

A quantitative evaluation method on the stability of roadway surrounding rock in partial confining stress based on plastic zone shapes

Xiaofei Guo*, Chen Li and Tianhong Huo

School of Energy and Mining Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

(Received October 21, 2020, Revised May 6, 2021, Accepted June 3, 2021)

Abstract. The reliability of reinforced concrete structures is frequently compromised by the deterioration caused by reinforcement corrosion. Evaluating the effect caused by reinforcement corrosion on structural behaviour of corrosion damaged concrete structures is essential for effective and reliable infrastructure management. In lifecycle management of corrosion affected reinforced concrete structures, it is difficult to correctly assess the lifecycle performance due to the uncertainties associated with structural resistance deterioration. This paper presents a stochastic deterioration modelling approach to evaluate the performance deterioration of corroded concrete structures during their service life. The flexural strength deterioration is analytically predicted on the basis of bond strength evolution caused by reinforcement corrosion, which is examined by the experimental and field data available. An assessment criterion is defined to evaluate the flexural strength deterioration for the time-dependent reliability analysis. The results from the worked examples show that the proposed approach is capable of evaluating the structural reliability of corrosion damaged concrete structures.

Keywords: lifecycle performance; stochastic deterioration modelling; structural reliability; reinforcement corrosion; residual strength

1. Introduction

Roof disaster is the most frequent and fatal disaster among all kinds of disasters in underground coal mine (Islavath *et al.* 2020, Rajwa *et al.* 2020, Zhao and Liu 2017). At present, most of roof disaster accidents occur in roadway (Cai 2020, Ardehjani *et al.* 2020, Li 2020b). With the strengthening of coal mining, the shallow resources are gradually exhausted, the mining depth is deepening year by year, and the roadway disasters such as large deformation, roof fall, floor heave, and rock burst are more serious (Feng *et al.* 2018, Konicek *et al.* 2013, Lamich *et al.* 2015). The stability evaluation of roadway surrounding rock and the quantitative identification of risk area of roadway surrounding rock will contribute to roadway stability control and disaster warning (Yang *et al.* 2017a, Yang *et al.* 2017b, Diederichs 2018, Kang 2020).

The roadway passes through the complex geological environment, and the surrounding rock and stress environment of the same roadway in different areas are also different, which brings difficulties to the stability evaluation of surrounding rock (Vatcher and Sjöberg 2015, Xia *et al.* 2016). Some scholars believe that the roadway roof disaster is closely related to the geological activities, structural distribution, stress characteristics, and other primary occurrence environments, and carried out research on the relationship between roadway roof disaster and structural change area, fault fracture zone, coal seam dip angle and

thickness changes (Yan *et al.* 2016). They tried to grasp the failure scope of surrounding rock in these areas, and then evaluate the stability of surrounding rock (Barth 2014, Le 2015). The occurrence of roadway roof disaster is caused by the deformation and failure of surrounding rock under the action of stress (Lekontsev and Sazhin 2014). The stability of roadway surrounding rock is directly related to the shape and scope of failure zone (Zhao 2014). And the support design of roadway surrounding rock is carried out by evaluating the shape and scope of roadway surrounding rock failure area (Li *et al.* 2020a). Many scholars have studied the instability and failure characteristics of coal and rock mass and analyzed the physical information such as infrared, acoustic waves, microseism, and electromagnetic radiation produced in the process of coal and rock mass failure (Zhang *et al.* 2020). By capturing this information, the purpose of roadway surrounding rock stability prediction is achieved (He *et al.* 2012).

Previous studies have shown that the stresses in different directions are different (Detournay and John 1988, Fan and Liu 2019, Atsushi *et al.* 2020, Vitali *et al.* 2020). In particular, the mining disturbance will aggravate the stress deviation in different directions and form a partial confining pressure environment (Kang *et al.* 2010, Garavand *et al.* 2020). At the same time, in the vicinity of the geological structure belt, the horizontal stress is several times of the vertical stress due to the compression of horizontal force, which will also form obvious partial confining pressure (Vidigal-Souza *et al.* 2020). Therefore, we define the stress field with different stresses in different directions around the roadway as partial confining pressure or partial confining stress. The roadway located in the mining-affected area or near the geological structure zone often has

*Corresponding author, Ph.D.
E-mail: 15201290185@163.com

serious deformation and damage and is prone to roof disaster (Ding and Liu *et al.* 2018). It can be seen that the stability evaluation of roadway surrounding rock in a partial confining pressure environment is particularly important. Aker *et al.* (Aker *et al.* 2014, Zhu *et al.* 2020) Studied the acoustic emission test of sandstone samples with a circular hole and found that the surrounding rock would appear X-type failure under uniaxial compression. Wang *et al.* 2020 found that the failure mode of surrounding rock under biaxial unequal pressure presents a non-uniform shape. Ma *et al.* (Ma *et al.* 2015, Guo *et al.* 2016) found that there were circular, elliptical, and butterfly-shaped plastic zone in the roadway surrounding rock in the partial confining stress, and derived the judging criterion of plastic zone shapes.

The plastic zone is a theoretical failure zone determined by the rock strength criterion. Within the precision requirements of mining engineering, the plastic zone is usually regarded as the failure zone to study the stability of surrounding rock in underground engineering. In this study, we compared the mechanical characteristics of the plastic zone with different shapes of roadway surrounding rock in partial confining stress and established the corresponding relationship between the shape of plastic zone and the stability of roadway surrounding rock. According to the judgment criterion of plastic zone shape, we established a quantitative analysis method of roadway surrounding rock stability.

2. The relationship between the shapes of plastic zone and the stability of surrounding rock around roadway

2.1 Model

In this study, the FLAC^{3D} numerical simulation software was used to study the shape and expansion of the roadway plastic zone. Based on the existing research results (Ma *et al.* 2015, Guo *et al.* 2016), when the displacement is fixed along the roadway axis, the boundary effect of the model thickness on the surrounding rock failure is not obvious, and the shape and size of the plastic zone with different thickness and cross-section are almost the same in the roadway axial direction. Therefore, the stress model of thin plate with axial displacement constraint is adopted in this study. The size of the model is large enough to ensure that the side length of the model is more than 40 times the tunnel diameter. Based on Saint Venant's principle, the influence of roadway on the boundary can be ignored in a large underground space. Therefore, the boundary of the model is constrained by surrounding displacement and loaded by initial internal force. The weight of rock in the model is small relative to the original rock stress, and the influence of rock weight in the model is not considered. The numerical simulation model is shown in Fig. 1. In the Fig.1, P_1 is the regional maximum principal stress, P_3 is the regional minimum principal stress, and η is the confining pressure ratio (the ratio of the regional maximum principal stress to the regional minimum principal stress), which is used to represent the deviation degree of stress in different directions. In this study, different stress conditions underground are simulated by changing the regional

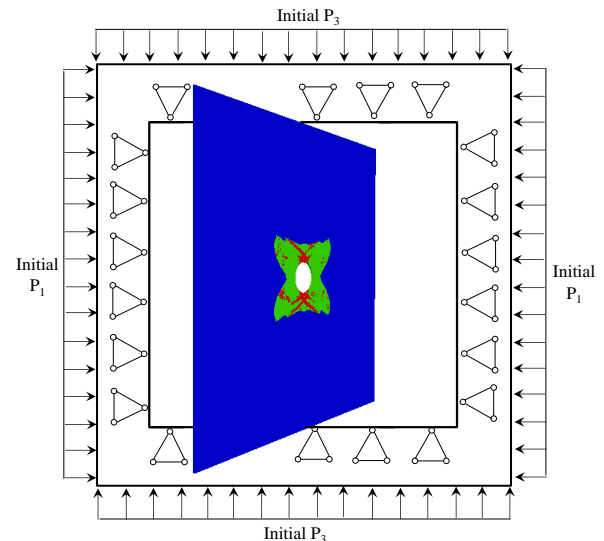


Fig. 1 Numerical simulation force model

maximum principal stress, the regional minimum principal stress and the confining pressure ratio.

2.2 Range characteristics of plastic zone with different shapes

The previous results show that the plastic zone of roadway surrounding rock in the partial confining stress can appear three shapes: circular, elliptical, and butterfly (Ma *et al.* 2015, Guo *et al.* 2016, Liu *et al.* 2020). When the depth is more than 400 m, the shape of the plastic zone is circular under hydrostatic pressure ($\eta=1$); the shape is elliptical when the confining pressure ratio is small ($1<\eta<2$); the shape is butterfly when the confining pressure ratio is large ($\eta>2$) (Ma *et al.* 2015, Guo *et al.* 2016). According to the general shapes and formation conditions of roadway plastic zone in partial confining stress, we studied the expansion law of plastic zone with three shapes under different stress levels by controlling the confining pressure ratio in each shape to be constant (circular: $\eta=1$; elliptical: $\eta=1.5$; butterfly: $\eta=3$). The mechanical properties of surrounding rock in the model are determined regarding the mechanical parameters of coal (cohesion: $C=3$ MPa; internal friction angle: $\varphi=25^\circ$; uniaxial compressive strength: $R_c=10$ MPa) (Ma *et al.* 2015, Guo *et al.* 2016). The regional maximum principal stress was increased from 10 MPa to 100 MPa, and the plastic zone scales of the three shapes under different stress levels were compared, as shown in Fig. 2. The roadway radius is represented by a . The range of plastic zone is expressed by the maximum distance between the boundary of plastic zone and the center of roadway, and is represented by R_{max} .

It can be seen that the size of the circular and elliptical plastic zone is similar and the scale is small under the same stress level. When the stress level is 10 MPa, the plastic zone is 0.3 times the roadway radius; when the stress level is 100 MPa, the plastic zone is 4 times the roadway radius, and 100 MPa has exceeded the limit stress level of the existing mining depth. In the process of stress increasing, the butterfly shaped plastic zone shows large-scale

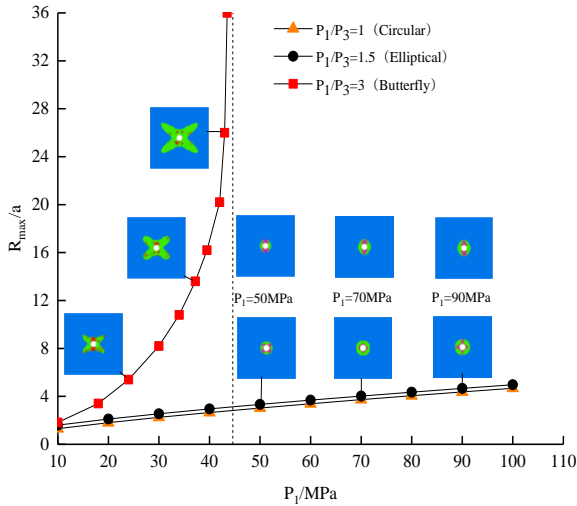


Fig. 2 Comparison curves of mechanical properties of three shapes plastic zone

characteristics. When the stress level is 10 MPa, the range of plastic zone is 0.8 times of roadway radius; when the stress level is 23 MPa, the size of plastic zone is 4.5 times of roadway radius, which has exceeded the size of circular and elliptical plastic zone under 100 MPa stress level; with the increase of stress level, the size of plastic zone increases exponentially.

Based on the comparative analysis, the following results can be obtained. 1) Under the same stress level, the butterfly shaped plastic zone is much larger than that of the circular and elliptical shape, showing a large-scale feature. 2) According to the development trend of the plastic zone range curves, the range of the circular and elliptical plastic zone expands slowly with the increase of the stress. The range of plastic zone is still very small, even at the limit stress level of 100 MPa. It can be inferred that the scope of a circular and elliptical plastic zone of roadway surrounding rock is small under the general underground conditions. 3) Even if the stress level is low, a large range of butterfly shaped plastic zone will appear. When the stress level reaches a certain value, the plastic zone will increase rapidly. Compared with the circular and elliptical plastic zone, the appearance of butterfly shaped plastic zone is accompanied by large-scale characteristics.

The size of plastic zone will have an important influence on the stability of surrounding rock of roadway (Leitman and Villaggio 2009, Zhao 2014). When the range of plastic zone is large, the deformation and damage of the roadway surrounding rock will be serious. On the one hand, the support body needs to bear more broken rock mass, and the anchorage range needs to be increased; on the other hand, the deformation of surrounding rock increases, and the elongation of anchor solid is required to be increased. Therefore, the appearance of butterfly shaped plastic zone is accompanied by large-scale characteristics, and it is closely related to roadway disaster.

2.3 Distribution characteristics of plastic zone with different shapes

Fig. 3 shows the numerical simulation results of plastic

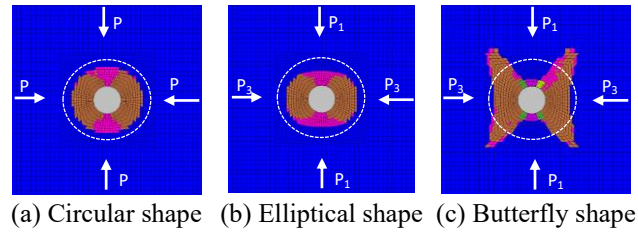


Fig. 3 Distribution characteristics of three shapes

zones with three shapes around the circular roadway. Under the condition of hydrostatic pressure, the plastic zone shape is circular, and it is evenly distributed around the roadway, and the dimensions of plastic zone in each direction are equal, as shown in Fig. 3(a). With the increase of confining pressure ratio, the plastic zone shape changes from round to ellipse. The radius of plastic zone is the smallest in the direction of maximum principal stress and is the largest in the direction of minimum principal stress. However, the contour of the plastic zone is still smooth, and its overall shape still presents a relatively uniform distribution, as shown in Fig. 3(b). After the butterfly shaped plastic zone appears in the roadway surrounding rock, the plastic zone is mainly distributed in the butterfly leaf, showing a concave convex distribution feature. Butterfly shaped plastic zone is extremely uneven around the roadway, as shown in Fig. 3(c). From the aspect of shape, the circular and elliptical plastic zone is distributed uniformly, and the butterfly plastic zone is not uniform.

The distribution characteristics of plastic zone have an important influence on the stability of surrounding rock (Zhao 2014, Li *et al.* 2020a). When the plastic zone is uniformly distributed, the crushed stones in the failure zone can be constrained with each other, and there is no concentrated extrusion to a certain area. The deformation around the roadway is uniform and the roadway is relatively stable. When the plastic zone is distributed unevenly, the roadway deformation in the seriously damaged area is serious. The broken stone in the seriously damaged area is concentrated squeezed by the surrounding elastic zone rock. At this time, the force on the support body increases. When the bearing capacity of the support body is exceeded, the surrounding rock of the roadway is unstable, and the roof fall will occur.

2.4 Surrounding rock stability corresponding to plastic zone with different shapes

When the stress state of surrounding rock changes from uniform pressure to non-uniform pressure, the shape of plastic zone evolves from round to ellipse and finally to butterfly. Fig. 4 shows the relationship between the range, shape of the plastic zone and the stress under 20 MPa stress level, loading in the direction of maximum principal stress (keeping the regional minimum principal stress at 20 MPa) or unloading in the direction of minimum principal stress (keeping the regional maximum principal stress at 20 MPa). The numerical simulation force model shown in the Fig. 1 is still used, and the mechanical properties of surrounding rock in the model are still the mechanical parameters of coal

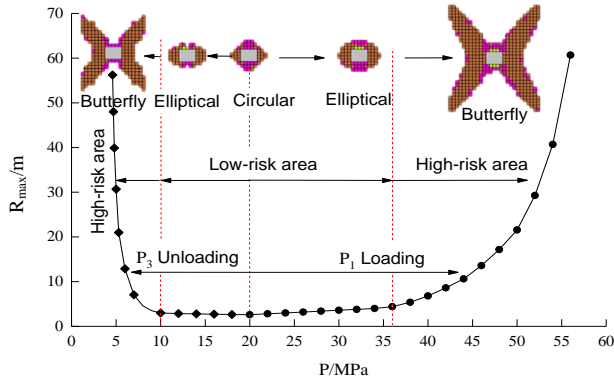


Fig. 4 The relationship between the shapes of plastic zone and the stability of roadway surrounding rock

($C=3$ MPa; $\varphi=25^\circ$; $R_C=10$ MPa). To exclude the influence of roadway shape on the shape of plastic zone, a rectangular roadway is selected in this experiment, which is 4 m wide and 3 m high.

In Fig. 4, the confining pressure in both directions is equal ($P_1=P_3=20$ MPa), the plastic zone of the roadway surrounding rock is circular, and its range is small. Unloading in the direction of the regional minimum principal stress or loading in the direction of the regional maximum principal stress, the shape of the plastic zone gradually changes from circular to elliptical, and the distribution of the plastic zone is uniform and the range is still very small. Before butterfly shape appears, the scope of plastic zone is very small, the surrounding rock structure of roadway is stable. The stability of the roadway surrounding rock can be ensured by adopting ordinary support. We can call this stress interval with circular and elliptical plastic zone as the low-risk area. With the increase of the difference of bidirectional confining pressure, butterfly shaped plastic zone appears in surrounding rock. The range of plastic zone becomes larger, the slope of curve increases, and the plastic zone becomes more sensitive to stress changes. At this time, the deformation and failure of surrounding rock are serious, and improper support will lead to the roof disaster. The roadway surrounding rock structure is in an unstable state. We call this stress interval with butterfly shaped plastic zone as the high risk area. Based on the evolution of the plastic zone, the circular and elliptical plastic zone is the relatively stable failure form of the roadway surrounding rock, and the butterfly shaped plastic zone is the unstable failure form. The relationship between the shape of plastic zone and the stability of surrounding rock is summarized as “non-butterfly is more stable, butterfly is more dangerous”.

3. Judging criterion of plastic zone shape and quantitative evaluation of surrounding rock stability

3.1 Judging criterion of plastic zone shapes

Guo *et al.* (2016) studied the shape evolution of the roadway plastic zone in partial confining stress, and found that the shape of plastic zone around the circular roadway in

a partial confining stress would show three shapes with obvious geometric characteristics: circular, elliptical and butterfly. The mechanical meaning of plastic zone shape was given, and the criterion for judging the shape was obtained by theoretical derivation, as shown in formula (1). When the stress environment and mechanical parameters of surrounding rock are known, the shape of plastic zone can be directly determined by the shape judging criterion.

$$\begin{cases} \tau = \infty & \text{-----circular} \\ \tau \geq 1 \text{ or } \tau \leq 0 & \text{-----elliptical} \\ 0 < \tau < 1 & \text{-----butterfly} \end{cases} \quad (1)$$

where τ is the shape coefficient of plastic zone, and the expression is shown in formula (2).

$$\tau = \frac{m_2}{2m_1} \quad (2)$$

where,

$$\begin{aligned} m_1 &= [12(1-\eta)^2 - 4(1-\eta)^2 \sin^2 \varphi] \left(\frac{-b_1 + \sqrt{b_1^2 - 4a_1c_1}}{2a_1} \right)^2 \\ &\quad - 8(1-\eta)^2 \left(\frac{-b_1 + \sqrt{b_1^2 - 4a_1c_1}}{2a_1} \right); \\ m_2 &= 6(1-\eta)^2 \left(\frac{-b_1 + \sqrt{b_1^2 - 4a_1c_1}}{2a_1} \right)^3 - 4(1-\eta)^2 \left(\frac{-b_1 + \sqrt{b_1^2 - 4a_1c_1}}{2a_1} \right)^2 \\ &\quad + \left[2(1-\eta)^2 - 4(1-\eta)^2 \sin^2 \varphi - \frac{4C(1-\eta) \sin 2\varphi}{P_3} \right] \left(\frac{-b_1 + \sqrt{b_1^2 - 4a_1c_1}}{2a_1} \right); \\ a_1 &= \frac{6(\eta-1)}{1-\sin \varphi}; \quad b_1 = (1+\eta) - \frac{(3\eta-5)(1+\sin \varphi)}{(1-\sin \varphi)}; \\ c_1 &= 2\eta - \frac{4C \cos \varphi}{P_3(1-\sin \varphi)} - \frac{2(1+\sin \varphi)}{1-\sin \varphi}. \end{aligned}$$

In the formula (2), m_1 , m_2 , a_1 , b_1 , c_1 are the transition parameters, which can be expressed as the analytical formulas of stress (P_1 : the regional maximum principal stress, MPa; P_3 : the regional minimum principal stress, MPa) and surrounding rock parameters (C : the rock cohesion, MPa; φ : the rock internal friction angle, rad). The shape coefficient of plastic zone represents the interaction between stresses and surrounding rock in the region. Combined with the corresponding relationship between the shape of plastic zone and the stability of surrounding rock, the judging criterion of plastic zone provides a unified scale for quantitative analysis of roadway stability. In the complex stress and surrounding rock environment of underground coal mine, the plastic zone shape of roadway surrounding rock can be judged by judging criteria of plastic zone shape, and the stability state of roadway surrounding rock can be predicted in advance.

3.2 A quantitative evaluation method of surrounding rock stability

In this paper, the stress structure of roadway surrounding rock in coal mine is abstracted as the stress model of the hole surrounding rock. The complex underground stress field is represented by the regional

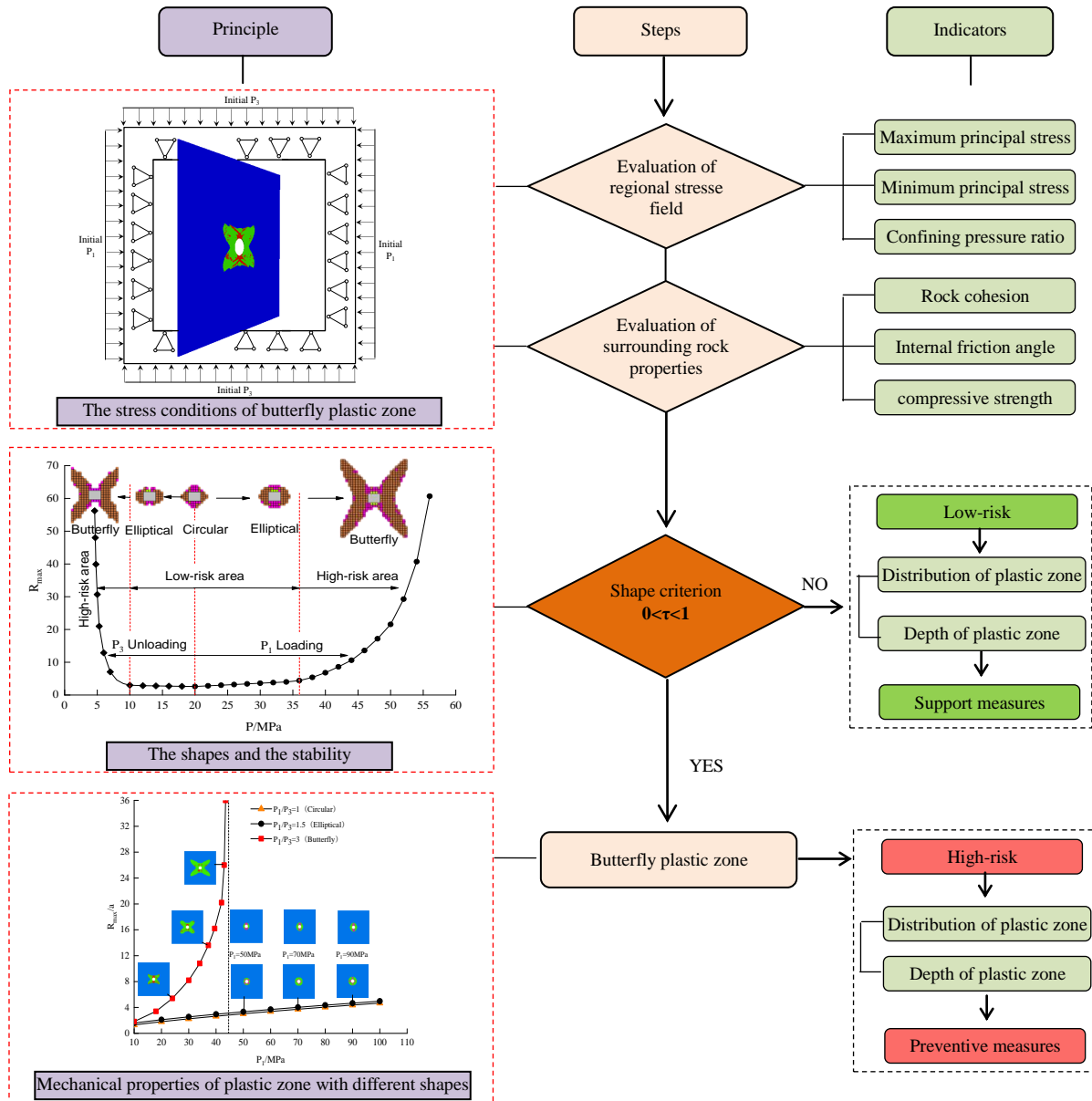


Fig. 5 Flow chart of quantitative evaluation method for roadway surrounding rock stability based on the judging criterion of plastic zone shape

maximum principal stress, the regional minimum principal stress, and the confining pressure ratio. By studying the mechanical properties of plastic zone with different shapes, the corresponding relationship between the shape of plastic zone and the stability of surrounding rock is established. According to the judging criterion of plastic zone shape, the shape of the roadway plastic zone is identified, and then the stability of roadway surrounding rock is predicted in advance. Therefore, we established a quantitative evaluation method of roadway surrounding rock stability based on the judging criterion of plastic zone shape. Its principle and flow chart are shown in Fig. 5.

1) Evaluation of regional stress field

A high confining pressure ratio is a necessary condition for the formation of butterfly shaped plastic zone in surrounding rock of roadway (Zhao 2014, Guo *et al.* 2016). Due to the influence of mining engineering and geological

structure belt, the difference between the maximum and minimum principal stress will be greatly different ((Kang *et al.* 2010, Garavand *et al.* 2020), forming a high partial confining pressure environment, which creates stress conditions for the butterfly shaped plastic zone of the roadway surrounding rock. Based on the formation mechanism and stress conditions of butterfly shaped plastic zone, the stress field should be analyzed and evaluated. The main research indexes are regional maximum principal stress, regional minimum principal stress, and confining pressure ratio. Whether the stress field is the forming condition of butterfly shaped plastic zone is preliminarily judged, and the possible shape of plastic zone of the roadway surrounding rock is preliminarily determined.

2) Evaluation of surrounding rock properties

The underground surrounding rock is a heterogeneous medium and occurs in layers. The criterion for judging the

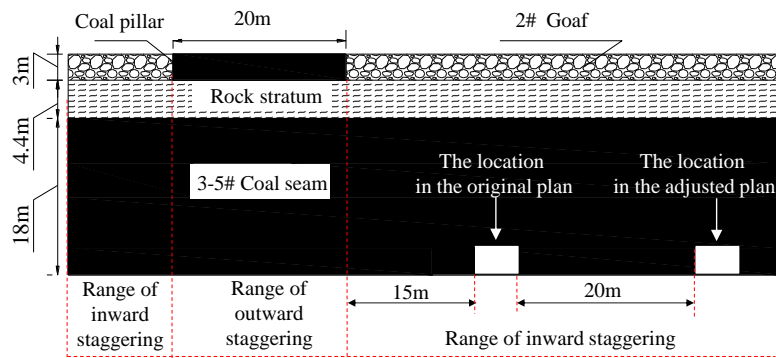


Fig. 6 Layout of excavation engineering

shape of the roadway plastic zone established in this paper is obtained under the condition of a homogeneous medium. To ensure the safety of the roadway, the rock stratum with the weakest lithology is selected in the adjacent layer of the roadway for judgment and analysis. In the process of geomechanics evaluation of the roadway surrounding rock, it is mainly to master the physical and mechanical properties of the surrounding rock strata. The main research indexes in this phase are rock cohesion, internal friction angle, compressive strength, etc., and the weakest rock layer in the rock stratum which plays a key role in the stability of surrounding rock is found as the research object of judgment analysis.

3) Determination of surrounding rock stability by the judging criterion of plastic zone shape

According to the mechanical properties of each rock stratum and the stress conditions around the roadway, the plastic zone shape of the selected rock stratum is determined. If it is determined that there is no butterfly shaped plastic zone in the surrounding rock, because the selected rock layer is the weakest, it is considered that there will be no butterfly shaped plastic zone in the surrounding rock of the roadway, that the stability of the surrounding rock is good, and that the risk of tunnel disaster is low. Then combined with the relevant technical means to determine the accurate range and depth of the surrounding damage area of the roadway, the quantitative support design of the surrounding rock is carried out. If the judgment result of the selected rock stratum is butterfly, it means that under the condition of homogeneous mechanical properties of the rock stratum, butterfly shaped plastic zone will appear in the roadway surrounding rock. The plastic zone in this area will have the characteristics of butterfly shaped plastic zone. The plastic zone is large in scope, uneven in distribution, and sensitive to stress change. Stress disturbance may cause obvious expansion of plastic zone and threaten the stability of roadway surrounding rock. At this time, we should pay attention to the plastic zone scope, depth, distribution area, and sensitivity under the surrounding rock conditions, and corresponding disaster prevention measures should be taken in time.

4. Field case analysis and verification

4.1 Project overview

Tashan Coal Mine is located in Datong City, Shanxi

Province. The average depth of 3-5# coal seam is 400 m and the average thickness is 18 m. Two working faces of 2# coal seam above it have been mined, and the average distance between them is 4.4 m. The average thickness of 2# coal seam is 3.0 m. The mining roadway of the first mining face of the 3-5# coal seam is arranged under the goaf of 2# coal seam, and the layout of excavation engineering is shown in Fig. 6. The location of the roadway in original plan was 15 m horizontally offset from the coal pillar. As a result, the deformation and damage of the roadway surrounding rock were serious during the excavation, and a large range of non-uniform roof subsidence and coal wall spalling phenomenon appeared. The roof of the roadway was deformed at many places, and the anchor bolts (cables) were broken. In the original plan, the roadway was seriously damaged and it was extremely difficult to maintain. The mine had to adjust the position of the roadway and continue to be 25 m away from the side of the coal pillar, which was equivalent to 40 m of internal displacement. In the adjusted plan, the deformation and damage of the roadway surrounding rock were improved and the stability of the surrounding rock was better. In this study, According to the different deformation and failure characteristics of roadway surrounding rock at different positions, combined with the actual engineering geological conditions, the quantitative analysis method of roadway surrounding rock stability is applied to determine and analyze the stress field and plastic zone shapes of roadway surrounding rock at different positions, and then conduct a quantitative evaluation on the stability of roadway surrounding rock.

4.2 Model and material

The research roadway is located in the 3-5# coal seam, above which are 10201 and 10202 goaf in the 2# coal seam, and the coal pillar between the two goafs is 20 m. The working face length of the goaf is 180 m, and the longitudinal length of the goaf is set at 480 m for research. According to the relevant research results (Garavand *et al.* 2020, Jiang *et al.* 2019, Li, 2020b), when the longitudinal length reaches a certain value, the stress field around the goaf will tend to be stable. At this time, different lengths in the advancing direction have little effect on the stress distribution. In this paper, we mainly study the stress distribution on the side of the coal pillar and the shapes of

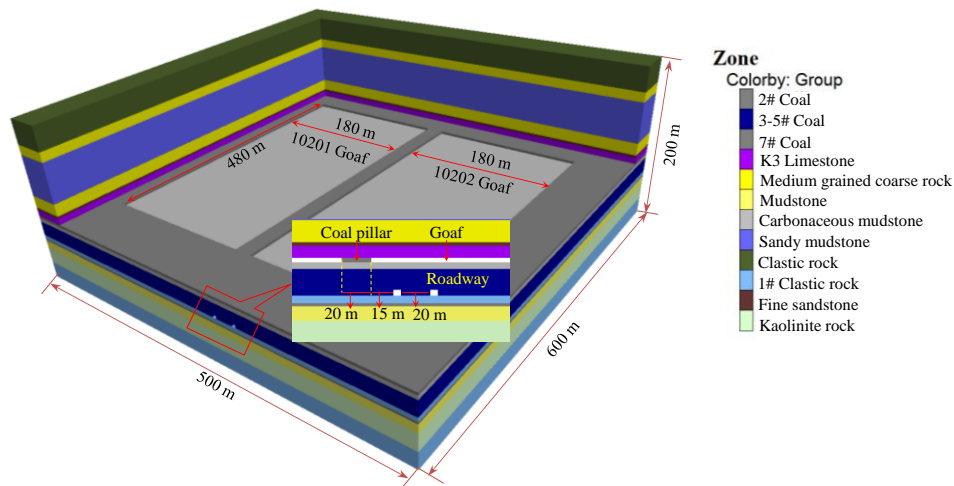


Fig. 7 Geometric dimensions of numerical simulation

Table 1 The mechanical parameter of coal and rocks

Rock name	Density (kg/m ³)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Internal friction angle (°)
Clastic rock	2560	11.1	8.9	3.72	37.57
Sandy mudstone	2500	10.2	8.4	3.72	36.4
Medium grained coarse	2600	11.7	9	6	38
Fine sandstone	2620	12.2	10	6.2	39
K3 Limestone	2700	14	10.7	6.4	39.4
2# Coal	1400	3.48	0.78	1.43	34.5
Carbonace mudstone	2340	9	8	5.5	36
3-5# Coal	1620	5.4	1.96	1.6	35
1# Clastic rock	2560	11.1	8.9	3.72	37.57
7# Coal	1400	3.48	0.78	1.43	34.5
Mudstone	2500	12.2	8.4	3.72	38
Kaolinite rock	2100	8.2	7.6	5.5	35

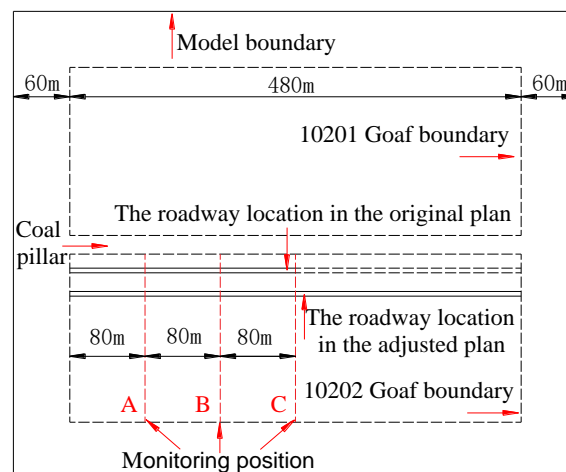
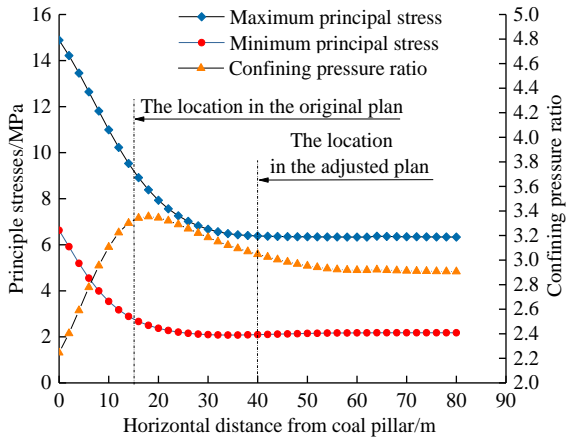


Fig. 8 Plan diagram of research position

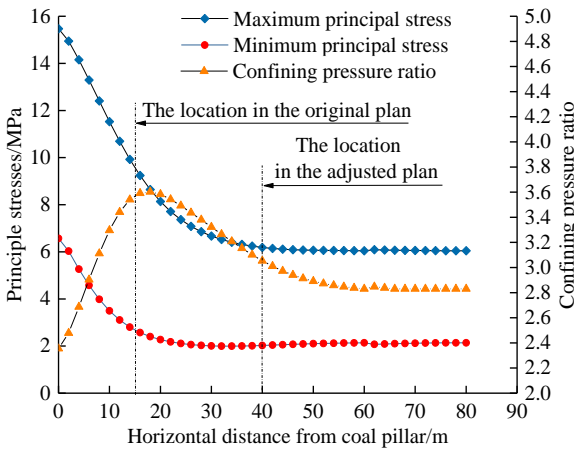
the roadway plastic zone. Considering the calculation amount of computer, so 480 m goaf is set in the longitudinal direction. To reduce the boundary effect, 60 m solid coal is reserved around the model excavation area, and the model size is 500 m × 600 m × 200 m, as shown in Fig. 7.

The lithology of each rock stratum in the model is determined according to the field comprehensive histogram (Guo 2019). The numerical simulation rock mechanical parameters are shown in Table 1.

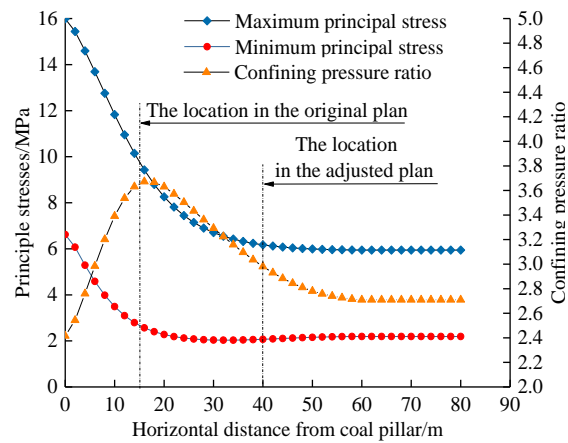
Based the in-situ stress measurement results, the



(a) Stress distribution at monitoring line A



(b) Stress distribution at monitoring line B



(c) Stress distribution at monitoring line C

Fig. 9 Principal stress distribution curves on the side of pillar under goaf

horizontal tectonic stress of the in-situ stress field is not obvious, and the difference between vertical and horizontal stress is very small. The vertical stress is calculated according to the depth of 400 m, which is about 10 MPa. Based on the above results, the stress conditions of the model boundary are determined. Taking the coal seam floor as the benchmark, the initial command is used to apply the stress of 10 MPa in both horizontal and vertical directions. The rock weight in the model is considered, and the stress gradient along the vertical direction is 0.025 MPa/m. In the

horizontal direction, the fixed displacement is used to constrain the boundary. In the vertical direction, the lower boundary of the model is constrained by the fixed displacement; the upper boundary of the model is free, and the stress is applied by the apply command.

4.3 The results

4.3.1 Distribution of regional stress field

In order to ensure the reliability of the results, three groups of monitoring data from different locations were used for comparative analysis. Considering the symmetry of the model, we selected three locations, 80 m, 160 m, and 240 m away from the boundary line of the goaf to study the stress distribution and the plastic zone shape of the roadway surrounding rock, as shown in Fig. 8.

Fig. 9 shows the distribution curves of principal stresses at different horizontal positions on the side of coal pillar under goaf obtained by numerical simulation. It can be seen from the figure that the principle stresses at different monitoring positions on the side of the coal pillar under the goaf have slight difference in numerical value, but the distribution law is completely consistent. With the increase of horizontal distance from the coal pillar edge, the maximum and minimum principal stresses gradually decrease, and finally tend to be stable; the minimum principal stress tends to be stable at first, and then tends to be stable after 20 m away from the coal pillar edge, and the stress value is stable at about 2.1 MPa; the maximum principal stress tends to be stable after 40 m away from the coal pillar edge, and the stress value is stable at 6.3MPa. The results show that the confining pressure ratio increases firstly, reaches the peak value, then decreases, and finally tends to be stable; the peak position of confining pressure ratio appears at 15 m to 20 m away from the coal pillar edge, and the highest value is about 3.6; then the confining pressure ratio begins to decrease, reaching 50 m, then tends to stabilize, basically stable at about 2.8. The difference between the maximum and minimum principal stresses on the side of the coal pillar under the goaf is very big, which forms a high partial confining pressure environment, and it breeds the stress conditions of butterfly shaped plastic zone for the roadways arranged in it.

The studied roadway is located at an internal stagger of 15 m and 40 m respectively, as indicated by the dotted line in Fig. 9. It can be seen from the figure that the roadway location in the original plan is close to the peak value of confining pressure ratio, where is the highest partial confining pressure on the side of coal pillar under the goaf. The surrounding rock of the roadway at this position may form butterfly plastic zone, which threatens the stability of surrounding rock. The location of roadway in the adjustment plan is located in the stress stable area, the maximum and minimum principal stresses tend to be stable, and the confining pressure ratio also drops to a lower value. At this position, the surrounding rock of the roadway may not form butterfly shaped plastic zone, and the surrounding rock of the roadway is stable. The accurate plastic zone shape of roadway surrounding rock at different locations will be determined by the judging criterion of plastic zone shapes.

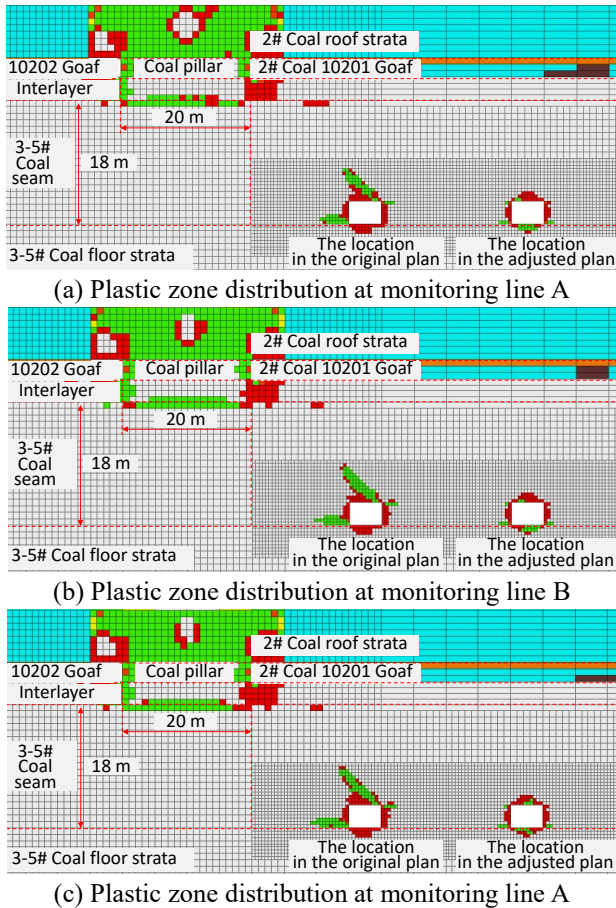


Fig. 10 The plastic zone distribution on the side of pillar under goaf

4.3.2 Characteristics of roadway surrounding rock plastic zone at different positions

Fig. 10 shows the section of plastic zone at three monitoring lines. It can be seen from the figure that the plastic zone distribution of roadway surrounding rock at three different positions on the side of coal pillar under goaf is basically consistent. In the original plan, butterfly plastic zone appears in the surrounding rock of roadway, and the scope of plastic zone is large. Butterfly leaf of plastic zone is distributed near the roadway roof and the side wall of coal pillar, which causes serious deformation and damage of roadway roof and side wall of coal pillar. It is consistent with the deformation and failure situation of roadway on site. In the adjusted plan, the plastic zone is evenly distributed around the roadway, and its range is small. The plastic zone shape is not butterfly, and the roadway surrounding rock is stable, which is consistent with the site situation. Considering the stress characteristics of the two positions, the roadway in the original plan is just near the peak value of confining pressure ratio on the side of the coal pillar under the goaf, and the maximum confining pressure ratio reaches 3.6, which creates stress conditions for the formation of butterfly shaped plastic zone of surrounding rock. The simulation results show that there is a butterfly shaped plastic zone in the surrounding rock of the roadway, and the range of the plastic zone is large. In the adjusted plan, the roadway is located in the stable area

after the confining pressure ratio decrease, and the surrounding rock of roadway is stable without butterfly shaped plastic zone.

4.3.3 Plastic zone shape judgement and verification analysis

The above numerical simulation results show that the plastic zone of roadway surrounding rock in the original plan is butterfly shaped, and that in the adjusted plan is elliptical. The numerical simulation results are consistent with the actual stability of roadway surrounding rock. Based on the judging criterion of plastic zone shape (formula 1 and 2), the plastic zone shape of roadway surrounding rock in different positions is accurately determined. In the calculation, the confining pressure of roadway surrounding rock is obtained by numerical simulation (as shown in Fig. 9), and the mechanical parameters of 3-5# coal seam are adopted for surrounding rock properties ($C=1.6$ MPa; $\phi=35^\circ$). The results are shown in Table 2.

The results show that the shape coefficient of the roadway plastic zone is greater than 1 in the adjusted plan. According to the judgment criteria, the plastic zone of the roadway surrounding rock is elliptical, which is consistent with the numerical simulation results. The shape coefficient of the roadway plastic zone in the original plan is greater than 0 and less than 1. According to the judgment criteria, the plastic zone of the roadway surrounding rock is butterfly, which is consistent with the numerical simulation results. In the adjusted plan, the plastic zone of roadway surrounding rock is elliptical, the range of plastic zone is small, and the surrounding rock of roadway is stable. In the original plan, the roadway is in high partial confining pressure environment, the shape of plastic zone of the roadway surrounding rock is butterfly, and the range of plastic zone is large, which leads to large deformation and high risk of roof fall. The results of the theoretical calculation and numerical simulation are in good agreement with the actual roadway deformation and failure, which proves the reliability of the theoretical method.

The example analyzed in this paper is only a case of high partial confining pressure caused by underground mining. Due to the existence of mining space, the stress field is redistributed around the goaf, resulting in the formation of high partial confining pressure environment in the local range around the goaf, which provides conditions for the formation of butterfly shaped plastic zone. Butterfly plastic zone is accompanied by serious deformation and failure of surrounding rock, which increases the risk of disaster. Based on the judging criterion, the plastic zone shape of roadway surrounding rock in certain stress

Table 2 Shape judgment of plastic zone

Detection line position	Original plan				Adjusted plan			
	P_1 /MPa	P_3 /MPa	τ	Shape	P_1 /MPa	P_3 /MPa	τ	Shape
A	9.53	2.89	0.179	Butterfly	6.35	2.11	1.55	Elliptical
B	9.24	2.60	0.164	Butterfly	6.14	2.04	2.29	Elliptical
C	9.42	2.56	0.146	Butterfly	6.11	2.09	2.85	Elliptical

environment is determined and analyzed, and the stability of roadway surrounding rock is mastered in advance. In the roadway layout, try to avoid the position where butterfly plastic zone will be formed. If butterfly failure occurs in the surrounding rock of roadway, timely measures should be taken to strengthen support. The stability analysis method of roadway surrounding rock based on the judging criterion of plastic zone shape has a good application effect for the study of roadway layout and stability analysis of surrounding rock in high partial confining pressure environment.

5. Conclusions

In this study, we compared the mechanical characteristics of the plastic zone with different shapes of roadway surrounding rock in partial confining stress and established the corresponding relationship between the shape of plastic zone and the stability of roadway surrounding rock. According to the judgment criterion of plastic zone shape, we established the quantitative analysis method of roadway surrounding rock stability. Based on the work presented in this paper, the following conclusions are made:

(1) The scope of circular and elliptical plastic zone is small even under the limit stress condition, and the surrounding rock with the circular and elliptical plastic zone is in a stable state.

(2) The butterfly plastic zone is accompanied by the characteristics of large scale and uneven distribution, and it could cause serious deformation and damage of surrounding rock and increase the risk of roadway disaster

(3) The criterion for judging the shapes of plastic zone quantitatively characterizes the shape category of plastic zone by mathematical expression, which makes it possible to quantitatively study the stability of the roadway surrounding rock

(4) This study established a theoretical method which could quantitatively evaluate the stability of roadways under certain stress and surrounding rock environment based on the judging criteria of plastic zone.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgments

The authors wish to sincerely thank various organizations for their financial support. This work was partially supported by the National Natural Science Foundation of China (Grant no. 52004289).

References

Aker, E., Kühn, D., Vavryčuk, V., Soldal, M. and Oye, V. (2014), "Experimental investigation of acoustic emissions and their

- moment tensors in rock during failure", *Int. J. Rock Mech. Min. Sci.*, **70**, 286-295. <https://doi.org/10.1016/j.ijrmms.2014.05.003>.
- Ardehijani, E.A., Ataei, M. and Rafiee, R. (2020), "Estimation of first and periodic roof weighting effect interval in mechanized longwall mining using numerical modeling", *Int. J. Geomech.*, **20**, 04019164. [https://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001532](https://doi.org/10.1061/(ASCE)GM.1943-5622.0001532)
- Barth, N.C. (2014), "The cascade rock avalanche: implications of a very large alpine fault-triggered failure, New Zealand", *Landslides*, **11**(3), 327-341. <https://doi.org/10.1007/s10346-013-0389-1>
- Cai, M.F. (2020), "Key theories and technologies for surrounding rock stability and ground control in deep mining", *J. Min. Strat. Control Eng.*, **2**, 5-13. <https://doi.org/10.13532/j.jmsce.cn10-1638/td.20200506.001>.
- Diederichs, M.S. (2018), "Early assessment of dynamic rupture hazard for rockburst risk management in deep tunnel projects", *J. S. Afr. I. Min. Metall.*, **118**(3), 193-204. <https://doi.org/10.17159/2411-9717/2018/v118n3a1>.
- Ding, L.J. and Liu, Y.H. (2018), "Study on deformation law of surrounding rock of super long and deep buried sandstone tunnel", *Geomech. Eng.*, **16**(1), 97-104. <http://doi.org/10.12989/gae.2018.16.1.097>.
- Detournay, E. and John, C.M.S. (1988), "Design charts for a deep circular tunnel under non-uniform loading", *Rock Mech. Rock Eng.*, **21**(2), 119-137. <https://doi.org/10.1007/BF01043117>.
- Fan, L. and Liu, S.M. (2019), "Fluid-dependent shear slip behaviors of coal fractures and their implications on fracture frictional strength reduction and permeability evolutions", *Int. J. Coal Geol.*, **212**, 103235. <https://doi.org/10.1016/j.coal.2019.103235>.
- Feng, G.R., Wang, P.F. and Chugh, Y.P. (2018), "Stability of gate roads next to an irregular yield pillar: A case study", *Rock Mech. Rock Eng.*, **52**, 2741-2760. <https://doi.org/10.1007/s00603-018-1533-y>.
- Garavand, A., Stefanov, Y.P., Rebetzky, Y.L., Bakeev, R.A. and Myasnikov, A.V. (2020), "Numerical modeling of plastic deformation and failure around a wellbore in compaction and dilation modes", *Int. J. Numer. Anal. Met.*, **44**(6), 823-850. <https://doi.org/10.1002/nag.3041>.
- Guo, X.F., Ma, N.J., Zhao, X.D., Zhao, Z.Q. and Li, Y.E. (2016), "The general shapes and criterion for surrounding rock mass plastic zone of round roadway", *J. China Coal Soc.*, **44**(8), 1871-1877. <https://doi.org/10.13225/j.cnki.jccs.2016.0787>.
- Guo, X.F. (2019), "Criterion of plastic zone shapes of roadway surrounding rock and its application", Ph.D. Dissertation, China University of Mining and Technology (Beijing), Beijing, China.
- Islavath, S.R., Deb, D. and Kumar, H. (2020), "Development of a roof-to-floor convergence index for longwall face using combined finite element modelling and statistical approach", *Int. J. Rock Mech. Min. Sci.*, **127**, 104221. <https://doi.org/10.1016/j.ijrmms.2020.104221>.
- Jiang, L.S., Kong, P., Shu, J.M. and Fan, K.G. (2019), "Numerical analysis of support designs based on a case study of a longwall entry", *Rock Mech. Rock Eng.*, **52**, 3373-3384. <https://doi.org/10.1007/s00603-018-1728-2>.
- Kang, H., Zhang, X., Si, L., Wu, Y. and Gao, F. (2010), "In-situ stress measurements and stress distribution characteristics in underground coal mines in China", *Eng. Geol.*, **116**, 333-345. <https://doi.org/10.1016/j.enggeo.2010.09.015>.
- Kang, H.P. (2020), "Spatial scale analysis on coal mining and strata control technologies", *J. Min. Strat. Control Eng.*, **2**, 5-30. <https://doi.org/10.13532/j.jmsce.cn10-1638/td.20200119.001>.
- Konicek, P., Soucek, K., Stas, L. and Singh, R. (2013), "Long-hole destress blasting for rockburst control during deep underground coal mining", *Int. J. Rock Mech. Min. Sci.*, **61**, 141-153. <https://doi.org/10.1016/j.ijrmms.2013.02.001>.

- Lamich, D., Marschalko, M., Yilmaz, I., Bednářová, P., Niemiec, D., Kubečka, K. and Mikulenkova, V. (2015), "Subsidence measurements in roads and implementation in land use plan optimisation in areas affected by deep coal mining", *Environ. Earth Sci.*, **75**, 69. <https://doi.org/10.1007/s12665-015-4933-2>.
- Le, T.M.H., Gallipoli, D., Sánchez, M. and Wheeler, S. (2015), "Stability and failure mass of unsaturated heterogeneous slopes", *Can. Geotech. J.*, **52**(11), 1747-1761. <https://doi.org/10.1139/cgj-2014-0190>.
- Leitman, M.J. and Villaggio, P. (2009), "Plastic zone around circular holes", *J. Eng. Mech.*, **135**(12), 1467-1471. [https://doi.org/10.1061/\(ASCE\)EM.1943-7889.0000062](https://doi.org/10.1061/(ASCE)EM.1943-7889.0000062).
- Lekontsev, Y.M. and Sazhin, P.V. (2014), "Directional hydraulic fracturing in difficult caving roof control and coal degassing", *J. Min. Sci.*, **50**(5), 914-917. <https://doi.org/10.1134/S106273911405010X>.
- Li, C., Zhang, W.L., Wu, Z., Sun, Y.H., Zhu, C. and Zhang, X.H. (2020a), "A case study on asymmetric deformation mechanism of the reserved roadway under mining influences and its control techniques", *Geomech. Eng.*, **22**(5), 449-460. <http://doi.org/10.12989/gae.2020.22.5.449>.
- Li, J. (2020b), "The coal pillar design method for a deep mining roadway based on the shape of the plastic zone in surrounding rocks", *Arab. J. Geosci.*, **13**(12), 454. <https://doi.org/10.1007/s12517-020-05501-9>.
- Liu, H.T., Qiao, B.Y. and Ma, N.J. (2020), "Stability analysis and design of roadways in adjacent seams: A case study from Tashan coal mine in China", *Arab. J. Geosci.*, **13**(8), 1-11. <https://doi.org/10.1007/s12517-020-05289-8>.
- Ma, N.J., Li, J. and Zhao, Z.Q. (2015), "Distribution of the deviatoric stress field and plastic zone in circular roadway surrounding rock", *J. China U. Min. Technol.*, **44**, 206-213. <https://doi.org/10.13247/j.cnki.jcumt.000309>.
- Rajwa, S., Janoszek, T. and Prusek, S. (2020), "Model tests of the effect of active roof support on the working stability of a longwall", *Comput. Geotech.*, **118**, 103302. <https://doi.org/10.1016/j.compgeo.2019.103302>.
- Vatcher, J. and Sjöberg, J. (2015), "Developing 3-d mine-scale geomechanical models in complex geological environment", *Eng. Geol.*, **203**, 140-150. <https://doi.org/10.1016/j.enggeo.2015.07.020>.
- Vidigal-Souza, P.A., Vilas-Boas, D.B., Brandão, A.G. and Holz, M. (2020), "Seismic stratigraphy of Camamu basin, Northeastern Brazil", *Pure Appl. Geophys.*, **177**(11), 5207-5224. <https://doi.org/10.1007/s00024-020-02580-3>.
- Xia, K.Z., Chen, C.X., Fu, H., Pan, Y.C. and Deng, Y.Y. (2016), "Mining-induced ground deformation in tectonic stress metal mines: A case study", *Eng. Geol.*, **210**(5), 212-230. <https://doi.org/10.1016/j.enggeo.2016.06.018>.
- Yan, H., He, F.L., Yang, T., Li, L.Y., Zhang, S.B. and Zhang, J.X. (2016), "The mechanism of bedding separation in roof strata overlying a roadway within a thick coal seam: A case study from the Pingshuo coalfield, China", *Eng. Fail. Anal.*, **62**(4), 75-92. <https://doi.org/10.1016/j.engfailanal.2015.12.006>.
- Yang, D.W., Ma, Z.G., Qi, F.Z., Gong, P., Liu, D.P., Zhao, G.Z., and Zhang, R.C. (2017a), "Optimization study on roof break direction of gob-side entry retaining by roof break and filling in thick-layer soft rock layer", *Geomech. Eng.*, **13**(2), 195-215. <http://dx.doi.org/10.12989/gae.2017.13.2.195>.
- Yang, S.Q., Chen, M., Jing, H.W., Chen, K.F. and Meng, B. (2017b), "A case study on large deformation failure mechanism of deep soft rock roadway in Xin'an coal mine, China", *Eng. Geol.*, **217**, 89-101. <https://doi.org/10.1016/j.enggeo.2016.12.012>.
- Zhang, W.L., Li, C., Ren, J.J. and Wu, Z. (2020), "Measurement and application of vibration signals during pressure relief hole construction using microseismic system", *Measurement*, **158**(6), 107696. <https://doi.org/10.1016/j.measurement.2020.107696>.
- Zhao, T. and Liu, C.Y. (2017), "Roof instability characteristics and pre-grouting of the roof caving zone in residual coal mining", *J. Geophys. Eng.*, **14**, 1463-1474. <https://doi.org/10.1088/1742-2140/aa8eb6>.
- Zhao, Z.Q. (2014), "Mechanism of surrounding rock deformation and failure and control method research in large deformation mining roadway", Ph.D. Dissertation, China University of Mining and Technology (Beijing), Beijing, China.
- Zhu, C., Chang, Y., Cui, X.B., Ren, F.Q. and Zhang, X.H. (2019), "Study on the size effect of fracture intersections based on the fractal theory", *Geotech. Geol. Eng.*, **37**(4), 2999-3006. <https://doi.org/10.1007/s10706-019-00818-z>.

JS