

# Study on Instability Change Law of Surrounding Rock of Tunnel Crossing Fault Fracture Zone Based on Cusp Point Mutation Theory

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**Abstract.** The instability process of surrounding rock is a nonlinear mutation. To truly reflect the nonlinear mutation in the failure of surrounding rock and grasp the opportunity of instability of surrounding rock, it is necessary to study the stability of surrounding rock by combining the existing methods with nonlinear scientific theory. Based on the numerical simulation results of a tunnel project crossing the fault fracture zone, the mutation theory is introduced to study the instability law of surrounding rock during tunnel excavation. The dynamic excavation process of surrounding rock tunnel in fault fracture zone is simulated by the finite difference software FLAC<sup>3D</sup>. Based on the cusp point mutation theory, the deformation law of each excavation step to the working face under different dip angles, strike angles and thicknesses of fault fracture zone is studied. Combined with the dichotomy method, curve fitting is used to analyze the instability threshold of surrounding rock and predict the opportunity of surrounding rock instability. The results indicate that (1) As the dip angle and strike angle of the fault gradually increase, the settlement of the surrounding rock arch first decreases and then increases, while as the thickness of the fault increases, the vertical displacement of the surrounding rock gradually increases. (2) When the dip angle of the fault is less than 90°, the sudden instability of the surrounding rock is advanced, while when it is greater than 90°, the time for sudden instability is delayed. (3) As the strike angle and thickness of the fault gradually increase, the excavation step for the tunnel to undergo sudden instability is gradually advanced. The research conclusion can provide theoretical guidance and suggestions for similar engineering construction in the future.

**Keywords:** Cusp Point Mutation; Fault Fracture Zone; Stability of Surrounding Rock; Numerical Simulation.

## 1. Introduction

Up to now, a variety of adverse geological phenomena, such as joints, laminated enclosing rocks, fault fracture zones, karst, etc., are frequently encountered in tunnels and underground projects. A large number of engineering practices show that after excavating caverns in these bad geological rocks, engineering problems such as down-layer slip, bending deformation, bending damage, and even local collapse often occur. Meanwhile, Zheng et al [1] conducted statistics on tunnel construction safety accidents in China in recent years and concluded that tunnel collapse is the most common accident with the highest number of fatalities. Therefore, it is more necessary to analyze and study the stability of tunnel surrounding rock.

Tang et al [2] used the mutation theory to predict the possibility of collapse in tunnel entrance excavation based on the Rangmi Pass Tunnel. Su et al [3] combined the strength reduction method and mutation theory to propose a method to quantify the self-stabilization capacity of tunnels, and calculated the self-stabilization capacity coefficient of tunnels under Class II surrounding rocks and used it as a quantitative indicator of whether the tunnel can be self-stabilized. Ye [4] introduced mutation theory to study the stability of tunnel surrounding rock based on the results of numerical simulation calculations, and analyzed the field monitoring and measurement data against the results of mutation analysis, based on a paralleling partial pressure section tunnel. Weng [5] used FLAC<sup>3D</sup>

software to increment the volume of the plastic zone of the measured section in each excavation step, and then established the cusp point mutation model to obtain the ultimate displacement of the stability of the surrounding rock in deeply buried soft rock tunnel. Liu [6] analyzed the influence of soft and weak inclusions on the stability of tunnel surrounding rock by numerical simulation based on mutation theory.

From the above literature, it can be seen that the research for the stability of the surrounding rock tunnel appears to be crucial, and at the same time, it can be seen that since tunnel instability is a nonlinear process, however, the mutation theory mainly reveals the instantaneous process of the change of material motion from non-equilibrium to equilibrium state, which makes the mutation theory has a wide application in the analysis of surrounding rock stability, while the related mutation models and theories are intensively studied in the field of surrounding rock stability.

Chen et al [7] and Zhu et al [8] established a mechanical model of the surrounding rock in the shallow buried section of the tunnel according to the instability of the tunnel surrounding rock, and used the Weibull distribution function to establish the cusp point mutation model of the surrounding rock destabilization damage according to the principle of total potential energy to derive the mechanical criterion of the surrounding rock destabilization. Tan [9] used the plastic zone volume mutation theory to study the volume mutation of plastic zone of surrounding rock during three-dimensional tunnel excavation. Hou [10], Xie et al [11], Wang [12] analyzed the mechanism of collapse and instability damage of the surrounding rock mass, and analyzed the stability of the surrounding rock from the parameters of stiffness ratio, hydrodynamic weakening coefficient ratio, and geometric-mechanical parameters by establishing a mutation model for the collapse and instability of the tunnel. Qiao [13] established the corresponding energy mutation criterion, displacement mode mutation criterion, and entropy mutation criterion based on the introduction of mutation theory, and applied them to determine the stability of the surrounding rock, and verified the accuracy of the criterion by numerical simulation analysis. Tai [14] used curve fitting and dichotomy method based on mutation theory to make a prediction of the potential damage range of the tunnel excavation surface, and combined with the test for mutual verification, which has strong reference. Shi et al [15] derived the curve function of the destabilization and collapse damage surface of the tunnel surrounding rock based on the generalized mutation theory, and gave the damage law of the surrounding rock under different parameters.

The above research shows that the mutation theory has good application value in the analysis of surrounding rock stability and can be used as a prediction method for surrounding rock instability, but at present, most of them mainly focus on various criteria for surrounding rock instability in the mutation theory, and there is no in-depth research on the geological situation of tunnel surrounding rock itself. Therefore, based on the cusp point mutation theory, FLAC<sup>3D</sup> is used to simulate the tunnel excavation with different dip angles, strike angles and thicknesses of fracture zone, consider the relationship between the deformation of palm face and excavation step, derive the quadratic polynomial by curve fitting, transform into the standard cusp point mutation model, find the threshold of surrounding rock destabilization, and study the change law of surrounding rock destabilization under different engineering conditions.

## 2. Engineering Overview

A new high-speed railway tunnel starts and ends at milepost DK13+580~DK16+425, with a total length of 2845m, a width of 12m and a height of 9.64m, as shown in Figure 1. The vegetation is relatively lush, mainly shrubs and weeds. The surface and shallow part of the crumbling slope deposit, loose, mixed composition, mainly gravel, block, clay, etc., the content of crushed stone is not uniformly distributed, the thickness is about 1.80~5.2m. The surrounding rock of the tunnel entrance is crumbling slope deposit, full - medium weathering potassium long granite. The rock is plastic and loose, about 6.2m thick; the fully and strongly weathered rocks are soft, [BQ] <250; the moderately weathered rocks are hard, Rc = 77.5 MPa; the joints and fissures are developed, closed and slightly

open, with a density of 3-4 fissures/meter, and 7-8 fissures/meter. A fracture structure F2 is developed at the mouth of the refuge, spreading along the ditch, intersecting the line axis obliquely, with a production  $228 \angle 71^\circ$ , and a fracture fragmentation width of 20 meters, filled with veins in the zone, with broken veins, and surrounded by potassium long phreatic rocks on both sides.

The tunnel entrance section (DK13+580~+640) is affected by faults and the integrity of the surrounding rock is poor. Surface water is not developed, groundwater is mainly the fourth system loose rock pore diving and bedrock weathering fracture water, the fourth system pore diving is mainly recharged by precipitation, the amount of water is poor, dripping phenomenon may occur after tunnel excavation, hydrogeological conditions are relatively simple. Influenced by shallow burial, fracture, basic quality level of rock, groundwater and other factors, the comprehensive judgment of the surrounding rock is level V. Thicker crumbling slope accumulation distributed above the tunnel opening is loose and has poor self-stabilization ability.



**Figure 1.** Tunnel entrance section.

### 3. The cusp point mutation

The cusp point mutation mainly reveals the instantaneous process of material motion changing from non-equilibrium state to equilibrium state, which can grasp the transient of sudden change of surrounding rock dynamically and has certain value in the study of surrounding rock deformation.

In order to study the destabilization threshold of laminated surrounding rock tunnel, based on the cusp point mutation, the deformation function is established by model data through FLAC<sup>3D</sup> finite difference simulation software, and the deformation function is transformed into the form of standard cusp mutation model to calculate the standard function mutation eigenvalue, and the critical destabilization state of surrounding rock is discerned by the eigenvalue. The numerical simulation results are combined with the cusp mutation model to establish the instability criterion of the surrounding rock.

#### 3.1. Key point displacement acquisition around the hole

After the tunnel excavation calculation using FLAC<sup>3D</sup>, the displacement of key points around the tunnel perimeter can be extracted by selecting the corresponding grid nodes through the post-processing procedure, so as to extract the displacement of key points with the excavation.

#### 3.2. Mutation modeling

Define the displacement mode  $M_{(k)}$  at the key point of the Kth excavation step hole perimeter:

$$M_{(k)} = \sqrt{\sum_{k=1}^n (\Delta u_{ix}^2 + \Delta u_{iz}^2)} \quad (1)$$

Where:  $\Delta u_{ix}$  and  $\Delta u_{iz}$  is the displacement increment in x, z direction of node i of the Kth excavation step; n is the number of nodes around the hole.

The displacements of each key point calculated by numerical simulation are extracted and the displacement mode sequence  $\{M\} = \{M_{(1)}, \dots, M_{(m)}\}$ , and the displacement mode sequence is fitted by Origin with a quadratic polynomial to construct a function between the displacement mode and the excavation step where: is the parameter to be fitted, is the excavation step.

$$M = V_{(t)} = a_0 + a_1 t^1 + a_2 t^2 + a_3 t^3 + a_4 t^4 \quad (2)$$

### 3.3. Determination of enclosing rock instability

The (Tschirnhaus) transformation [16] was used to transform the fitted displacement modulus polynomial function into the cusp mutation standard form. Letting  $t=x-A$  and  $a=a_3/4a_4$ , the transformation is

$$V_{(x)} = b_0 + b_1 x + b_2 x^2 + b_4 x^4 \quad (3)$$

Where  $a_i$  is related to  $b_i$  as follows

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \\ b_4 \end{pmatrix} = \begin{pmatrix} A^4 & -A^3 & A^2 & -A & 1 \\ -4A^3 & 3A^2 & -2A & 1 & 0 \\ 6A^2 & -3A & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} a_4 \\ a_3 \\ a_2 \\ a_1 \\ a_0 \end{pmatrix} \quad (4)$$

Dividing both sides equally by  $b_4$  gives the standard form:

$$V_{(x)} = x^4 + \mu x^2 + vx + c \quad (5)$$

$$u = \frac{a_2}{a_4} - \frac{3a_3^2}{8a_4^2} \quad (6)$$

$$v = \frac{a_1}{a_4} - \frac{a_2 a_3}{2a_4^2} + \frac{a_3^3}{8a_4^3} \quad (7)$$

The destabilization criterion principle of the cusp mutation model yields the rock evolutionary state and the critical state eigenvalue  $\Delta$ :

$$\Delta = 8\mu^3 + 27v^2 \quad (8)$$

$\Delta = 0$  as the judgment standard of surrounding rock destabilization; when  $\Delta > 0$ , the surrounding rock is in a stable state; when  $\Delta < 0$ , the surrounding rock is in a destabilized state.

## 4. Tunnel entrance section modeling

### 4.1. Model Assumptions

(1) Assume that the surrounding rock mass is a continuous, homogeneous elastic-plastic medium and the deformation is isotropic.

(2) Due to the shallow burial depth of the tunnel entrance section, only the effect of self-weight stress is considered in the initial stress field, and the structural stress is not considered for the time being.

(3) The secondary lining support of the tunnel is mainly considered as a safety reserve, so only the role of the initial support is considered.

(4) The effect of groundwater on the surrounding rock and tunnel is not considered in the model calculation.

#### 4.2. Computational model and boundary conditions

According to St. Venant's principle, after tunnel excavation and construction, stress redistribution occurs only within a certain area close to the cavern, so the width of the left and right boundaries of the tunnel is taken as 3.5 times the single cavern span, the lower boundary is taken as 4 times the tunnel headroom, and the upper boundary is taken to the ground surface. The numerical model of the shallow buried tunnel through the fault fracture zone was established by Midas GTX.

Model length (Y-axis)  $\times$  width (X-axis)  $\times$  height (Z-axis) = 60m  $\times$  72m  $\times$  54.64m. The shape of the tunnel section refers to the highway two-lane tunnel section, width = 11.1m, height = 8.5m, tunnel burial depth = 11.05m, set up a fault fracture zone through the model in the middle of the tunnel. Full section excavation is used. The model surface is a free boundary, the bottom is a fixed boundary condition, surrounded by normal displacement constraint boundary conditions, the establishment of the model shown in Figure 2. The tunnel entrance section was excavated by the three-step temporary elevated arch method as showed in Figure 3, with an excavation depth of 1m, and the length of the upper and middle steps were both 10m, with each excavation step followed by the initial bolt-shotcrete support, and the initial support model is shown in Figure 4.

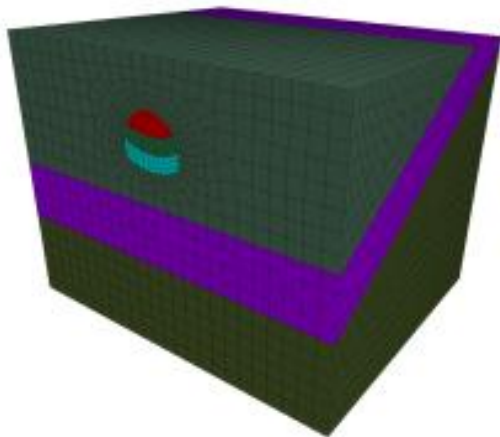


**Figure 2.** Three-dimensional numerical model.

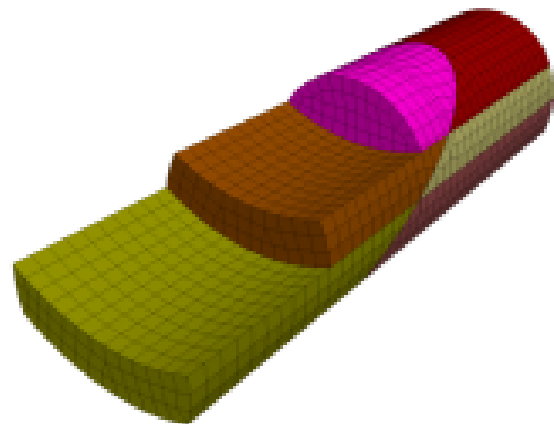


**Figure 3.** Three-step temporary elevated arch method.

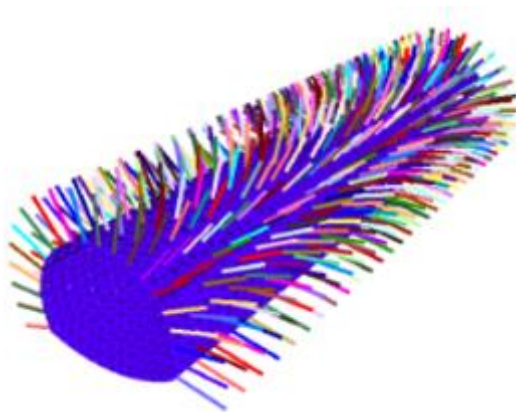


**Figure 4.** Bolt-shotcrete support.

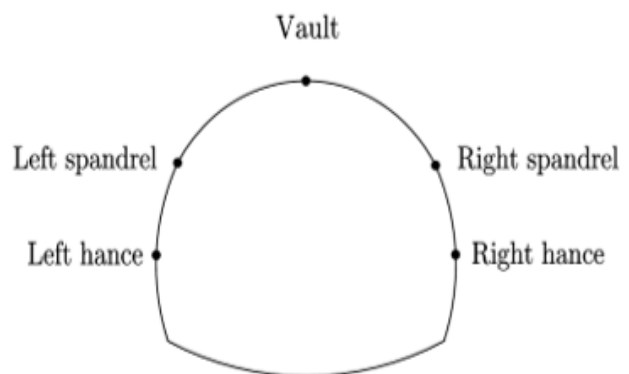


**Figure 5.** Monitoring points setting.

### 4.3. Parameter Selection

The tunnel envelope and fault fracture zone adopt the Moore-Cullen principal structure relationship, the tunnel support structure only considers the initial support, the shotcrete adopts shell unit, and the anchor adopts cable unit. The material mechanical parameters of each surrounding rock and support structure are determined according to the geological survey report and relevant geotechnical specifications, and the grouting reinforcement area and reinforcement network are determined according to the principle of equivalence, and the specific values of each parameter are shown in Table.1.

**Table 1.** Mechanical parameters of surrounding rock and initial support.

| Materials        | Modulus of elasticity/GPa | Poisson's ratio | Density /kg·m <sup>-3</sup> | Cohesion/GPa | Internal friction angle/ ° |
|------------------|---------------------------|-----------------|-----------------------------|--------------|----------------------------|
| Surrounding rock | 0.242                     | 0.407           | 1800                        | 0.1          | 25                         |
| Fault fracture   | 0.132                     | 0.435           | 1400                        | 0.05         | 12                         |
| Shotcrete        | 25                        | 0.3             | 2500                        | —            | —                          |
| Anchor           | 200                       | 0.3             | 2100                        | —            | —                          |

### 4.4. Engineering condition design

To study the influence of the dip angle, strike angle and thickness of the fault zone in the entrance section of the shallow buried tunnel on the stability of the surrounding rock in the excavation process, we set fault zones of different attitudes as shown in Table.2 and set monitoring points as shown in Figure 5. The stability of the surrounding rock in the tunnel excavation process under the engineering conditions in Table.2 can be judged by comparing and analyzing the displacement of the monitoring points using cusp point mutation theory.

**Table 2.** Setting of engineering condition.

| Dip angle / ° | Strike angle / ° | Thickness / m | Engineering condition |
|---------------|------------------|---------------|-----------------------|
| 30            | 90               | 10            | 1-1                   |
| 45            |                  |               | 1-2                   |
| 60            |                  |               | 1-3                   |
| 90            |                  |               | 1-4                   |
| 120           |                  |               | 1-5                   |
| 150           |                  |               | 1-6                   |
| 0             | 30               | 10            | 2-1                   |
|               | 45               |               | 2-2                   |
|               | 60               |               | 2-3                   |
|               | 90               |               | 2-4                   |
| 0             | 90               | 10            | 3-1                   |
|               |                  | 15            | 3-2                   |
|               |                  | 20            | 3-3                   |

## 5. Analysis of numerical simulation results

### 5.1. Analysis of surrounding rock stability

#### 5.1.1. Analysis of vertical displacement of surrounding rock at different dip angles

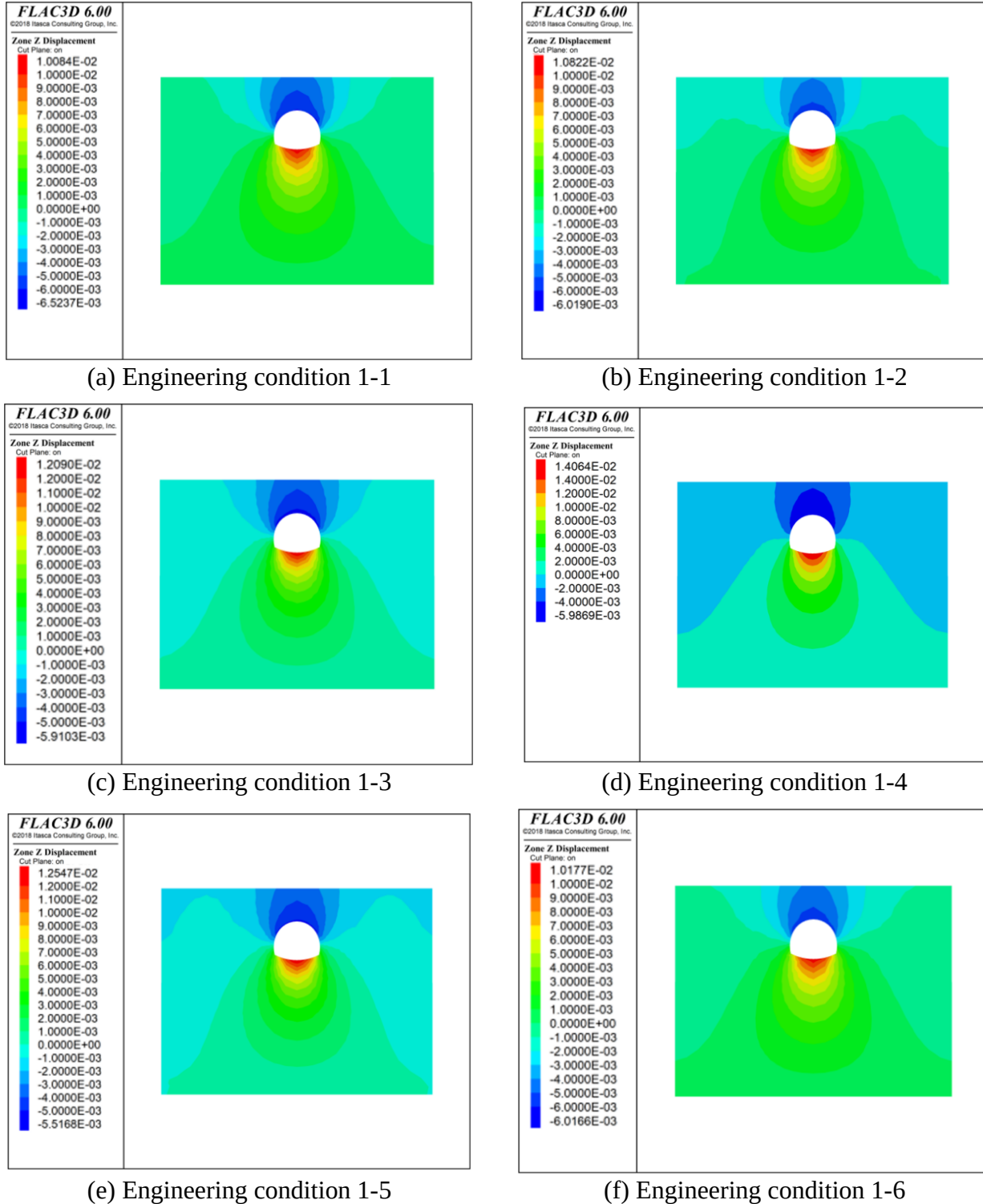


**Figure 6.** Vertical displacement of surrounding rock at different dip angles.

From the vertical displacement diagram of the surrounding rock as showed in Figure 6, it can be seen that the settlement of the vault is smaller than the bulge of the elevated arch, mainly because of the shallow depth of the tunnel. At the same time, with the gradual increase of the fault dip angle, the vault settlement is first decreasing and then increasing, while the change trend of the bulge is the

opposite, due to the tunnel excavation, the surrounding rock affected area range is increasing to decreasing trend, and the fault dip is  $90^\circ$  when the affected area is the smallest.

### 5.1.2. Analysis of vertical displacement of surrounding rock under different strike angles

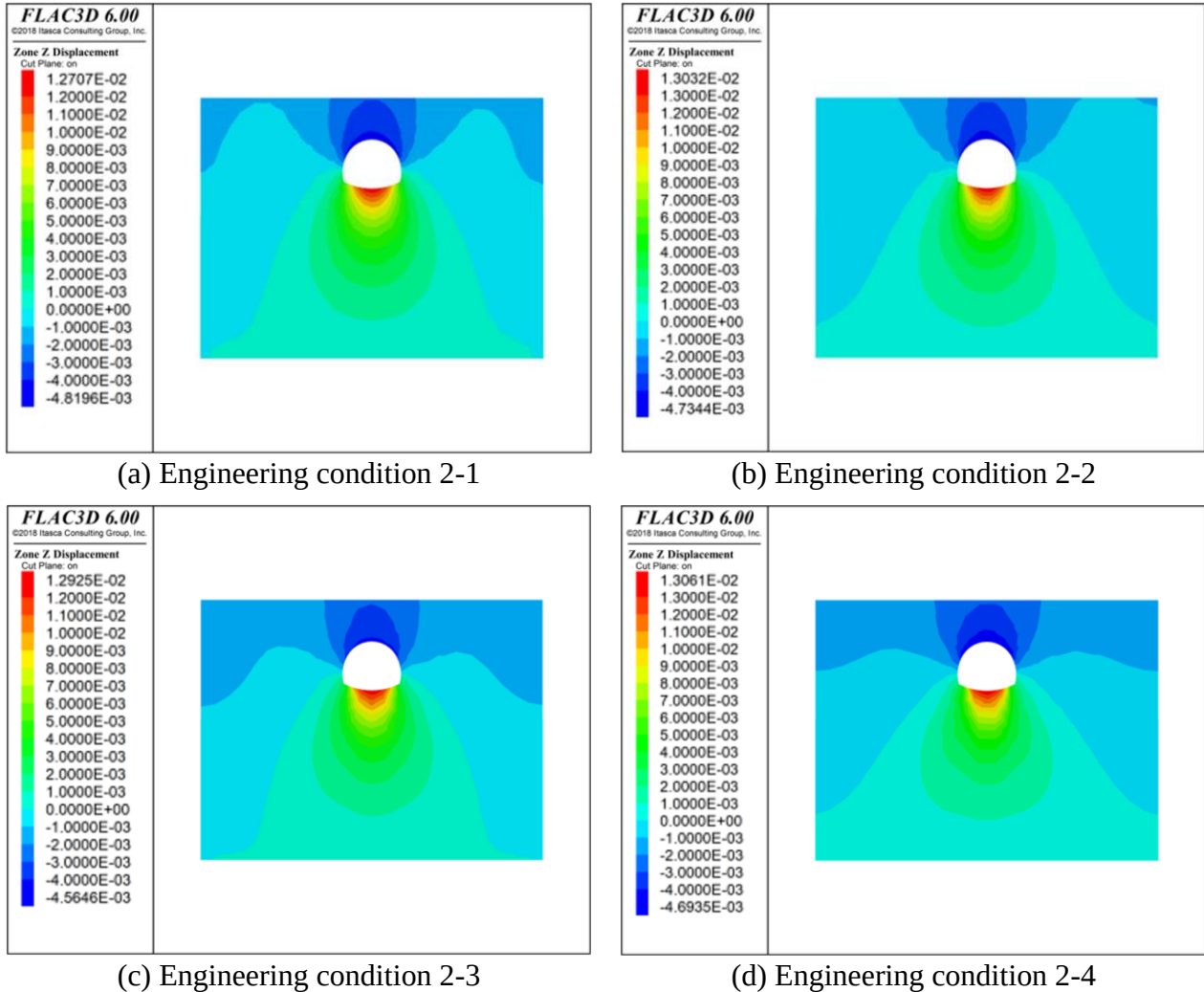
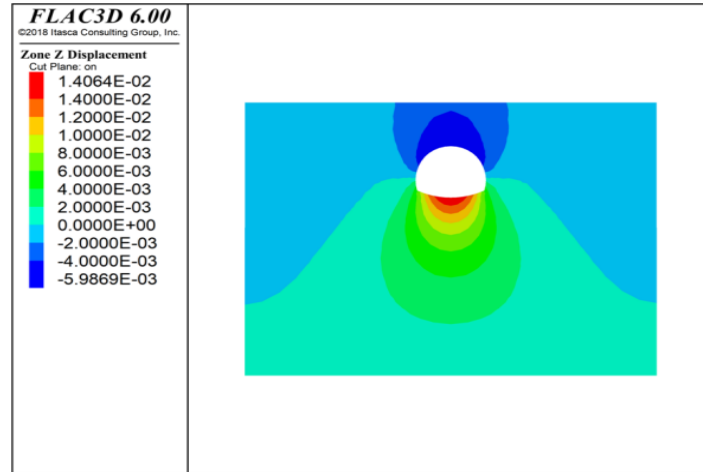


**Figure 7.** Vertical displacement of surrounding rock under different strike angles.

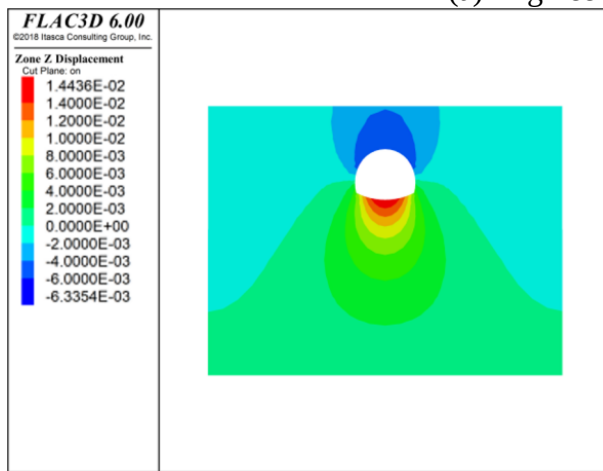
From the vertical displacement diagram of the surrounding rock as showed in Figure 7, it can be seen that with the gradual increase of the fault strike angle, the settlement of vault shows a change trend of first decreasing and then increasing, and the change trend of the bulge of the elevated arch is more complicated, but the change is small, mainly because the change of the fault strike angle has less influence on the vertical displacement and more influence on the horizontal displacement of the tunnel.

### 5.1.3. Analysis of vertical displacement of surrounding rock under different fault thicknesses

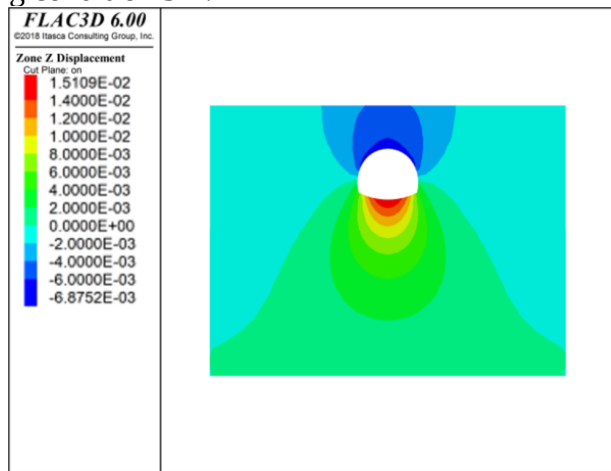
From the vertical displacement diagram of the surrounding rock as showed in Figure 8, it can be seen that with the increase of the fault thickness, the settlement of the vault of the surrounding rock and the bulge of the elevated arch shows a gradually increasing trend, which is due to the increase of the fault thickness to reduce the stability of the surrounding rock and make the deformation of the surrounding rock increase.



(a) Engineering condition 3-1.



(b) Engineering condition 3-2.



(c) Engineering condition 3-3.

**Figure 8.** Vertical displacement of surrounding rock under different fault thicknesses.

## 5.2. Analysis of enclosing rock destabilization law

Due to the different engineering geological conditions, construction methods, etc., for the final value of the surrounding rock deformation of the palm face of tunnel excavation, the specification does not give clear provisions, generally use experience to set the control value, with its 70% to 85% as the early warning value, to play a monitoring and early warning role for the surrounding rock instability. However, the static early warning value does not grasp the dynamic process of surrounding rock deformation, and there is a certain lag. However, the sudden change theory can have a better grasp of the equilibrium to non-equilibrium transient, and can effectively analyze the dynamic moment of surrounding rock instability.

Adopting the idea of dichotomous method, the horizontal convergence of 1~80 excavation step tunnel vault settlement and left arch spandrel is studied, taking engineering condition 1-1 as an example, obtained by curve quadratic polynomial fitting, with excavation step as the independent variable and deformation amount as the dependent variable of quadratic polynomial equation, and its corresponding coefficients  $a_0, a_1, a_2, a_3, a_4$  are brought into the table, and the calculation results are shown in the table.

The obtained mutation characteristic value  $\Delta$  is compared with 0. By the theory of cusp mutation, it is known that when  $\Delta > 0$ , the surrounding rock is in stable state; when  $\Delta < 0$ , the surrounding rock is in unstable state, and the stability of the surrounding rock can be judged. The critical point when the surrounding rock is about to be destabilized occurs in the excavation step when the eigenvalue  $\Delta$  is converted to positive or negative. If  $\Delta > 0$  at the  $n$ th excavation step and  $\Delta < 0$  at the  $n+1$  step, then the  $n+1$  excavation step is the critical point of imminent instability of the surrounding rock.

The values of vault settlement, elevated arch bulge, and horizontal convergence of left and right arch spandrels under each engineering condition are calculated and the results are shown in Table.3.

**Table 3.** Calculation of sudden change of displacement at each excavation step control point under engineering condition 1-1 (unit: m).

| Excavation<br>step | $a_0$   | $a_1$     | $a_2$     | $a_3$     | $a_4$     | $\mu$         | $\nu$         | $\Delta$ |
|--------------------|---------|-----------|-----------|-----------|-----------|---------------|---------------|----------|
| 80                 | 0.63905 | -0.001.67 | -0.00124  | 3.02E-05  | -1.97E-07 | -<br>2.54E+03 | 4.01E+04      | <0       |
| 40                 | 0.67321 | -0.02905  | 0.002639  | -1.44E-04 | 2.15E-06  | -<br>4.32E+02 | -<br>9.28E+04 | >0       |
| 60                 | 0.56918 | 0.0194    | -0.00271  | 6.56E-05  | -4.69E-07 | -<br>1.57E+03 | 2.03E+04      | <0       |
| 50                 | 0.58388 | 0.0134    | -0.00214  | 4.65E-05  | -2.66E-07 | -<br>3.41E+03 | -<br>1.44E+05 | <0       |
| 45                 | 0.6123  | 0.000756  | -8.03E-04 | -2.32E-06 | 3.04E-07  | -<br>2.66E+03 | -<br>7.65E+03 | <0       |
| 43                 | 0.63247 | -0.00878  | 2.71E-04  | -4.43E-05 | 8.28E-07  | -<br>7.45E+02 | -<br>2.10E+04 | >0       |

**Table 4.** Calculation of sudden change in displacement of control point under different dip conditions.

| Engineering condition | Mutation excavation step |
|-----------------------|--------------------------|
| 1-1                   | 45                       |
| 1-2                   | 44                       |
| 1-3                   | 43                       |
| 1-4                   | 44                       |
| 1-5                   | 45                       |
| 1-6                   | 46                       |

From Table.4, we can calculate the sudden change in displacement of control points under different dip conditions: when the dip of the fault is less than  $90^\circ$ , that is, when the dip of the fault is small, the timing of the sudden change in instability of the surrounding rock is more advanced, mainly because the dip of the fault is larger, the influence on the surrounding rock is larger, making the excavation of the tunnel deformation is larger, making it occur in advance of instability. When the dip of the fault is greater than  $90^\circ$ , that is, when the dip of the fault is larger, the timing of the sudden destabilization of the surrounding rock is more delayed, mainly because the impact of the fault on the second half of the tunnel is larger, so in the first half of the excavation, the impact is almost small, and does not produce instability, when the excavation through the second half of the tunnel, the stability of the surrounding rock is reduced. Therefore, when in the field construction, in order to ensure the stability of the surrounding rock in the study section, should pay full attention to the dip angle of the fault, timely follow up or strengthen the support of the surrounding rock in the section affected by the fault, to ensure that the established standard potential function of the tip point has a sudden change characteristic value greater than 0, to prevent the occurrence of surrounding rock instability.

**Table 5.** Calculation of sudden change in displacement of control point under different strike engineering conditions.

| Engineering condition | Mutation excavation step |
|-----------------------|--------------------------|
| 2-1                   | 47                       |
| 2-2                   | 46                       |
| 2-3                   | 46                       |
| 2-4                   | 45                       |

From the calculation of the sudden change in displacement of control points under different strike conditions in Table.5, it can be concluded that: with the gradual increase of the strike of the fault, the excavation step of the tunnel in which the sudden change occurs is gradually advanced, thus indicating that the timing of the possible destabilization of the surrounding rock is gradually advanced, mainly because the gradual increase of the strike has a greater impact on the horizontal convergence displacement of the tunnel, which makes the deformation of the surrounding rock increase.

**Table 6.** Calculation of sudden change in displacement of control points under different thickness conditions.

| Engineering condition | Mutation excavation step |
|-----------------------|--------------------------|
| 3-1                   | 46                       |
| 3-2                   | 45                       |
| 3-3                   | 42                       |

From Table.6, the calculation of sudden change in displacement of control points under different thickness conditions, it can be concluded that: with the gradual increase of fault thickness, the excavation step of sudden change in the tunnel is gradually advanced, mainly because of the gradual increase of the thickness of the fault fragmentation zone, the influence area on the tunnel surrounding rock increases, making the surrounding rock destabilization range increases and deformation is easily produced.

## 6. Conclusions

In this paper, based on the cusp point mutation theory, we establish a three-dimensional numerical model of the tunnel under different fault dip angle, strike angle and thickness by relying on a high-speed railroad tunnel under a crossing fault fragmentation zone through FLAC<sup>3D</sup> numerical simulation software, and study the change law of the sudden destabilization of the surrounding rock under this tunnel. The conclusions are as follows:

(1) With the gradual increase of the fault dip angle and strike angle, the settlement of the surrounding rock vault shows a trend of first decreasing and then increasing, while the change trend of the bulge of the elevated arch is not the same, while the increase of the fault thickness, the settlement of vault and the bulge of the elevated arch both show a gradual increase trend.

(2) When the fault dip angle is less than 90°, the time of sudden destabilization of the surrounding rock is more advanced, while when the fault dip angle is more than 90°, the time of sudden destabilization of the surrounding rock is more delayed. With the gradual increase of fault strike angles and thickness, the excavation step of sudden change in the tunnel is gradually advanced.

(3) The use of mutation theory can dynamically grasp the process of surrounding rock deformation, and play a good role in predicting the deformation and instability of tunnel surrounding rock through the fault fragmentation zone, timely detection of deformation sudden change, and the use of appropriate deformation control measures at key locations to control late deformation, in order to reduce the occurrence of various types of risks in tunnel construction.

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