Study on Temporal and Spatial Characteristics of Overlying Strata in Deep Coal Mining Process

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Research

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Abstract

This paper adopts the stress relief method to test the in-situ stress in the field to obtain the in-situ stress distribution characteristics of No. 2+3# coal seam. A three-dimensional model was established with the No. S3012 working face as the engineering background, and the measured in-situ stress values were applied to the three-dimensional model, and the spatial-temporal evolution characteristics of coal and rock mass around the stope during coal seam mining were studied. The specific conclusions are as follows: the three-dimensional stress distribution map in front of, behind and on both sides of the working face in the process of coal mining are obtained. As the working face goes on, the maximum value of the supporting stress formed in front of, behind and on both sides of the working face shifts to the corner, presenting a “hump-like” distribution. The stress concentration coefficient of front, back and both sides of stope increases linearly with the increase of mining size. Under the same mining size, the stress concentration coefficient in front of stope is the smallest, and the stress concentration coefficient on both sides is the largest. The three-dimensional displacement field distribution nephogram of overlying strata in the process of coal mining is obtained. With the continuous advance of the working face, the roof strata of coal seam undergo continuous dynamic subsidence process, and the roof subsidence increases continuously, showing the shape of “bowl” with sharp bottom. In the process of working face mining, the roof displacement of coal seam showed an "O" shape evolution characteristic. The three-dimensional distribution cloud map of the plastic zone of coal and rock mass in the process of working face mining was obtained, and the failure volume of the plastic zone gradually increases with the continuous progress of the working face.

1. Introduction

China is one of the countries with the worst disasters in the world, especially the dynamic disasters generated in the process of coal resource mining, such as coal and gas outburst, rock burst, gas and other disasters (Zhou, Xie and Zuo 2005), which not only cause huge losses to people's lives and property, but also seriously hinder the society, environment and safe and efficient mining of coal resources. The occurrence of these disasters is closely related to the stress environment of the coal and rock mass. It is of great significance for the prevention and control of dynamic disasters such as coal and gas outburst to make clear the distribution characteristics of the stress field of the coal and rock mass and the evolution characteristics of the stress field of the surrounding rock mass during the mining process (Cheng, et al. 2013; Tang et al. 2014).

The in-situ stress field refers to the undisturbed natural stress field, also known as the original stress field, which consists of the tectonic stress field and the self weight stress field of coal and rock mass. The tectonic stress field is formed by geological tectonic movement, which is complex and variable with uneven stress distribution. The horizontal stress in the shallow part of the crust is generally larger than the self weight stress, which is about 1.5 ~ 2.0 times of the self weight stress (Yu and Xian 1990), while the horizontal stress is generated by the structural stress (Tang and Kong 2007). There are many in-situ stress testing methods, among which the commonly used ones are stress (strain) relief and hydraulic
fracturing (Jing et al. 2007). In 1966, Li Siguang established China’s first in-situ stress observation station in Yaoxian, Hebei Province (Liu et al. 2000; Cai 2000), and then in-situ stress testing developed rapidly. Zhang et al. (2016) put forward Kaiser effect method for in-situ stress test, and the test results are consistent with those of in-situ hollow inclusion stress relief method. In addition, the in-situ stress test is carried out by using the stress relief method, and the rockburst tendency of Micangshan tunnel is analyzed (Yang et al. 2019). However, for the measurement of in-situ stress under the condition of soft surrounding rock in deep coal mines, neither the hydraulic fracturing method nor the stress relief method can obtain the effective in-situ stress value. Based on the mechanical characteristics of strong rheology of soft rock under the action of high ground stress (Sun 2007), it is considered that the rock mass stress sensor can be embedded in the deep soft rock after drilling. With the rheology of the surrounding rock, the stress around the drilling hole gradually recovers to a certain value. The ground stress or disturbed stress state of the surrounding rock can be obtained through the monitoring of the perceived stress change of the rock mass stress sensor and the related inversion calculation, according to this, the rheological stress recovery method is proposed to test the in-situ stress (Jiang et al. 2016; Liu et al. 2016, 2020).

The appearance of underground stope pressure is closely related to the fracture structure of the overlying strata, the structural form and stability of the overlying strata directly impact on the occurrence characteristics of mine pressure. At present, domestic and foreign scholars have conducted a lot of research on the law of strata pressure in working face, and achieved rich results. In view of the impact characteristics of overburden structure movement on the strata pressure, micro seismic positioning monitoring technology (Jiang et al. 2006; Dou et al. 2012), EH-4 detection technology (Zhang et al. 2015) and other methods are used to carry out relevant research on the spatial structure form and disaster causing mechanism of overlying rock. Jia et al. (2015) analyzed the opening and closing process and form of "open close" fracture in depth according to the main factors of sand break and water break when the longitudinal fracture of overlying strata in the shallow buried and thin bedrock coal face is connected. According to the field measurement of mine pressure, it is considered that the periodic weighting step increases with the increase of bedrock thickness, and the weighting strength decreases with the increase of bedrock thickness (Zhang et al. 2011). It is revealed that the collapse and initial mining of the working face are the mechanism of the problem of pressure support (Lin 2013). Wang and Ju (2014) used the method of field observation and theoretical analysis to analyze the law of mine pressure appearance and its occurrence mechanism in the overlong fully mechanized mining face. The indoor similar simulation test method can effectively study the fracture characteristics of overburden in shallow and large mining height (Yin 2019; Ren et al. 2013), Liu et al (2016) analyzed the stress evolution process of surrounding rock in the pressure relief area when mining in the short distance coal seam, and believed that the stress in the floor rock in the working face decreased linearly. Computer simulation is also one of the commonly used means, the commonly used numerical simulation software includes RFPA (Tang et al. 1999), FLAC3D (Zhang et al. 2019; Yang et al. 2020), 3DEC/UDEC (Gao et al. 2019), etc. Zhang et al. (Zhang et al. 2018) used the method of numerical simulation, similar simulation and on-site monitoring to study the law of mine pressure appearance of repeated mining in very close seam.
To sum up, although scholars at home and abroad have carried out a series of researches on the evolution characteristics of stress field of coal and rock mass, most of them are related researches in plane state, and most of the models are based on displacement constraints, or similar simulation and numerical simulation tests under hydrostatic pressure. There are few reports on the study of stress field, displacement field and plastic zone evolution characteristics of coal and rock mass in the three-dimensional state, especially the study of applying the measured in-situ stress value on the boundary of the three-dimensional model. In the No. 2 + 3# coal seam of Shanmushu Coal Mine, there are many times of gas overrun in the roadways during driving, among which, there was one coal and gas outburst accident in the No. S3012-2 roadways during driving, the No. 2 + 3# coal seam is a typical coal and gas outburst coal seam, and the occurrence of coal and gas outburst and other disasters is closely related to the stress field environment. Therefore, this paper used a combination of on-site in-situ stress test, three-dimensional similar simulation test, mining stress monitoring and theoretical analysis to analyze in detail the evolution characteristics of three-dimensional mining stress field, displacement field and plastic zone of coal and rock mass during the coal mining process. The research results have guiding value for preventing the occurrence of disasters such as coal and gas outburst.

2. Project Overview

The No. 2 + 3# coal seam in No. S3012 working face of Shamushu Coal Mine belongs to coal and gas outburst coal seam. The gas overrun occurred many times in the process of driving and mining of each roadway, and one coal and gas outburst accident occurred during the driving of No. S3012-2 air roadway. The buried depth of No. 2 + 3# coal seam is 400 ~ 520m, the average thickness of coal seam is 3.1m, the average dip angle is 4°, the strike length of working face is 752m, and the inclined length is 138m. The working face layout is shown in Fig. 1.

The direct roof of No. 2 + 3# coal seam is sandy mudstone with a thickness of about 3.0m, the basic roof is sandstone carbonaceous mudstone with an average thickness of 6m. The direct bottom is clay rock, which is soft and expands with water, with an average thickness of 2.8m. The basic bottom is sandy mudstone with sandstone, with an average thickness of more than 5m. During the mining period, the working face is affected by some faults, resulting in roof fracture and coal seam missing, which causes adverse factors to the working face and has a great impact on the coal quality. The lithology of strata near No. 2 + 3# coal seam is shown in Table 1.
Table 1
Lithology of the adjacent strata of No.2 + 3# coal seam

| Layer number | Main lithology             | Thickness/m | Layer number | Main lithology                         | Thickness/m |
|--------------|---------------------------|-------------|--------------|----------------------------------------|-------------|
| 1            | siltstone                 | 12.83       | 12           | mudstone                               | 10          |
| 2            | fine sandstone            | 5           | 13           | k8 argillaceous limestone               | 0.5         |
| 3            | siltstone                 | 15          | 14           | sandstone-carbonaceous mudstone         | 6           |
| 4            | siltstone-fine sandstone-mudstone | 15  | 15           | mudstone-argillaceous limestone         | 3           |
| 5            | mudstone-fine sandstone   | 15          | 16           | No. 2 + 3# coal seam                   | 3.1         |
| 6            | siltstone-fine sandstone  | 44.3        | 17           | claystone                              | 2.8         |
| 7            | mudstone-siltstone        | 30          | 18           | sandy mudstone                         | 6.3         |
| 8            | k9 limestone              | 0.7         | 19           | graystone                              | 2.9         |
| 9            | No. 1# coal seam          | 0.65        | 20           | sandy mudstone                         | 9.3         |
| 10           | sandstone-claystone       | 8.5         | 21           | gray claystone                         | 2.4         |
| 11           | C2 coal seam              | 0.42        | 22           | medium and fine sandstone              | 6.3         |

3. In-situ Stress Test

In the measurement of in-situ stress in coal mine, it is more appropriate to apply stress relief method in the stage of mine construction and production. Core drilling holes are arranged in the rock mass to separate a section of core from the surrounding rock under three-dimensional stress. The data relationship curve of "strain-relief distance" in the process of core separation is tracked and recorded by installing hollow core inclusion stress meter, so as to realize the purpose of in-situ stress measurement. KX-81 hollow inclusion stress gauge is selected for this test, and the test site is selected in the surrounding rock layer of No. 2 + 3# coal seam, and the buried depth is about 450m. The depth of the construction large hole is 10.55m, and the installation angle is 36.5 ° and the drilling angle is 5° and the azimuth angle is 325° during installation. The site construction, installation and test process are shown in Fig. 2.

(a)drilling construction  b)stress gauge installation  c)data collection

Figure 2 Filed test process
KJ327-F mine intrinsic safety digital strain gauge is used, and the accuracy is 0.1%. The release process can be divided into three stages: in the first stage, before the core sleeve moves to the strain gauge position, the stress contact curve changes smoothly, and the variation range of each strain value is small. In the second stage, when the core sleeve is close to the position of strain gauge, the change range of strain value increases, and with the increase of release depth, the strain value gradually increases to the maximum value. In the third stage, after the strain reaches the peak value, the strain value fluctuates and tends to be stable with the increase of relief depth, and the stress relief process ends. The stress relief process curve is continuous and complete, and the data is valid, which can be used as the basis for stress calculation, as shown in Fig. 3.

According to the test results in Fig. 3, the in-situ stress calculation program of hollow inclusion is used for iterative solution, and the in-situ stress test results of the measuring point are obtained, as shown in Table 2.

| Principal stress | Measured value/MPa | Azimuth angle/° | Dip angle/° | Vertical stress (σ_v/MPa) | σi/σ_v |
|------------------|--------------------|----------------|-------------|--------------------------|--------|
| σ₁               | 24.79              | 144.45         | 3.91        | 10.8                     | 2.30   |
| σ₂               | 14.55              | 52.64          | 24.86       |                          | 1.35   |
| σ₃               | 9.87               | 64.8           | 242.81      |                          | 0.91   |

4. Three-dimensional Strata Behavior Characteristics Of Stope

4.1 3D model establishment

According to the engineering situation of s3012 working face, FLAC^3D^5.0 (Wang 2015) numerical simulation software is used to establish a three-dimensional model. The model size is X×Y×Z=300m×400m×250m, X direction is coal seam dip, Y direction is coal seam strike, Z direction is vertical direction, as shown in Figure 4. If the coal seam is located about 204m away from the top of the model and the buried depth of the coal seam is about 488m, the thickness of the overlying strata is about 284m, and the weight of the overlying strata is taken as γ=25kN/m². Uniform load of 7.1MPa was applied at the top of the model, displacement constraint was applied at the bottom of the model, and stress constraint was applied around the model. The maximum principal stress was 24.79MPa in X direction and 14.55MPa in Y direction.

Assuming that the interior of each rock stratum is isotropic continuous medium, all rock masses conform to Mohr Coulomb failure criterion. In this numerical simulation, a total of 240m is mined, and each mining is 20m, which is completed in 12 times. The mining range is 84~216m in X direction and 110~350m in Y direction.
direction, with protective coal pillars left and right in front of and behind the working face. Figure 5 only shows that the mining dimensions of the working face are 20m, 40m, 600m, 120m, 180m and 240m.

4.2 Three dimensional stress field analysis

In order to more intuitively show the stress evolution law in front, back, and both sides of the coal seam mining process, make a profile inside and parallel to the coal seam, and import the results into Tecplot10.0 software for analysis. The stress evolution law in front, back, and both sides of the coal seam in the process of mining are shown in Figure 6.

It can be seen from Figure 6 that the coal and rock mass around the coal seam are in stress balance state before the working face is mined. Under the influence of mining, the stress field around the coal and rock mass redistributes, and the stress concentration phenomenon appears in front of and behind the working face and on both sides, and the stress relief area appears in the roof and floor strata of the working face. With the working face moving forward, the range of stress field gradually increases and moves forward gradually, thus forming mobile abutment stress. The height and width of stress relief zone also increase with the increase of excavation size. When the working face is mined for 20m, the maximum concentrated stress is 16.99MPa at about 10m in front of the working face, and the stress concentration coefficient is 1.4. The maximum concentrated stress is 17.28MPa and the stress concentration coefficient is 1.43 at about 10m behind the working face. There is a stress concentration at 6m on the left and right sides of the working face, the maximum value is 18.23MPa, and the stress concentration coefficient is 1.51. It can be seen that the value of the concentrated stress on both sides of the working face is greater than that on the back and greater than that on the front, and there are 84m protective coal pillars on both sides of the working face, resulting in the same value of the maximum concentrated stress on both sides.

When the working face is 40m, the stress concentration area in front of the working face moves forward, and the maximum value of the concentration stress is 16.87MPa and the stress concentration coefficient is 1.39 at about 10m in front of the working face. The maximum concentrated stress is 17.50MPa and the stress concentration coefficient is 1.45 at about 10m behind the working face. The maximum concentrated stress is 20.03MPa and the stress concentration coefficient is 1.66 at 6m on the left and right sides of the working face. It can be seen that the maximum value of the front and back concentrated stress of the working face after 20m and 40m of coal mining occurs about 10m in the front and back of the goaf, and the maximum value of the two sides concentrated stress of the working face appears about 6m in the right and left of the goaf. When the working face is mined for 60m, the concentrated stress is 16.77MPa at about 10m in front of the working face, and 17.15MPa at about 10m in back of the working face, but the stress concentration in front, back and both sides of the working face is in the shape of "hump-like", that is to say, after the coal seam is mined to 60m, the maximum concentrated stress value appears at the corner of the goaf in front of the working face. At this time, the maximum concentrated stress value in front of the working face is 17.69MPa, and the stress concentration coefficient is 1.46. The maximum concentrated stress behind the working face is 18.16MPa, and the stress concentration coefficient is 1.5. Similarly, the maximum value of concentrated stress is 20.78MPa and the coefficient of
stress concentration is 1.72 at 6m near the goaf on the left and right sides of the working face. With the continuous advance of the working face, the maximum value of the concentrated stress in front, rear and left and right of the working face increases gradually. When the working face is pushed 240m, the maximum value of the concentrated stress in front of the working face reaches 20.84MPa, and the stress concentration coefficient is 1.72. The maximum concentrated stress at the back of working face is 23.6MPa, and the stress concentration coefficient is 1.95. The maximum concentrated stress of the left and right sides of the working face is 24.73MPa, and the stress concentration coefficient is 2.04.

Based on the above analysis, it can be seen that when the working face is mined for 20m and 40m, the maximum abutment stress formed in front and back of the working face occurs in front and behind the middle of the working face. The maximum abutment stress on both sides of the working face occurs on both sides of the middle of the working face. When the working face is recovered to 60m, the maximum value of the abutment stress formed at the back of the working face is shifted from the front and back of the middle of the working face to both sides, so that the maximum value of the supporting stress appears at the corner in front of the working face, and the abutment stress formed at both sides of the working face has the same variation law, showing a "hump-like" distribution. According to the above analysis, the change law of stress concentration coefficient in front, back and both sides of the goaf is shown in Figure 7.

It can be seen from Figure 7 that with the continuous forward movement of the working face, the stress concentration coefficient of the front, back and both sides of the goaf increases gradually, and under the same mining size, the stress concentration coefficient in front of the working face is the smallest, and the stress concentration coefficient of both sides of the working face is the largest. There is a linear relationship between the stress concentration factor and the mining size, as shown in equation (1).

\[
\gamma = m + nl
\]  

(1)

In the formula, \(\gamma\) is the stress concentration factor, \(l\) is the working face mining size (m), \(m\) and \(n\) are linear fitting coefficients.

The fitting parameters of linear regression are given in Table 3.

**Tab. 3** Fitting parameters of coal-rock stress concentration factor and mining dimension around working face

| Stress concentration factor | Fitting parameters | \(R^2\) |
|-----------------------------|--------------------|--------|
|                             | \(m\)              | \(n\)  |        |
| forward                     | 1.55287            | 0.01246| 0.9562 |
| near                        | 1.36718            | 0.00293| 0.9922 |
| both sides                  | 1.3714             | 0.00149| 0.9830 |
In order to more clearly show the stress variation law during the mining process of the working face, make a section along the X direction of the three-dimensional model (that is, X = 150m profile), make a section along the direction of the coal seam inside the coal seam, extract the intersection of the two sections, and draw the abutment stress evolution law in the mining process of the working face, as shown in Figure 8.

In the mining process

It can be seen from Figure 8 that after the coal seam mining, there is a stress concentration phenomenon in front and back of the working face, the roof and floor strata at the working face are pressure relief areas. The larger the coal seam advances, the larger the pressure relief area. With the working face moving forward, the stress concentration coefficient in front and back of the working face are increasing, and the stress concentration coefficient behind the working face is slightly higher than the front stress concentration coefficient. It can be seen that with the continuous advancement of the working face, the coal wall and the goaf move forward continuously, resulting in the formation of movable abutment stress in front and back the working face, and the formation of a stress reduction zone, a stress increasing zone and an original stress zone in front of the working face.

4.3 Three dimensional displacement field analysis

In order to visually show the migration law of overburden strata during coal seam mining, make a cutting plane along the coal seam in the roof rock layer 0.75m away from the coal seam, extract the cutting plane displacement and import the results into Tecplot10.0 software for analysis. The migration law is shown in Figure 9.

It can be seen from Figure 9 that as the working face continues to move forward, the amount of coal roof subsidence gradually increases, and the roof rock layer is in the shape of a “bowl” with a sharp bottom. When the working face is stopped at 20m, the roof subsidence is 210.19mm; when the working face is recovered at 40m, the roof subsidence is 349.73mm; when the working face is recovered at 60m, the roof subsidence is 460.76mm; when the working face is recovered at 120m, the roof subsidence is 460.76mm; The sinking amount is 700.07mm; when the working face is mined at 180m, the roof sinking amount is 879.13mm; when the working face is mined at 240m, the roof sinking amount is 1060.20mm.

In order to more vividly represent the roof strata migration rule in the mining process of the working face, cut the three-dimensional model along the X direction (i.e. X=150m section), cut the roof strata 0.75m away from the coal seam along the coal seam direction, extract the intersection line of the two sections, and draw the roof strata migration law in the mining process of the working face as shown in Figure 10.

In the mining process of the working face, the coal seam roof rock layer undergoes continuous dynamic subsidence process, make the cutting plane at Z=100m, and extract the displacement nephogram at Z=100m during the mining of the working face, as shown in Figure 11.
It can be seen from Figure 11 that in the process of mining, the displacement of the coal seam roof exhibits an "O" shape evolution law, that is, there is a displacement "O" shape circle. In the early stage of mining, the displacement of roof strata is approximately elliptical, and the X direction is the long axis of ellipse, and the Y direction is the short axis of ellipse. With the development of working face, that is, the ratio of long axis to short axis is decreasing, and the subsidence area of roof in goaf is expanding. When the ratio of long axis to short axis is close to 1, the influence area of roof subsidence is approximately "O" shape. With the continuous development of the working face, the X-direction becomes elliptical short axis, the Y-direction becomes elliptical long axis, and the subsidence area of the roof in the goaf increases along the long axis.

4.4 Three dimensional plastic zone analysis

In order to more vividly represent the destruction law of the roof and floor rock layers during working face mining, the distribution law of the plastic area of the coal and rock mass in the mining process of the working face is extracted by writing fish statement, as shown in Figure 12.

It can be seen from Figure 12 that after the coal seam is mined, there is a plastic area around the working face, and the area of the plastic zone gradually increases as the working face goes on. After the coal seam is excavated for 20m, the coal and rock mass around the working face have shear and tensile failure, among which the shear_now failure of plastic yield units is 11481, the tensile_now failure is 0, the shear_past failure is 115076, the tensile_past failure is 4835. After the coal seam is excavated for 40m, the shear_now failure of plastic yielding units is 213229, the tensile_now failure is 186, the shear_past failure is 318839, and the tensile_past failure is 13374. After the coal seam is excavated for 60m, the shear_now failure of plastic yielding units is 379657, the tensile_now failure is 147, the shear_past failure is 599482, and the tensile_past failure is 25752. After the coal seam is excavated for 120m, the shear_now failure of plastic yielding units is 553339, the tensile_now failure is 69, the shear_past failure is 1480000, and the tensile_past failure is 84830. After the coal seam is excavated for 180m, the shear_now failure of plastic yielding units is 678039, the tensile_now failure is 582, the shear_past failure is 2540000, and the tensile_past failure is 4915348. In the mining process of the working face, the variation curves of the number of plastic zone units are shown in Figure 13.

It can be seen from Figure 13 that with the continuous development of the working face, the number of shear_now failure units increase gradually, reaching the maximum when the working face is recovered to 80m, and then the fluctuation increases. The number of tensile_now failure units increases with the
development of the working face, and reaches the maximum when the working face advances to 240m. The number of shear_past failure units, tensile_past failure units and the total failure units increased parabola with the progress of the working face.

5. Conclusions

1) The in-situ stress values of No.2+3# coal seam are obtained by stress relief method: the maximum principal stress is 24.79 MPa, the intermediate principal stress is 14.55 MPa and the minimum principal stress is 9.87 MPa.

2) The spatial-temporal evolution characteristics of coal and rock mass around the stope during coal mining are studied by numerical simulation method, the conclusions are as follows:

- As the working face goes on, the maximum value of the abutment stress formed in front, behind and on both sides of the working face shifts to the corner, presenting a "hump-like" distribution. The stress concentration coefficient of front, back and both sides of stope increases linearly with the increase of mining size. Under the same mining size, the stress concentration coefficient in front of stope is the smallest, and the stress concentration coefficient on both sides is the largest;

- With the continuous advance of the working face, the roof strata of the coal seam undergo continuous dynamic subsidence process, and the roof subsidence increases continuously, showing a sharp bottom "bowl" shape, and the roof displacement of coal seam presents "O" shape evolution characteristics;

- Obtain the three-dimensional distribution nephogram of the plastic zone of coal and rock mass during the mining process of the working face, and the failure volume of the plastic zone gradually increased with the working face going on.

Declarations

Data Availability: The data used to support the findings of this study have not been made available because research project is in progress.

Conflicts of Interest: The authors declare no conflict of interest.

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Figures
Figure 1

S3012 working face layout

(a) drilling construction  (b) stress gauge installation  (c) data collection

Figure 2

Filed test process

Figure 3
Stress relief curves during the drilling process

Figure 4

FLAC3D three-dimensional model

Figure 5

Working face mining dimension diagram
Figure 6

Stress evolution law in front, back and both sides of the coal seam mining process
Figure 7

Variation law of stress concentration factor in front, back and both sides of goaf during mining process

Figure 8

Stress evolution law of X=150m section and intersection along the coal seam direction in the mining process
Figure 9

Movement law of coal seam roof rock stratum during mining face
Figure 10

Variation curves of roof subsidence during coal seam mining

Figure 11
Displacement nephogram of roof strata in Z=100m section during coal seam mining

Figure 12

Distribution law of plastic zone in mining process of working Face
Figure 13

Failure units number of coal and rock mass in mining process of working Face