Numerical study on the influence of spatial shape of fault fracture zone on the scope of tunnel collapse

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Abstract. Fault fracture zone is an important factor leading to tunnel collapse. Studying the influence of the fault's spatial shape on the scope of tunnel collapse is important. In this paper, the discrete element numerical simulation method is used to study the possible collapse range and displacement caused by fault dip angle and thickness. The results show that the change of fault dip angle has a greater impact on the collapse range and displacement value, while fault thickness has a smaller effect on it. However, when the thickness of the fault is large, the collapsed body of the vault cannot be self-stabilized, and the bottom collapsed body needs to provide support for it to keep stable. The research can provide guidance for the prediction of the scope of the collapse and the rescue of the accident caused by the collapse.

1. Introduction
The geological conditions in the tunnel engineering are complex and changeable. Fault fracture zone is a common bad geological in tunnel construction. The tunnel often collapses due to complex geological factors and excavation disturbance during tunnel excavation [1]. In recent years, scholars have conducted some research in this field [2] [3]. However, there is less research on the influence of spatial shape of fault fracture zone on the scope of tunnel collapse. The dip angle and the thickness of the fault varies greatly due to the different damage degrees of surrounding rock caused by the change of the earth's crust. In this paper, the numerical simulation method is used to study the effect of dip angle and the thickness of the fault on the collapse body.

2. Project Overview
Baimangxueshan 3 # Tunnel is located in Baimaxueshan Nature Reserve in Deqin County, Diqing Tibetan Autonomous Prefecture. Its length is 3951m. The width of the construction clearance is 10.0m, and the height is 5.0m. The maximum buried depth is 294.39m. The main lithology of the surrounding rock is slate, sandstone, etc., and the tunnel passes through a large fault fracture zone. According to the statistics of bedrock outcrop survey, the joints in the rock mass around the tunnel are developed. The soft rock in the tunnel crossing section, which has low weathering resistance and is easily softened by water. There may be bad phenomena such as large deformation and collapse.

During the excavation, a sudden collapse occurred at the tunnel section about 30m from the tunnel face, and the collapsed depth was 68m. The collapse section was 15m away from the secondary lining, and the distance from the palm face was 30m. The collapse occurred in the section where the initial
support had been completed, and the initial support on both sides was less damaged and the integrity was still good.

3. Numerical Simulation

3.1. Model establishment and model parameters
The block discrete element method (3DEC) is a simulation code based on discrete element method. It can describe the mechanical behavior of discrete media, which is applicable to the calculation and analysis of jointed rock masses [4]. It has been widely used in the research of slope landslide, underground structure collapse and characteristics of blasting bodies.

Fault fracture zone is an important factor to the tunnel collapse. According to the field geological survey, the surrounding rock of the collapse section is V-Class, and the rock joints are very developed. The failure and collapse of the fault is mainly controlled by the joints. In this paper, the 3DEC is used to study the influence of spatial shape of fault fracture zone on the scope of tunnel collapse.

The size of the model are as follows: 100m (length) \( \times \) 120m (width) \( \times \) 80m (height), and the span of the tunnel is 12m. The width of the fault fracture zone is 10m according to the field measurement data. The fault strike is perpendicular to the axial direction of the tunnel, with a dip angle of 80°. The size of the model are shown in Figure 1. The upper boundary of the model is the surface, so it is set as a free boundary. The front, back, left and right boundaries are constrained by displacement, the bottom is a fixed boundary. The initial stress is applied according to the gravity stress field.

![Figure 1. Schematic diagram of model size.](image)

In the model, the lining and the invert are simulated by solid elements. The initial lining thickness is 24cm. The parameters of the rock and tunnel structure elements in the model are shown in Table 1.

| Element type          | Elastic modulus /GPa | Poisson's ratio | Density /(kg/m³) |
|-----------------------|----------------------|-----------------|------------------|
| Sounding rock mass    | 4.3                  | 0.30            | 2600             |
| Fault rock block      | 7.9                  | 0.33            | 2700             |
| Initial lining        | 28.0                 | 0.22            | 2300             |
| Invert                | 29.5                 | 0.20            | 2500             |

| Sets | Inclination /° | Dip angle /° | Spacing /m |
|------|----------------|--------------|------------|
| J1   | 220            | 40           | 1.0        |
| J2   | 105            | 60           | 1.2        |
| J3   | 0              | 90           | 1.2        |

Table 2. The spatial distribution parameters of the joints

Because the lining will also be cut by the joint surface in the fault. In order to achieve a better simulation effect, the virtual joint parameter assignment method is used for the joints after cutting, according to the method proposed in the paper [5][6]. This method is to assign specific parameters to
the joints in the faults, so that the properties of the rock mass are the same as the intact rocks. The parameter calculation formula is shown in equation 1.

\[ G / K_{js} = 0.008 - 0.012 \]

\[ K_{jn} / K_{js} = 2 \sim 3 \]

\( G \), the shear stiffness of intact rock; \( K_{js} \), the shear modulus of virtual joint; \( K_{jn} \), the normal stiffness of the virtual joint.

The mechanical parameters of all joints are shown in Table 3.

| Joint type                  | Normal stiffness / (GPa/m) | Shear modulus / (GPa/m) | Friction angle /° | Cohesion. /kPa | Tensile strength /MPa |
|-----------------------------|---------------------------|-------------------------|-------------------|----------------|-----------------------|
| Joint within the fault      | 10                        | 10                      | 10                | 0.1            | 0                     |
| Fault-wall interface        | 10                        | 10                      | 30                | 1.0            | 0                     |

3.2. Model calculation scheme
The study of the influence of fault inclination and thickness on the cavity of the collapsed vault and the scope of the collapsed block is studied by the control variable method. The values of the variable parameters are shown in Table 4.

| Variable parameters               | Inclination dip /° | Thickness /m | Normal stiffness / (GPa/m) | Joint shear modulus / (GPa/m) | Joint friction/° |
|-----------------------------------|-------------------|--------------|----------------------------|-------------------------------|-----------------|
| Basic parameters                  | 80                | 10           | 10                         | 1                             | 10              |
| Variable inclination dip          | 60/70/90/100      |              |                            |                               |                 |
| Variable thickness                | 5/7.5/2.5/15      |              |                            |                               |                 |

4. Analysis of simulation results

4.1. Collapse process and collapse result analysis
When a large deformation occurs in the tunnel, the damage of the lining gradually increases under the huge load of the surrounding rock of the vault. Then, the surrounding rock of the vault collapses to the tunnel invert under the action of gravity. Part of the surrounding rock collapse will form a stable state at the top of the arch, and the collapse area will no longer increase, as shown in Figure 2 (a). However, some collapse cannot reach equilibrium, the collapse body will continue to fall until the entire tunnel section is filled, as shown in Figure 2 (b). If there are workers inside the tunnel, they may be trapped and their personal safety may be threatened.

(a) the collapse body does not fill tunnel section fully   (b) the collapse body fill tunnel section fully

Figure 2. The collapse shape under different conditions

After the tunnel collapsed, the collapse body has a large vertical displacement, and the surrounding rock will also loose and displacement. As shown in figure 3(a), due to the influence of joints in the fault, a large displacement occurs within 2.5 m of the vault on the left side of the fault, and a large displacement occurs with in 6.8m on the right. During the treatment of collapse, it is necessary to fix the rock mass with large displacement before removing the collapsed body on the invert. Otherwise, it may cause further expansion of the landslide range. From the type of fault joint failure, tensile failure
mainly occurred on the joins, and only a small number of joints suffered shear failure. This is because the fillers existed between joints, which results in little cohesion between the rock blocks. Therefore, when the surrounding rock loses the support of the lining, the joints will tensile fail.

(a) Vertical displacement profile of collapse body   (b) Types of joint failure of collapses

Figure 3. Types of joint failure and displacement of collapse body

4.2. Influence of fault dip angle on collapse
The fault dip angle is changed according to the parameters in Table 4. Then observe and calculate the volume of the collapse body, and the range of the cavity or loose area of the collapse body above the vault.

It can be seen from Figure 4 that when the fault dip angle increases from 60 ° to 100 °, the amount of collapse rock mass increases gradually. When the dip angle reaches 90 °, the amount reaches the maximum, the length of the collapsed body falling on the invert arch almost reached twice the width of the fault. When the dip angle increased from 60 ° to 70 °, the collapsed rock masses of the dome and arch increased slightly, so the whole collapses on the inverted arch is increased. When the dip angle exceeds 70 °, the amount of the collapse body increases greatly. When the dip angle reaches 80 ° and 90 °, the collapse body has completely blocked the tunnel section. Therefore, if there are people in front of the collapse section, they will be trapped in the tunnel, causing a safety accident. However, from the distribution of the collapse body on the cross section, it can be seen that due to the influence of the joints in the fault, the collapse body is not completely evenly distributed on the cross section, and the thickness at the arch shoulder is much smaller than the thickness of the left arch shoulder. Therefore, if there are persons need to rescue in a tunnel collapse accident, the escape pipe can be inserted from the right arch shoulder of the cross section, achieving higher rescue efficiency. When the dip angle reaches 100 °, the amount of collapse on both sides is reduced compared with 80 ° and 90 °. The main reason is that the amount of collapsed rock mass from the vault is reduced greatly, but the amount of rock collapse of both sides is still large. This phenomenon is different from the tunnel collapse in homogeneous material, indicating that the spatial distribution characteristics of joints in fault fracture zones affect the collapse path of rock blocks, forming the shape of the collapse body shown in the figure.

| Angle | 60° | 70° | 80° | 90° | 100° |
|-------|-----|-----|-----|-----|------|
| Front view | ![Image](image1) | ![Image](image2) | ![Image](image3) | ![Image](image4) | ![Image](image5) |
| Side view | ![Image](image6) | ![Image](image7) | ![Image](image8) | ![Image](image9) | ![Image](image10) |

Figure 4. Range of collapse body at different dip angle
The vertical displacement profile of the rock mass after the collapse is shown in Figure 5. The maximum displacement value gradually increases when the fault dip angle increases from 60° to 90°. When the dip angle is 60°, the maximum displacement value of the collapsed rock mass is 7.31m. When the dip angle reaches 90°, the maximum displacement value of the collapsed body reaches 14.49m, almost double compared to the value at 60°. It also can be concluded that the amount of rock mass collapse when the dip angle is 90° is greater than the dip angle is 60°. At the same time, it can be judged that when the dip angle is 90°, the falling speed of the collapse body is relatively fast compared to 60°. Even the deep surrounding rock can fall quickly to reach the bottom of the tunnel in a short time, so that the maximum displacement value of the rock mass increases rapidly. When the dip angle continues to increase to 100°, the maximum displacement value decreases, and the influence range of the collapse also becomes smaller.

![Figure 5. Vertical displacement of rock mass at different dip angles of fault](image)

### 4.3. Influence of fault thickness on collapse

It can be seen from Figure 6, when the fault thickness is 5m, the collapse body forms a stable collapse cavity. The collapse body fell to the bottom of the tunnel, but the tunnel section was not completely blocked due to the small number of collapse bodies. From the side view, it can be seen that due to the influence of the joint in the fault, the depth of the collapse is smaller on the left side while larger on the right side. As the thickness of the fault increases, the amount of collapse body increases sharply. After the thickness exceeds 7.5m, the collapse body completely block the tunnel section. Therefore, when the thickness of the fault is small, the collapse body in the tunnel can be cleared before treating the vault if necessary. However, when the thickness of the fault is large, the fault collapse cavity and the top surrounding rock must be reinforced before clearing the collapse body.

![Figure 6. Range of collapse body at fault different thickness](image)
mass orning a certain bearing capacity for the surrounding rock above, to prevent further collapse of the rock body.

Figure 7. Vertical displacement of rock mass at different thickness

5. Conclusion

In this paper, we can get the following conclusions:

1. Through the virtual joint technology, the discrete element software can well describe the deformation, instability and failure process of jointed rock mass.

2. The fault dip angle has a great influence on the extent and displacement of the collapse body. When the fault is vertical, the range and displacement of the collapse body reach the maximum.

3. The influence of the thickness on the maximum displacement of rock mass is small. When the thickness of the fault is large, the collapse can only be stopped by the bearing capacity provided by the bottom collapse body.

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