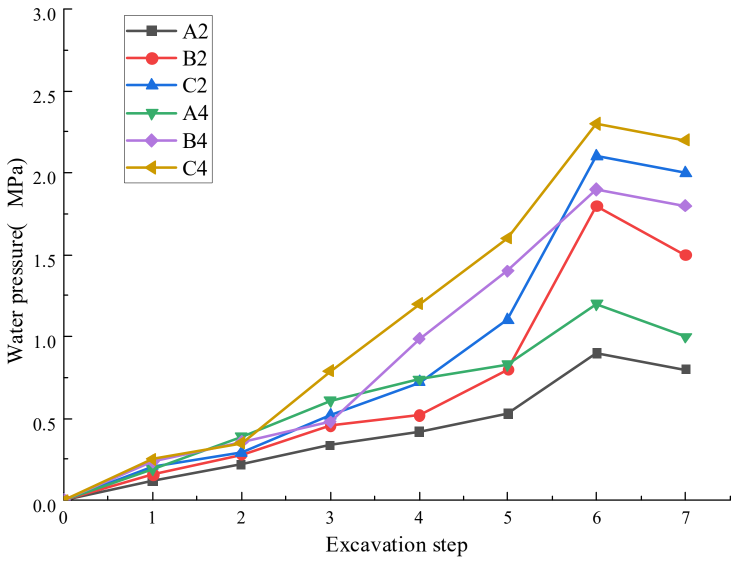


(a) The lateral displacement of 1 and 3



(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) After the first step of excavation, the karst water mainly gathers near the cavity, and there is basically no flow expansion in the joint fissure. After the second step of excavation, the high-pressure karst water migrates slightly in the original joint fissure. As the tunnel face continues to excavate to the cavity side, after the fourth step, the fifth step and the sixth step of excavation, the high-pressure karst water expands along the joint fissure to the area directly in front of the tunnel face and forms a pressure zone within a certain range. (2) When the thickness of the water and mud resistant rock mass is not enough to resist the karst water pressure, that is, after the seventh step of excavation, the water and mud resistant rock mass shows a state of overall collapse and the deformation of the vault and arch bottom of the tunnel face is small. (3) When the water pressure is larger, the difference of water pressure distribution at the monitoring point becomes more and more obvious, and the water pressure near the cavity is larger. With the increase of water pressure in the cavity, the failure mode of the water and mud resistant rock mass changes from the front of the tunnel face to the overall breakthrough of the tunnel face except the vault and arch bottom. When the thickness

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of the water and mud resistant rock mass is less than the minimum safe thickness, the lateral extrusion displacement distribution in the horizontal direction of the water and mud resistant rock mass is relatively discrete, and the karst water pressure gradually increases from the increasing trend to the decreasing trend. At this time, the high-pressure karst water has caused the water and mud resistant rock mass to split and destroy. The water and mud resistant rock mass in front of the tunnel face is broken down and split, which leads to the occurrence of water and mud inrush and other disasters.

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) When the water pressure inside the cavity is 3MPa, in the process of excavation 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) In 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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