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Multiple Information Evolution Characteristics of Surrounding Rock Mass Seepage Failure in Deep Underground Engineering

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Abstract

As a very common and high risk engineering disaster, it is necessary to study the evolution of water inrush and mud inrush. Based on the three-dimensional discrete element numerical simulation platform considering the fluid-solid coupling effect and rock mass structure characteristics, a numerical model of water-resistant rock mass with multiple fractures in front of the face was established to study the multiple information evolution characteristics of surrounding rock mass seepage failure in the sequential excavation process under the condition of non-persistent joints dip angle of 70°. The results show that with tunnel excavation, the extrusion displacement and seepage pressure of the face continue to increase, and there are obvious hydraulic connections between the non-persistent joints. The extruded displacement and flow velocity of the face have obvious abrupt precursor characteristics when the water inrush channel is formed.

Keywords

Deep underground engineering; Water and mud inrush; Infiltration damage; Characteristics of multiple information evolution.

1. INTRODUCTION

With the gradual advancement of the "One Belt, One Road" strategy, the construction of deep underground projects has shifted to the western mountainous areas with more complex geological conditions. The deep buried, high stress, strong karst, high water pressure and large flow tunnels both in quantity and scale to get unprecedented development, but the difficulty of handling the engineering disasters accompanying the rapid development is also rare [1-6]. As a very common and high risk engineering disaster in tunnel construction, water inrush and mud inrush seriously affect the normal construction of tunnel, cause the delay of construction period, greatly threaten the safety of construction personnel and engineering equipment, and then cause bad social influence [7-8]. Therefore, it is of great engineering significance to study the sudden change process of water inrush in deep underground engineering for tunnel design and construction.

In recent years, many experts and scholars have carried out a series of researches on the characteristics of multiple information evolution of surrounding rock mass seepage failure and obtained many beneficial results. Wang [9] studied the deformation and failure characteristics of water-resistant stratum during tunnel construction under different cavern sizes and karst water pressure. Geng [10] used PFC to simulate the whole process of water and mud inrush caused by tunneling in water rich fault zone with different dip angles, and revealed the influence of fault dip angle on water and mud inrush. Liu et al [11]. analyzed the variation law of plastic zone, displacement field and seepage field in rock mass of face when tunnel excavation was close to the karst pipeline in the upper and lower sides of the front. Ni et al [12]. used the two-dimensional particle flow discrete element method to simulate the crack propagation during tunnel excavation, and analyzed the influence of the distance between tunnel face and water source on the crack propagation of tunnel face. In the above study, the water-resistant layer in front of the tunnel working face is basically regarded as a porous continuous medium, and the rock mass of the water-resistant layer has no crack or contains only one crack.

In this paper, the water inrush of the multiple fractures water-resistant rock mass in front of the tunnel working face is taken as the research object, and the numerical model of the multiple fractures water-resistant rock mass in front of the tunnel face is established by the three-dimensional discrete element method. During the process, the sudden change of the water-resistant rock mass in front of the tunnel is analyzed, and the variation law of displacement, water pressure and seepage velocity is analyzed, which provides a theoretical basis for the early warning of water inrush at the tunnel face and the adoption of targeted measures to control the occurrence of water inrush disasters.

2. NUMERICAL MODEL

2.1. Building Numerical Models

In this paper, a three-dimensional discrete element embedded fracture seepage module is used to study the multi-information evolution law of water inrush channel of water-resistant rock mass in tunnel face. The size of the calculated model is 40m×40m×40m, the tunnel cross-section is three-center circle, the radius is 4.97m, 9.58m, 6.3m, and the tunnel height is 10m. The origin of the model coordinates is taken at the central point of the tunnel cross-section at x=0m. According to the buried depth of the tunnel, the weight of rock mass in the upper part of the tunnel is converted into ground stress and applied to the upper boundary of the model. The displacement constraint is applied to the left and right boundaries of the model. The lower boundary is the fixed boundary, and the upper boundary is the stress boundary. In the three-dimensional discrete element software, the water inrush disaster source is generally simplified and the water pressure is directly applied to the model boundary, as shown in Figure 1. At the right boundary of the model, namely the direction of tunnel excavation, different ranges of water pressure are applied according to the size of water inrush disaster sources, and the left side is used as the impermeable boundary. Non-persistent joints are set in the local range near the disaster source side of the outburst prevention layer of the tunnel face, and the joint row spacing is 2m. The tunnel calculation model is shown in Figure 2.

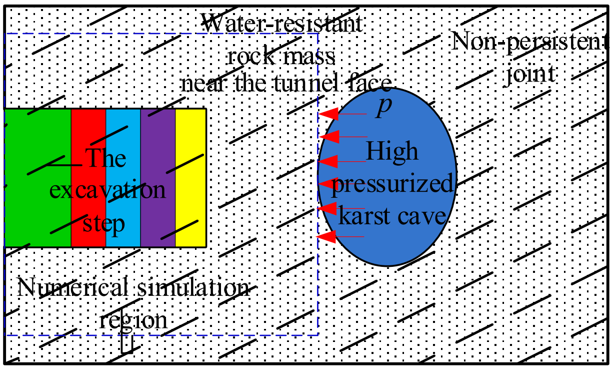

Figure 1. Simplified model of numerical simulation

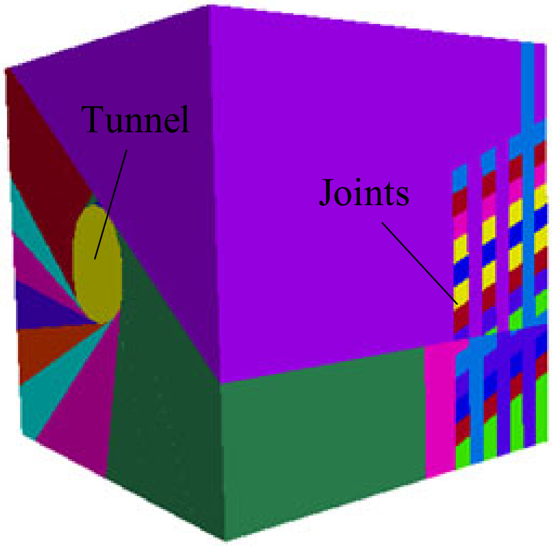

Figure 2. Tunnel and non-persistent joints model

2.2. Constitutive Model and Calculation Parameters

The surrounding rock block adopts coulomb-moore model, and the joint model adopts coulomb sliding model. The mechanical parameters of surrounding rock mass are shown in Table 1.

Table 1. Mechanical parameters of surrounding rock mass

Bulk (GPa)	Shear (GPa)	Density (kg/m3)	Angle of internal friction (°)	Cohesion (MPa)	Tensile strength (MPa)
22.6	11.1	26.6	42	0.86	0.45

Since the joints must cut the whole block in 3DEC, when establishing tunnels and non-persistent joints, it is inevitable to produce some joints that are not needed in the model but cannot be deleted. These joints can be collectively referred to as virtual joints. The properties of joints can be obtained from laboratory tests. The tangential stiffness of rock mass joints with soft soil and silt is generally between 10 MPa/m and 100MPa/m, and the value of closed joints in granite and basalt is over 100GPa/m. For the stiffness of virtual joints, the approximate range is determined according to formula (1), and then the displacement change of the model at initial equilibrium under different joint strengths is analyzed. The stiffness of virtual joints is the group of joints with the best effect at initial equilibrium of the model [13]. The determined joint parameters are shown in Table 2.

$$k_n \ and \ k_s \leq 10\left[\max\left(\frac{K+4/3G}{\Delta Z_{\min}}\right)\right] \tag{1}$$

Where, k_n is tangential stiffness, k_s is normal stiffness, K and G are the bulk modulus and shear modulus of the block, $\triangle Z_{\min}$ is the minimum width of adjacent joint element in the normal direction.

Table 2. Mechanical parameters of joints

Name	The normal stiffness (GPa)	The tangential stiffness (GPa)	Angle of internal friction (°)	Cohesion (MPa)	Tensile strength (MPa)
Joints	18.6	6.2	30	0.5	-
Virtual joints	18.6	6.2	42	0.86	0.45

This paper mainly studies the water inrush process of the tunnel and simplifies the excavation and construction simulation of the tunnel. The tunnel adopts the full section excavation method. The first step is to excavate 14m, the second step is to excavate 6m, then excavate 4m each time, and then excavate 2m each time after two steps. When it is 6m away from the water inrush disaster source, reduce the excavation step size to 1m until the water-resistant rock mass of the tunnel face is damaged. The design of tunnel excavation steps is shown in Figure 3. There are many factors affecting the water inrush of water-resistant rock mass in the face of karst tunnel. This paper mainly considers the karst water pressure, the scale of water inrush disaster source and joint inclination. In the calculation process, the displacement of the central point of the excavation face is not changing, which is regarded as the model balance. Due to the limitation of space, this paper selects some results that the underlying karst water pressure in front of the face is 2MPa, the scale of water inrush disaster source is 40m in diameter and the joint inclination is 70°. The calculation model of the joint inclination angle of 70° is shown in Figure 4.

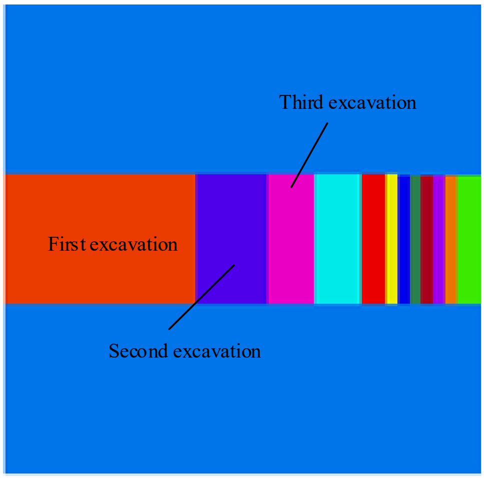

Figure 3. Tunnel excavation steps

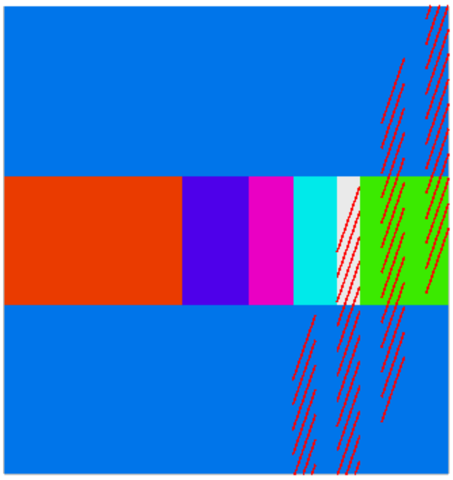

Figure 4. Calculation model of joint angle of 70°

3. MULTIPLE INFORMATION EVOLUTION CHARACTERISTICS OF SURROUNDING ROCK MASS SEEPAGE FAILURE

3.1. Evolution Characteristics of Displacement Field

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In order to analyze the change of extrusion displacement of tunnel face during sequential excavation, the diameter of water inrush disaster source is 40m, the water pressure is 2MPa, and the joint inclination angle is 70°. The evolution process of displacement field is shown in Figure 5.

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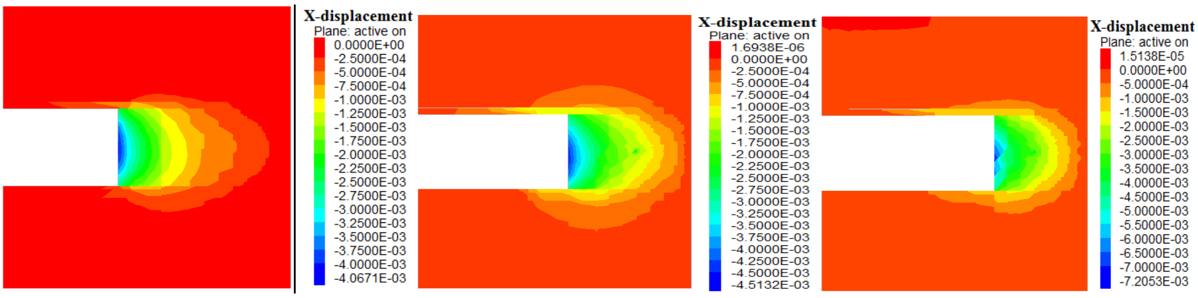
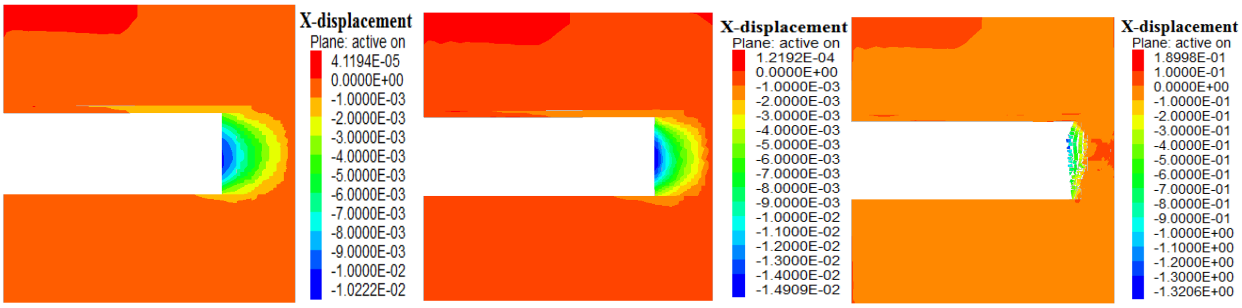


(a) First excavation (b) Second excavation (c) Third excavation



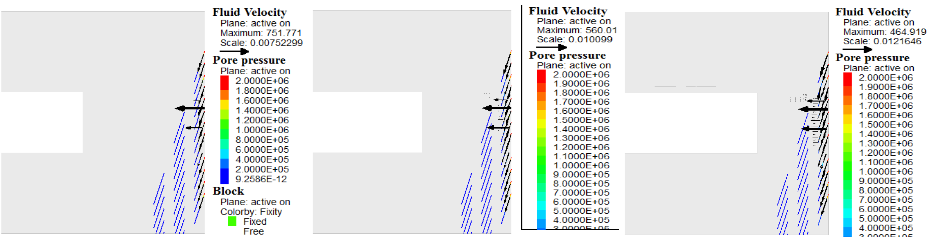
(d) Fourth excavation (e) Fifth excavation (f) Sixth excavation

Figure 5. Evolution process of displacement field

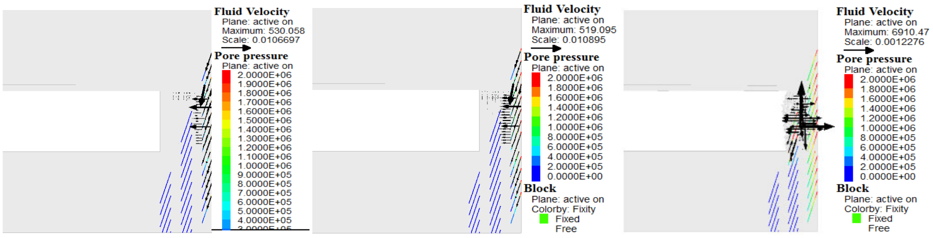
As can be seen from Figure 5, (1) the maximum extrusion displacement of the tunnel face after the first excavation is 4.067mm, the maximum extrusion displacement of the tunnel face after the second excavation is increased by 10% compared with the first excavation, the maximum extrusion displacement after the third excavation is increased by 60% compared with the previous two excavation, and the maximum extrusion displacement of the fourth and fifth excavation is increased by nearly half compared with the previous excavation, it shows that the displacement of the face of the tunnel is gradually transformed from single unloading to joint influence of unloading and forward pressure during the continuous excavation to the side with water inrush disaster source, and the influence of the water source in front of the face of the tunnel on the stability of the water-resistant layer gradually appears; (2) After the completion of the first three excavation steps, the displacement of the face on the longitudinal section of the tunnel axis is nearly up-down symmetric, and the effect of non-persistent joints is not obvious. After the completion of the fourth and fifth excavation steps, the up-down displacement begins to change, and at this time, the non-persistent joints begin to crack and slide, and the water-resistant layer tends to be unstable; (3) After the sixth excavation, the extrusion displacement of the tunnel face increased sharply, reaching more than 1.3m. At this time, the rock mass of the water-resistant layer of the tunnel face produced crack slip and penetration under the action of excavation unloading and high-pressure fissure water, and an obvious damage area was formed in a certain range in front of the tunnel.

3.2. Evolution Characteristics of Water Pressure and Seepage Field

In order to analyze the evolution characteristics of water pressure and seepage field during sequential excavation, the diameter of water inrush disaster source is 40m, the water pressure is 2MPa, and the joint dip angle is 70°. The evolution process of seepage field is shown in Figure 6.



(a) First excavation (b) Second excavation (c) Third excavation



(d) Fourth excavation (e) Fifth excavation (f) Sixth excavation

Figure 6. Evolution process of seepage field

As can be seen from Figure 6, (1) After the first, second and third steps of the tunnel excavation, the water-rich disaster source of the front high-pressure enters into the non-persistent joint connected with it. At this time, the fissure water is basically maintained in the water-resistant layer of the rightmost column of non-persistent joints connected to the disaster source, and the seepage of the water-resistant layer on the face of the tunnel is not obvious after three excavations, it shows that the influence of excavation disturbance on seepage stability of the water-resistant layer is limited; (2) After the fourth excavation of the tunnel, the distance between the tunnel face and the non-persistent joints was further decreases, and the excavation disturbance effect gradually appeared. The water pressure of the rightmost column of non-persistent joints further increases, and the rock bridge between the front and rear column of non-persistent joints splits, realizing hydraulic connection; (3) After the fifth step excavation, the third column of non-persistent joints is basically in the same section as the tunnel face. The pressure between the first two columns of non-persistent joints continues to increase, and the hydraulic connection further increases; (4) After the sixth excavation, the tunnel face was in front of the third column of non-persistent joints, and there were many cracks in the middle of the tunnel face and the non-persistent joints, the seepage pressure increases continuously, and finally the water-resistant rock layer fails to withstand the action of water pressure, resulting in overall instability and damage, and the water flow velocity increases sharply, forming a water inrush accident.

4. CONCLUSION

A three-dimensional discrete element numerical simulation platform is used to simulate the evolution process of the instability and water inrush of the non-persistent joints water-resistant layer of the tunnel face during the sequential excavation of the tunnel. As the face is close to the high-pressure water-rich disaster source, the extrusion displacement of the water-resistant layer on the face of the tunnel is gradually transformed from single unloading to joint influence of unloading and forward pressure, and the extrusion displacement amplitude of the tunnel face increases. Moreover, under the action of high water pressure, the seepage pressure increases continuously, the rock bridge between the non-persistent joints splits, and the hydraulic connection is realized. Finally, the water inrush channel on the tunnel face is formed, the tunnel face displacement and water flow velocity rise sharply, which breeds significant water inrush precursor information. The precursory information of water inrush can provide theoretical basis for water inrush warning of tunnel working face and taking targeted measures to control the occurrence of water inrush disaster.

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