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DEM-based analysis of water inrush process of underground engineering face with intermittent joints in karst region

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Abstract

Water inrush disaster of karst tunnel often led to significant economic losses and serious casualties, which is an urgent engineering roadblock to be solved in the construction of tunnel in karst area. In this paper, three-dimensional discrete element method considering fluid-solid coupling effect and structural characteristics of water-mud resistant rock mass is adopted to systematically study the evolution law of displacement field and seepage field of intermittent joint type water-mud resistant rock mass of tunnel face and its water inrush criti-cal characteristics during the process of sequential excavation of karst tunnel close to the frontal high-pressure water-rich karst cavity. The results show that: With the tunnel face gradually approaching the front-concealed high-pressure water-rich karst cavity, the stability of water-mud resistant rock mass is increasingly affected by high-pressure karst water, and karst water pressure gradually becomes the main control factor. The closer the tunnel face is to the front-concealed high-pressure water-rich karst cavity, the greater the extrusion displace-ment of karst tunnel face and its increase amplitude, the higher damage degree of water-mud resistant rock mass of face. With the advance of tunnel excavation, the intermittent cracks in the water-mud resistant rock mass of face gradually connect and form a stable hydraulic connection. The flow velocity and seepage pres-sure of karst water rise significantly now of overall instability of face and the formation of water in-rush channel, showing obvious precursor characteristics. The research achievements provide a reference for early warning and prevention and control of water inrush disaster of karst tunnel face.

Keywords

Karst tunnel, Tunnel face, Intermittent joint, Water inrush process, Numerical simulation

1. Introduction

In recent years, China has accelerated the Belt and Road Initiative, and the infrastructure construc-tion such as transportation, water conservancy and hydropower in western mountainous areas and karst areas with extremely complex topographic and geo-logical conditions has ushered in a period of rapid development. Tens of thousands of kilometers of traffic tunnels projects and more than 20 world-class large water conservancy and hydropower projects have been or will be put into construction. There are many high-risk deep-long karst tunnel projects with significant characteristics of large bur-ied depth, high stress, strong karst, high water pres-sure and large flow, whose scale, and engineering disaster treatment difficulty are rare at home and abroad (Li et al. 2017). The construction of tunnels in karst areas is affected by many factors such as the degree of karst development, karst filling conditions and tunnel excavation disturbances, and often encounter various geological disasters. Among them, water inrush is the most common and extremely dangerous category which not only affects the nor-mal construction of the tunnel, resulting in delays of construction period, but also seriously endangers the safety of construction personnel and construction machinery (Li et al. 2020). During the construction of Yuanliangshan Tunnel of Yuhuai Railway, there were three rare large-scale filling karst caves, and large-scale water and mud inrush disasters occurred as many as 71 times. The maximum water pressure of water inrush was 4.6 MPa (Liu et al. 2004). The water in-rush disaster of Yesanguan Tunnel of Yiwan railway caused a tragic accident with many constructions' equipment destroyed, 52 construction workers trapped and 10 people dead (Chen 2016). A water in-rush hazard occurred during the construction of the Chaoyang Tunnel in Libo County, Guizhou Prov-ince, China, and a continuous water inflow of about 57000 m3 of water within 40 minutes took place at the tunnel excavation face, resulting in three casualties (Zhang et al 2020). Therefore, it is urgent to carry out research on the process and mechanism of karst tunnel water inrush disaster to effec-tively curb the occurrence of karst tunnel malignant water inrush disaster.

The instability water inrush process of water-mud resistant rock mass of face is an important content of karst tunnel water inrush mechanism research, and it is also an important basis for prediction, early warning and effective prevention and control of wa-ter inrush disaster of karst tunnel. In recent years, some scholars have made many beneficial explora-tions on water inrush process of karst tunnel face and made positive progress. Liu et al. (2006) used the finite difference method to analyze the variation law of plastic zone, displacement field and seepage field of the water-mud resistant rock mass of face when the tunnel excavation is close to the front-concealed karst pipeline on the upper and lower side. Wang (2015) used three-dimensional finite element method to research deformation and failure charac-teristics of water-mud resistant rock mass in advanc-ing process of the tunnel face when there were filling karst caves with different scales and different water pressures in front of the tunnel. Wang (2018) adopt-ed the model test method to study the evolution law of the stress, displacement, and seepage pressure of water-mud resistant rock mass of tunnel face during the process of tunnel excavation approaching the front water pressure filling karst cave. Li et al. (2020) carried out a series of model tests on the sta-bility of water-mud resistant rock mass of karst tun-nel face under different conditions and revealed the influence rule of ground stress, water pressure and thickness of water-mud resistant rock mass on water inrush disaster of tunnel face. Jiang (2017) studied the influence law of ground stress and water pres-sure on the stability of the water-mud resistant rock mass of face and its water inrush failure characteris-tics based on the water inrush model test of karst tunnel. Yang et al. (2019) used numerical simulation method to study deeply response characteristics of the displacement, stress, and seepage pressure of wa-ter-mud resistant rock mass of tunnel face in the wa-ter inrush disaster process of the front-concealed karst cave of large, buried depth and high water pres-sure tunnel. Li et al. (2019) carried out the model test research on water inrush process of karst tunnel face and revealed the instability failure law of wa-ter-mud resistant rock mass and the response law of multiple physical information in the process of water inrush. Li et al. (2020) studied the variation law of displacement, stress, and seepage pressure during the water inrush process of tunnel face based on the model test of Jinan subway tunnel project. Wu et al. (2021) analyzed the dynamic evolution characteris-tics of the stability of karst tunnel face during the tunnel construction according to the safety coeffi-cient based on the upper limit theorem of limit analy-sis and the Hoek-Brown failure criterion. Guo et al. (2022) investigated the catastrophe information characteristics of water inrush in karst tunnel by drilling and blasting method. Li et al. (2023) proposed a method for determining the thickness of the water-resistant rock mass and its corresponding ap-plication flow. Chen et al. (2023) analyzed the fail-ure characteristics and mechanism of clay filler in karst cave.

The above-mentioned studies have played a positive role in promoting the understanding of the failure and instability of water-mud resistant rock mass of karst tunnel face and the water-inrush disas-ter process in different periods, which have laid an important foundation for further research in this pa-per. However, in the above studies, the water-mud resistant rock mass of karst tunnel face is regarded as an intact rock mass, the real structural properties of the water-mud resistant rock mass of face are not fully considered, and the water-rock interaction is simplified. So it is necessary to further study the wa-ter inrush disaster process of crack-type face of karst tunnel This paper takes water-inrush instability pro-cess of intermittent jointed face of karst tunnel as the research object, and intends to use three-dimensional discrete element method to analyze the evolution law of displacement field and seepage field and other multivariate information and its criti-cal water inrush characteristics in the process of wa-ter inrush disaster of intermittent jointed type water-mud resistant rock mass of face. The research results are of great significance to improve the predictability and initiative of prevention and control of water in-rush disaster of karst tunnel.

2. Intermittent Jointed Type Water-Mud Resistant Rock Mass

The water-mud resistant rock mass of karst tunnel face refers to the rock mass between the face and the front-concealed high-pressure water-rich karst structure. It is the final barrier for front-concealed high-pressure karst water to enter the tunnel excavation space, and the structure where the final water inrush rupture is located (Li et al. 2020). There are obvious differences in water inrush mechanism of water-mud resistant rock mass with different structures of karst tunnel face, so it is necessary to fully consider its structural properties in studying on the water inrush disaster evolution process of water-mud resistant rock mass. The common water-mud resistant rock mass structures of karst tunnel face include integrity-type, crack-type, and filling structure-type at the bottom of water inrush channel with good cementation (Shi 2014). The engineering rock mass generally contains joints and fissures of various scales and sizes, and fractured rock mass is the most common construction object for rock mass engineering such as tunnels. According to the coalescence degree of joints in fractured rock mass, it can be divided into persistent joint rock mass and non-persistent joint rock mass. The rock outcrop survey shows that long and coalescent joints in natural rock mass only account for a small part of the total number of joints, and more of them are short and intermittent joints (Sun et al. 2020). In addition, many tunnel projects are constructed in rock mass with good rock mass quality as much as possible, to avoid the adverse effects of large-scale coalescent joints.

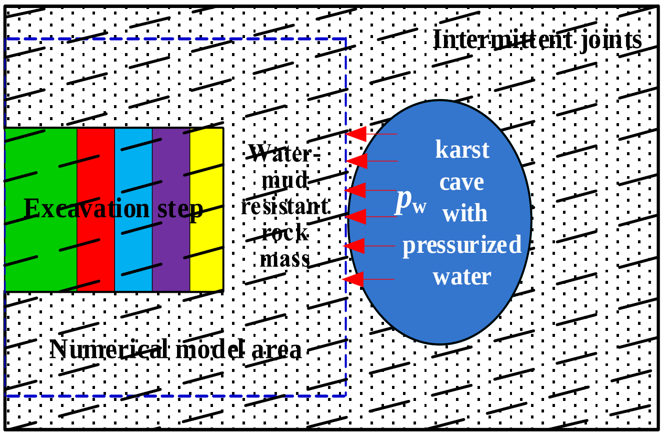
Based on the above understanding, the joints that play a leading role in the surrounding rock mechanical and hydraulic characteristics of tunnel engineering are mostly intermittent distribution, and intermittent jointed rock mass is a common type of complex rock mass structure in rock underground engineering (Do et al. 2020). Therefore, it is of great significance to study the water inrush failure process and mechanism of this type of water-mud resistant rock mass of karst tunnel face. There are rock bridges and staggered and continuous structural planes in the intermittent jointed type of water-mud resistant rock mass of face. Under the wedge splitting action of the high-pressure karst water, the blind end of the structural plane starts to crack and expand, and the intermittent cracks gradually cut through the barrier of the rock bridge and connect with each other. Finally, the water inrush channel is formed in the water-mud resistant rock mass. The water inrush type of intermittent joint type water-mud resistant rock mass of karst tunnel face is usually water pressure splitting type. For example, the water inrush disasters at DK124+602 in Yesanguan Tunnel of Yiwan railway and DK354+879 and DK361+764 in Yuanliangshan Tunnel of Yuhuai railway are all caused by the hydraulic splitting failure of intermittent joint cracks in water-mud resistant rock mass under the action of high-pressure karst water (He et al. 2017).

3. Dem-Based Analysis of Water Inrush Process of Kasrt Tunnel Face

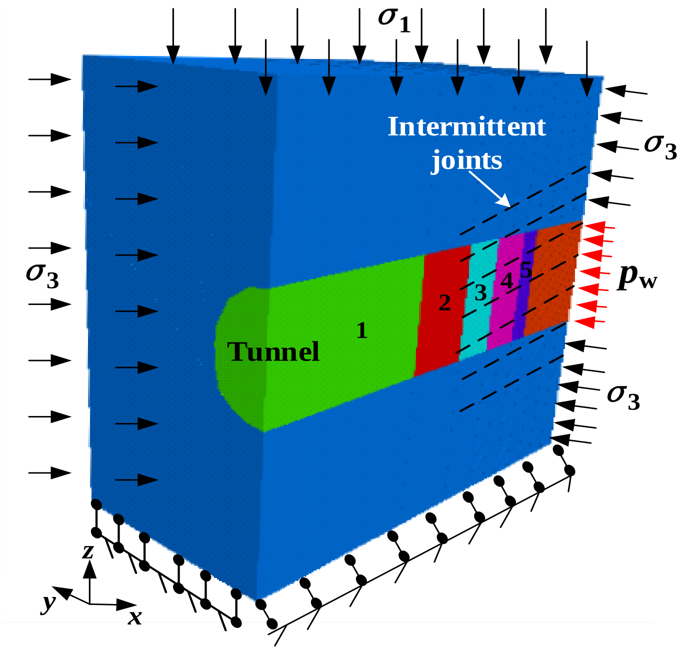
The water inrush of a karst tunnel face is a system imbalance process under the influence of excavation disturbance, which is a triggering factor, and under the influence of multi-factor and multi-condition of mutual coupling of the water-mud resistant rock mass of tunnel face. The water inrush of intermittent joint face of karst tunnel involves the process of crack initiation, expansion, and connection of water-mud resistant rock mass. It is a highly nonlinear problem in mathematics, and it is difficult to describe the water inrush disaster process of tunnel face by analytical method. In this paper, three-dimensional discrete element method is used to analyze the displacement field, seepage field and water pressure distribution characteristics of intermittent joint type water-mud resistant rock mass in the process of sequential excavation of karst tunnel, so as to reproduce the evolution process of instability and water inrush of intermittent jointed face of karst tunnel.

3.1 Numerical calculation model and model parameters

A high-pressure water-rich karst cavity is developed in front of tunnel face (Fig. 1(a)), the water pressure of the karst cavity is 2 MPa (it remains unchanged during the calculation process), and the calculation model size is 40 m×40 m×40 m. The cross section of the tunnel is a three-centered circle with a radius of 4.97 m, 9.58 m and 6.30 m respectively and the height of tunnel is10 m. The origin of the model coordinates is taken at the center point of the tunnel cross section at x=0 m. Assuming the buried depth of the tunnel is 500 m, the weight of the overlying stratum (ρ=2.66 g/cm3) is converted into uniform stress ($\sigma 1$=13.25 MPa) and applied to the upper boundary of the numerical model (z=20 m). The upper part of the model is a free boundary, and the lower part (z=-20 m) is a fixed boundary. The left and right boundaries (x=±20 m), front and rear (y=±20 m) boundaries of the model are subject to displacement constraints, and the horizontal ground stress $\sigma 2$=$\sigma 3$=10 MPa is applied, as shown in Fig. 1. After simplifying the tunnel-karst cavity system shown in Fig. 1 (a), the calculation model shown in Fig. 1(b) is established. The karst water pressure is applied within the cross-sectional area of the tunnel on the right boundary of the model (i.e., the karst cavity side), the horizontal side pressure $\sigma 3$ is applied to the rest parts, and the left side is set to impervious boundaries.



(a) Tunnel-karst cavity system



(b) Calculation model

Figure. 1 Tunnel-karst cavity system and its simplified numerical calculation model

The intermittent joints are set in the local area near the karst cavity side of the water-mud resistant rock mass of tunnel face, the joint dip angle ψ=20°, and the joint row spacing is 2 m. M-C model (change cons=2) is adopted for the water-mud resistant rock mass of tunnel face, Coulomb sliding model (change jcons=1) is adopted for the intermittent joints, and the mechanical parameters of rock block and intermittent joints of water-mud resistant rock mass are shown in Table 1 and Table 2 (Chen 2018).

Table. 1 Physical and mechanical parameters of rock block of water-mud resistant rock mass

Bulk Modulus (GPa)	Shear Modulus (GPa)	Density (g/cm³)	Internal friction angle (°)	Cohesion (MPa)	Tensile Strength (MPa)
22.6	11.1	2.66	42	0.86	0.45

Table. 2 Physical and mechanical parameters of intermittent joints of water-mud resistant rock mass

Material	Normal Stiffness (GPa/m)	Shear Stiffness (GPa/m)	Internal friction angle (°)	Cohesion (MPa)	Tensile Strength (MPa)
Intermittent joints	18.6	6.2	30	0.50	—

The tunnel adopts a full-section excavation method. The first excavation length is 16 m, the second excavation length is 6 m, the third and fourth excavation length is 4 m, the fifth excavation length is 2 m, and the subsequent excavation length is 1 m each time (Fig. 1 (b)), until the tunnel face is damaged by water inrush. After excavation, the supporting effect is approximately simulated by increasing the surrounding rock parameters of the tunnel. In the process of sequential excavation of the tunnel close to the water-rich karst cavity in front of the tunnel face, a monitoring section is set after each excavation, and six monitoring points are set at the characteristic parts of the tunnel, such as vault, spandrel, arch waist, arch foot, and arch bottom as shown in Fig. 2. After each excavation, record the displacement, water pressure and other information of the monitoring point.

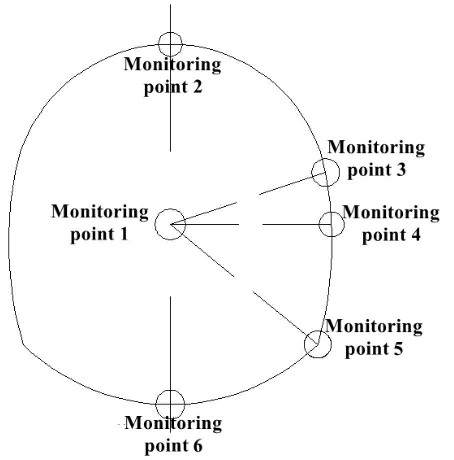


Figure. 2 Monitoring point layout

3.2 Disaster process of water inrush and multivariate information evolution characteristics

In the process of karst tunnel excavation, the evolution characteristics of displacement field of the water-mud resistant rock mass of tunnel face are shown in Fig. 3. The displacement shown in the Fig. 3 is the displacement state when the model is calculated to balance after each excavation, and the displacement nephogram after the sixth excavation is the displacement situation when the tunnel face is obviously unstable and damaged.

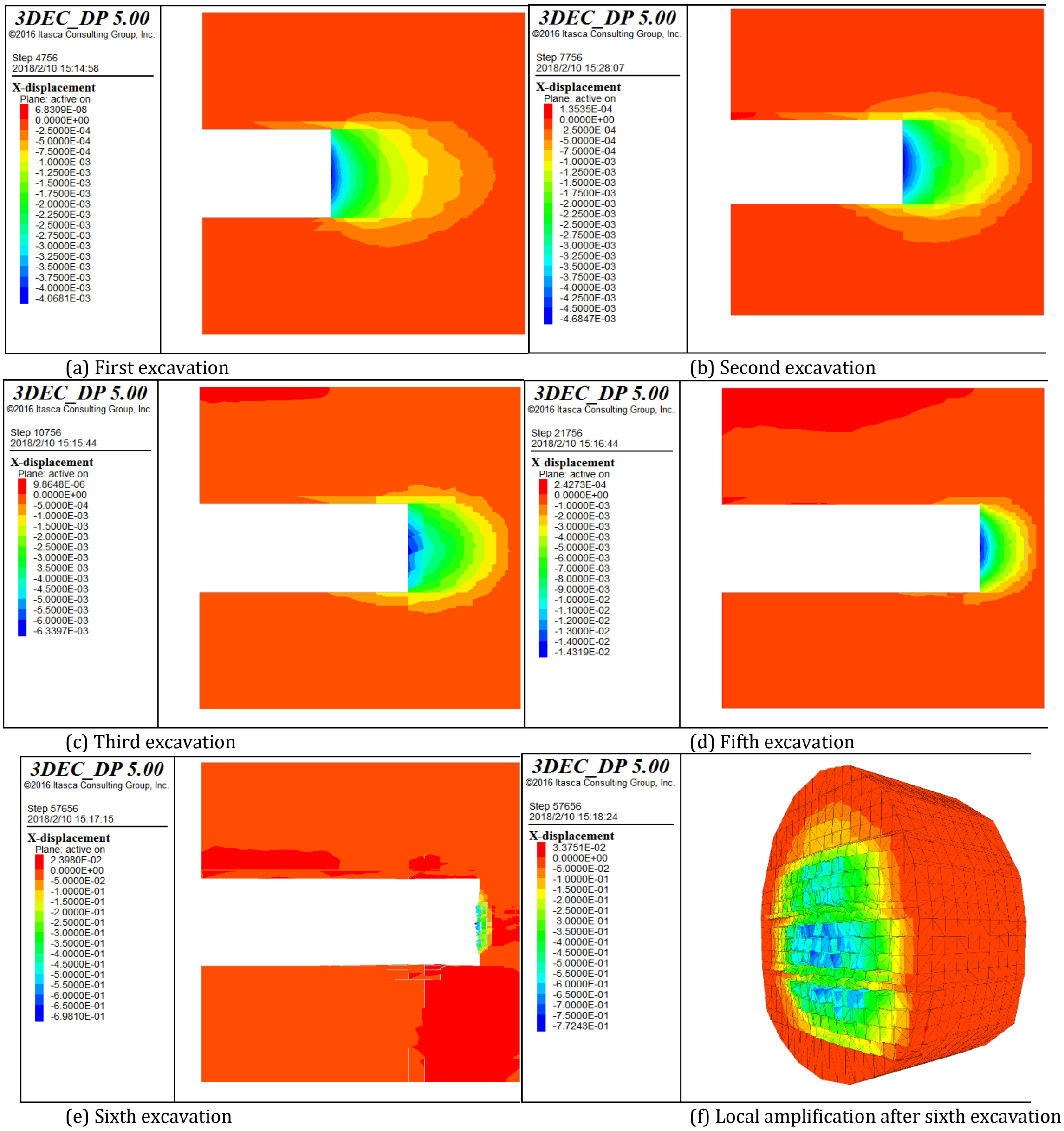


Figure. 3 Displacement field characteristics of water-mud resistant rock mass during karst tunnel excavation

It can be seen from Fig. 3 that: (1) The maximum extrusion displacement of tunnel face after the first excavation is 4.07 mm, the maximum extrusion displacement after the second excavation is 4.68 mm, and the maximum extrusion displacement of tunnel face after the first two excavation is equivalent. The displacement after the third excavation (6.34 mm) increased significantly compared with the previous two excavations. The extrusion displacement after the fifth excavation (14.32 mm) increased more than twice compared with the first and second excavations. This indicates that with the tunnel excavates and moves towards the high-pressure water-rich karst cavity, the extrusion displacement of the water-resistant rock mass of the tunnel face is initially caused by a single unloading, and gradually transits to the influence of unloading and karst water pressure of the front-concealed karst cavity. The influence of the front-concealed karst cavity on the stability of the water-mud resistant rock mass of the tunnel face gradually appears. (2) After the completion of the early excavation step of the karst tunnel, the displacement of tunnel face is nearly symmetrical up and down on the longitudinal section passing through the tunnel axis, which indicates that the excavation has not entered the intermittent joint part of water-mud resistant rock mass, and the intermittent joint type of water-mud resistant rock mass is still in a stable state without obvious cracking and sliding. (3) After the sixth excavation, the displacement of the tunnel face increases sharply, and the maximum extrusion displacement is more than 698.1 mm. At this time, the cracks of water-mud resistant rock mass of face expand and connect under the combined action of excavation unloading and high-pressure karst water. The obvious failure zone is formed in a certain range in front of tunnel face, and the water-mud resistant rock mass is unstable and fractured, resulting in water inrush damage. (4) During the excavation of the tunnel, the maximum extrusion displacement of the tunnel face is always concentrated near the monitoring point 1. Taking the extrusion displacement at monitoring point 1 of the tunnel face as a physical quantity to measure the deformation of the tunnel face, which can intuitively characterize the change process of tunnel face deformation with the sequence of tunnel excavation, as shown in Fig. 4. When the deformation of the tunnel face increases suddenly, it indicates that water-mud resistant rock mass of face is damaged by water inrush.

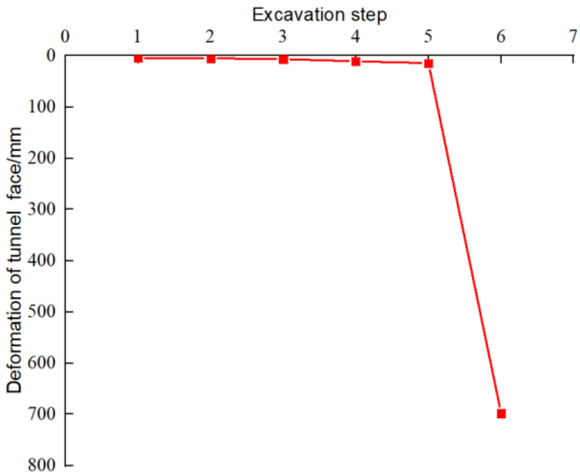
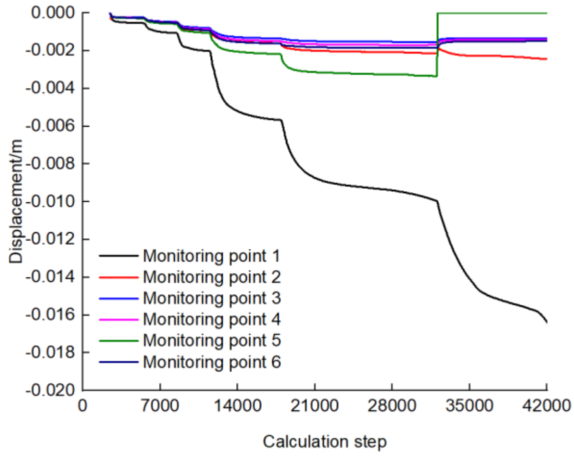


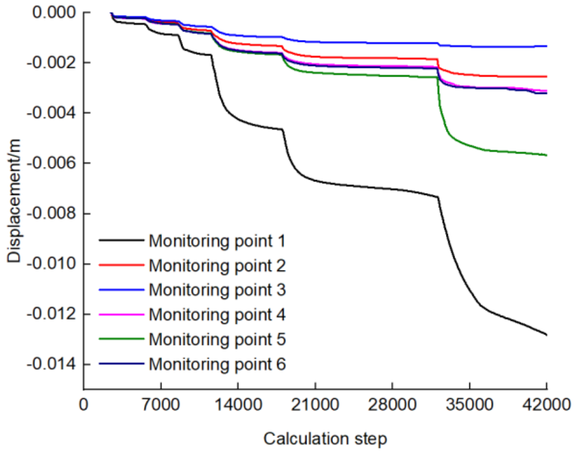
Figure. 4 Deformation trend of face during excavation of karst tunnel

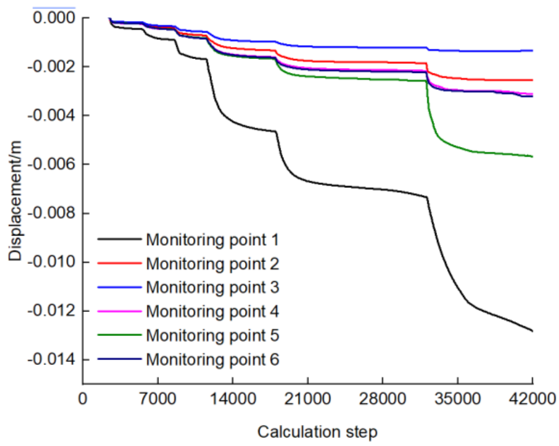
Taking the displacement of each measuring point on three monitoring sections with the distance of 2 m (x=18 m), 4 m (x=16 m) and 6 m (x=14 m) from the side near the karst cavity of water-mud resistant rock mass of karst tunnel face to the front-concealed karst cavity as an example to analyse, the extrusion displacement of six measuring points on three monitoring sections is shown in Fig. 5.

It can be seen from Fig. 5: (1) With the advance of tunnel excavation, the extrusion displacements at each monitoring point on different monitoring sections have obvious changes. Although the values of extrusion displacement at each monitoring point are different, the overall variation law is basically the same. (2) During the whole excavation process of karst tunnel, the displacement of each monitoring point on different monitoring surfaces increases continuously, and with the decrease of the distance from the front-concealed karst cavity of the tunnel face, the greater the increase of face displacement after excavation, and the calculation steps required for model balance also increase, which reflects that the damage degree of water-mud resistant rock mass of tunnel face increases gradually under the fluid-solid coupling effect. (3) On the same monitoring section, the displacement of monitoring point 1 on each monitoring section is much larger than that of the tunnel contour surface, which is consistent with the result of the displacement nephogram of the tunnel face shown in Fig. 3. Moreover, the closer the monitoring section is to the tunnel face after excavation, the greater the displacement of each monitoring point on it.

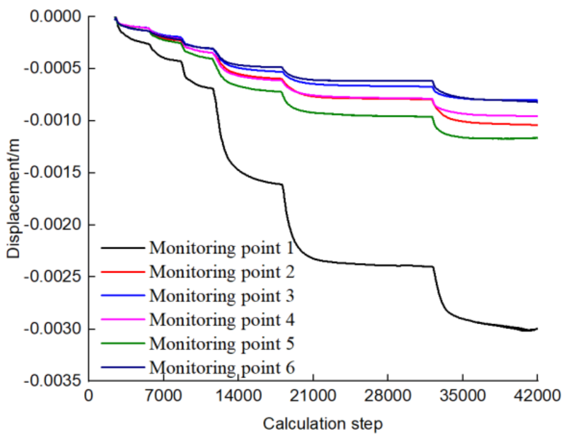


(a) Monitoring surface x=14 m





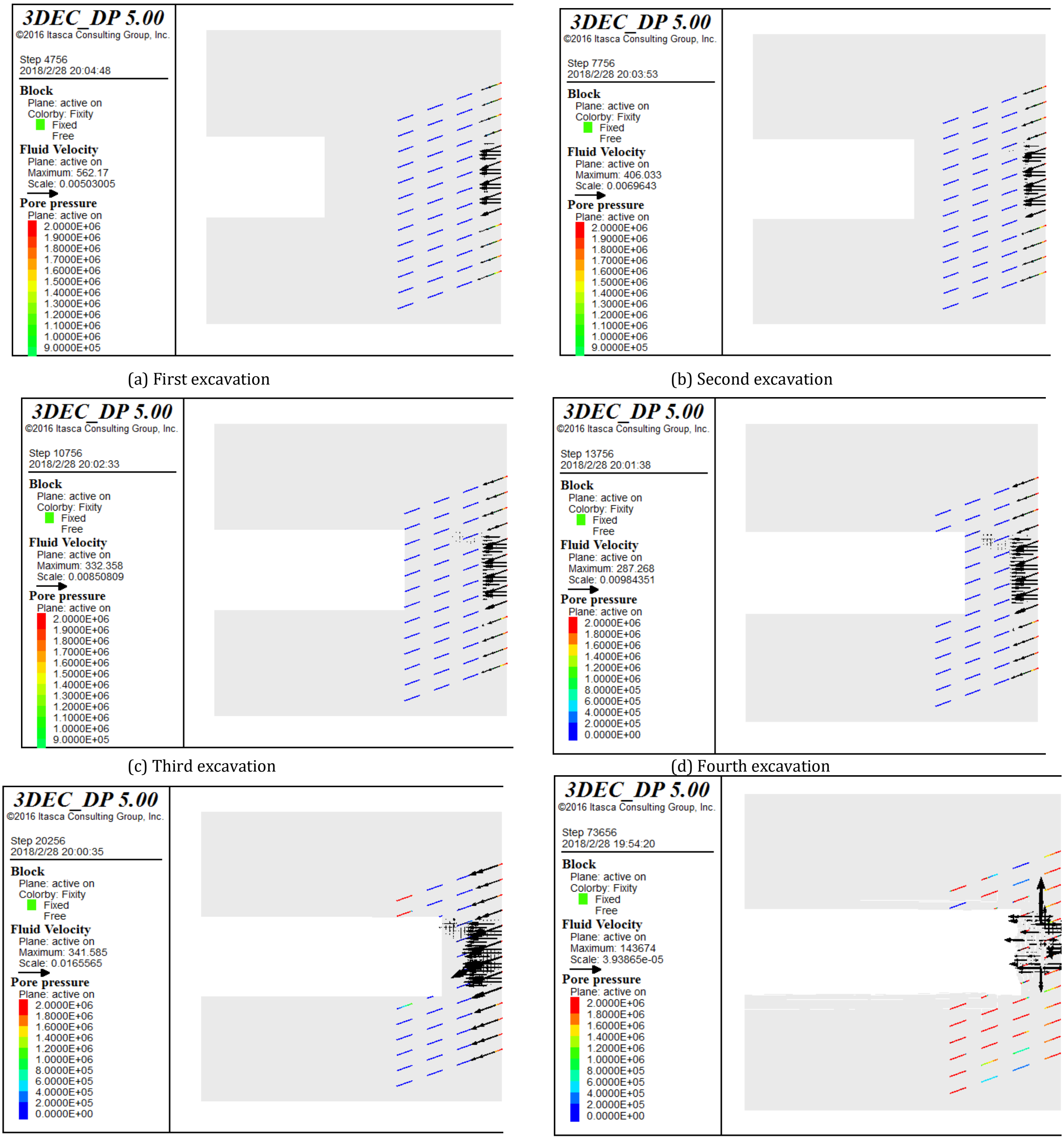
(b) Monitoring surface x=16 m



(c) Monitoring surface x=18 m

Figure. 5 Displacement changes of monitoring points during karst tunnel excavation

During the excavation of karst tunnel, the evolution process of seepage field of water-mud resistant rock mass of tunnel face is shown in Fig. 6. It can be seen from Fig. 6: (1) After the first and second excavations of the tunnel, the karst water is basically maintained in the water-mud resistant rock mass within the influence range of the rightest column of intermittent joints connected with the karst cavity. After the two excavations, the seepage of the water-mud resistant rock mass of face is not obvious, indicating that the excavation disturbance currently has little effect on the seepage stability of the water-mud resistant rock mass. (2) After the third excavation of the tunnel, the excavation disturbance begins to appear, and some rock bridges between the front and rear two columns of intermittent joints begin to split, resulting in joint connection and hydraulic connection. (3) After the fourth excavation of the tunnel, the fourth and third columns of intermittent joints are basically connected, filled with karst water, and the water pressure continues to increase. The rock bridge between the second and third columns of intermittent joints also begins to split, karst water appears, and obvious karst water seepage begins to appear on the face. (4) After the fifth excavation, the intermittent joints in the water-mud resistant rock mass are basically all connected, and the water-mud-resistant rock mass is in the state of imminent instability and failure. Many cracks are formed between the middle upper part of the tunnel face and the intermittent joints, and there is a small-scale water gushing phenomenon in the lower part under the action of seepage pressure, which can be regarded as the precursor characteristics of water inrush of tunnel face. (5) After the sixth excavation, the water-mud resistant rock mass of the tunnel face cannot resist the water pressure of the front-concealed karst cavity. Under the combined action of excavation disturbance and water pressure, overall instability and failure occur, and then a stable water inrush channel is formed. The water inrush velocity suddenly increases to 143674 mm/s (the maximum flow velocity of the tunnel face does not change significantly after the first five excavations). In the process of karst tunnel excavation, the maximum velocity variation of water-mud resistant rock mass is shown in Fig. 7. When the flow velocity increases suddenly, it indicates that the water-mud resistant rock mass of face is unstable and damaged as a whole, and the water inrush channel is formed.



(a) First excavation

(b) Second excavation

(c) Third excavation

(d) Fourth excavation

(e) Fifth excavation

(f) Sixth excavation

Fig. 6 Evolution process of seepage field of water-mud resistant rock mass during karst tunnel excavation

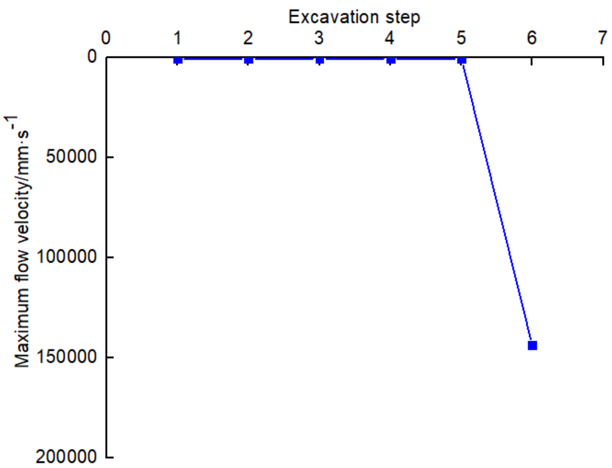


Figure. 7 Variation trend of maximum flow velocity of face during excavation of karst tunnel

In the process of karst tunnel excavation, the displacement changes of monitoring point 1 on each monitoring section is the most obvious than that of other monitoring points. In the process of water inrush disaster of water-mud resistant rock mass of karst tunnel face, the significant changes of each physical quantity have similar laws. It can be seen from Fig. 8: (1) With the continuous excavation of the tunnel, under the combined influence of excavation disturbance and front-concealed high-pressure karst water, the intermittent cracks continue to expand and connect, and the front-concealed karst water continues to enter the cracks in the water-mud resistant rock mass. The seepage pressure at monitoring point 1 continues to rise, and the change rules of seepage water excavation sequence at monitoring point 1 on the three monitoring sections are basically the same. (2) Among the three monitoring sections, the measuring point 1 (19, 0, 0) of the section x=19 m is the closest to the front-concealed high-pressure water-rich karst cavity. The transportation distance of karst water at the measuring point is the closest, and the energy consumption is the least. Therefore, the decrease of water pressure is the smallest, and the seepage pressure is the largest here. On the contrary, the measuring point 1 (17, 0, 0) of x=17 m section is the farthest from the karst cavity and the seepage pressure is the smallest. (3) The seepage pressure at point 1 of the three monitoring sections increases obviously from the fifth excavation step to the sixth excavation step, which can be regarded as the seepage pressure precursor characteristics of water inrush caused by the instability of the water-mud resistant rock mass of face.

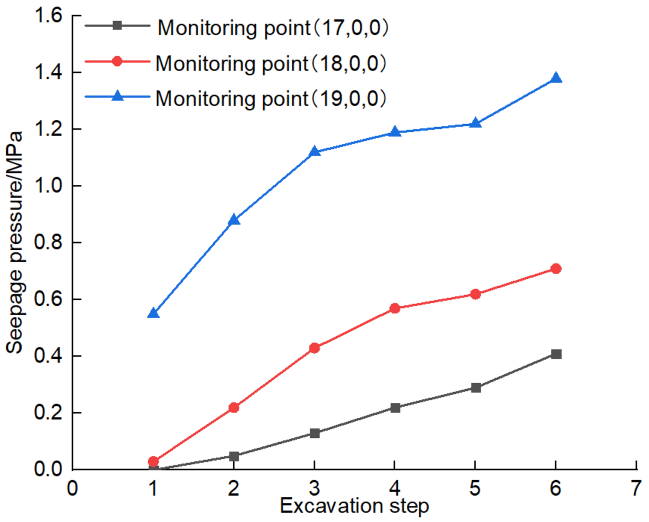


Figure. 8 Variation characteristics of seepage pressure at measuring point 1 on three monitoring sections

4. Conclusions

In this paper, the disaster process of water inrush and instability of non-persistent joint type face of karst tunnel is reproduced based on DEM. The main results are as follows:

(1) With the continuous excavation of the tunnel, the tunnel face is gradually close to the front-concealed high-pressure water-rich karst cavity, and the stability of the water-mud resistant rock mass of face is increasingly affected by the high-pressure karst water. The front-concealed karst water pressure has gradually become the main control factor. The maximum extrusion displacement of face suddenly increased from 4.07 mm, which was mainly controlled by excavation unloading at the beginning of excavation, to 698.1 mm, which was mainly affected by the front-concealed karst water pressure.

(2) With the advance of tunnel excavation, the displacement of each monitoring point on the monitoring section increases obviously, and the overall change law is basically the same. On the same monitoring section, the displacement of monitoring point 1 is much larger than that of other monitoring points on the tunnel contour surface. The closer the tunnel face is to the high-pressure water-rich karst cavity, the greater the displacement increase amplitude of face after excavation, and the higher the damage degree of the water-mud-resistant rock mass of face.

(3) Under the combined action of excavation disturbance and high-pressure karst water, the intermittent cracks in the water-mud resistant rock mass of tunnel face continuously expand and connect, and gradually form a hydraulic connection. Now of the overall instability of face and the formation of water inrush channel, the flow velocity and seepage pressure of karst water rise significantly, showing obvious precursor characteristics.

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