In-site investigation of regional outburst prevention in coal roadway strip of a deep mine using an improved method

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Abstract
With the increase of mining depth, the occurrence mechanism of coal and gas outburst becomes more complex, and stress-dominated outburst disaster has become one of the major safety problems in deep coal mines. Therefore, stress relief of coal seam has become an urgent technical demand for outburst prevention method in deep mines. In this study, based on zonal disintegration characteristics of deep surrounding rock, a regional strip outburst prevention method, called strip stress relief combined with gas extraction through stress-relief floor roadway, was proposed, and relevant in-site investigations were carried out in the Qujiang coal mine in China. Our results show that the zonal disintegration phenomenon occurs in the high-stress surrounding rock at great depths, and induces the stress-relief effect on the upper coal seam, in which the permeability and extraction radius of boreholes are increased greatly. The results of deformation and failure of surrounding rock of floor roadway show that from the surface to deep regions, fractured and nonfractured zones were alternatively distributed in the surrounding rock of deep floor roadways, the damage degree of surrounding rock was gradually weakened, and the width of fractured area was gradually reduced. The displacement of surrounding rock presented the characteristics of alternative distribution of wave peak and trough. Moreover, the deformation and failure of surrounding rock presented a time-dependent rheological behavior. In the stress-relief zone, the coal seam permeability was enhanced significantly, with the maximum value being 43 times larger than that of the original coal seam. The effective gas extraction radius of the borehole was improved by 15%-45%. During the driving period of coal roadways, the outburst risk prediction indexes $K_1$ and $S$ of the working face were lower than the critical value, and the driving speed of the coal roadway improved from 40 m per month to 100 m per month. This indicates that the proposed strip regional outburst prevention method can simultaneously reduce the ground stress and the gas content, and can effectively eliminate the outburst risk of coal roadway in deep mines.
INTRODUCTION

With the increase of mining depth, the ground stress and gas pressure of coal seam increase, and the permeability of coal seam decreases. The occurrence mechanism and types of coal and gas outburst (hereinafter referred to as “outburst”) have become more complex in deep mines, that is different from those observed in shallow mines. In deep mines, the surrounding rock is usually subjected to high ground stress, high gas pressure, and severe mining disturbance, and frequently presents the failure characteristics of large deformation, strong rheology, brittle-ductile transition, zonal disintegration, etc., all of which significantly increase the risk of dynamic disasters. The outburst risk gradually transforms from a single dynamic disaster to a compound dynamic disaster. Specifically, under the mutual induction and interaction of outburst and rockburst, the rockburst-outburst compound dynamic disasters gradually occur in deep mines, the type of outburst disaster changes from an initial gas-dominated outburst to a final stress-dominated outburst. In addition, the threshold of occurrence condition of stress-dominated outburst is lower than that of a typical (gas-dominated) outburst. In some deep mines, unexpected outburst (stress-dominated) occurred at heading faces in condition that the gas content of coal seam was lower than the critical value of traditional outbursts after gas extraction.

In shallow mines, gas extraction is the fundamental measure to prevent outburst. In recent years, the regional gas extraction technologies such as pre-extraction through surface vertical well, surface horizontal well, cross-seam boreholes, in-seam boreholes, and gas pre-extraction in protected seam have been popularized and applied in different mining areas, which promoted gas extraction, utilization, and production safety of coal mine. Meanwhile, for low-permeability coal seams with high risk of outburst, various stimulation methods such as deep-hole blasting, hydraulic flushing, hydraulic slotting, hydraulic fracturing, CO₂ fracturing, and high-pressure air blasting have been proposed and applied, which could enhance the gas extraction efficiency and shorten the gas extraction period.

Data on coal mine accidents show that the number of outbursts in the heading face accounts for more than 70% of the total number of outbursts. Therefore, outburst prevention in heading face is important to reduce coal mine outburst accidents. The regional method currently adopted for outburst prevention in heading face is gas pre-extraction through cross-boreholes. Although the method of gas extraction can significantly reduce the gas pressure and content of coal seam and thus weaken the internal energy of gas, it cannot reduce the high ground stress that may trigger the stress-dominated outbursts in deep mines. For example, a stress-dominated outburst accident occurred at heading face after gas extraction in the Dingji coal mine on April 19, 2009, and another similar outburst accident occurred in the Qujiang coal mine on 30 September 2013. Investigations into these accidents revealed that the accident sites are located at great depth and that the high ground stress played a major role in outburst. Thus, there is an urgent need for regional stress-relief technology to prevent outbursts in deep mines. Although technical measures such as hydraulic fracturing and hydraulic slotting can reduce the ground stress and improve the permeability of coal seam to some extent, they have some limitations. For example, hydraulic fracturing can form large-area fractures in coal seam, but the number of fractures is small. Besides, it is difficult to control the direction of fractures and avoid stress concentration in the fracturing area. By contrast, hydraulic slotting technology can effectively overcome the defect of local stress concentration produced by hydraulic fracturing; however, the resulting stress-relief range is small, which requires extensive drillings in order to form a large regional stress-relief area.

Under conditions of high ground stress, fractured and nonfractured zones are alternatively distributed in the surrounding rock around deep roadway, which is referred as the “zonal disintegration”. Since its discovery in the 1970s, the phenomenon has attracted the attention of many scholars worldwide, resulting in many studies being conducted on the distribution characteristics and generation mechanism of the fractured zone in deep surrounding rock. These studies mainly involved methods such as field investigation, theoretical analysis, laboratory experiment, and numerical simulation. Compared with the shallow rock, the failure range of surrounding rock around deep roadway is larger, and the stress distribution of deep surrounding rock is significantly different. From the perspective of outburst prevention, the zonal disintegration phenomenon can be utilized to relieve stress and enhance permeability of coal seam. Based on the depth and geological structure of coal seam, we could adjust the spatial position of the floor roadway for gas extraction, so that coal roadway strip is within the stress-relief range of floor roadway. This not only could reduce the elastic energy of coal, but also could improve the coal seam permeability. Furthermore, after gas extraction through cross-seam boreholes, the outburst risk of the coal roadway strip would be reduced.

In this paper, we analyzed the energy mechanism of deep coal and rock dynamic disasters, proposed a regional method for outburst prevention in roadway strips referred as “stress
relief combined with gas extraction through a stress-relief floor roadway” and conducted relevant in-site investigations into deep coal mine to verify the application effect of the proposed outburst prevention method. This has significant research value and practical implications for the technological progress of outburst prevention in deep mines.

2 | ENERGY MECHANISM OF DEEP COAL AND ROCK DYNAMIC DISASTER

2.1 | The energy source for outburst

From an energy perspective, outburst can be defined as the process of energy accumulation, transfer, and release from a coal and rock system. Thus, the failure process of coal and rock mass can be regarded as an instability phenomenon driven by energy accumulation and release. When the energy released by the coal and rock system is larger than the consumption of energy by coal fragmentation and motion, coal and rock dynamic disasters may occur. As shown in Figure 1, the total energy released ($E_{\text{total}}$) during a disaster mainly includes the gas internal expansion energy ($E_{\text{gas}}$) and the elastic energy of coal and surrounding rock ($E_{\text{coal}}$ and $E_{\text{rock}}$), which can be related as follows:

$$E_{\text{total}} = E_{\text{gas}} + E_{\text{rock}} + E_{\text{coal}}$$

Because of the effect of both ground stress and gas pressure, large amounts of elastic energy and gas internal energy are accumulated in the coal and rock mass. Before excavation, the coal rock structure generally remains in a stable state. However, after excavation, the ground stress redistribution in the surrounding rock will lead to increased energy concentration in coal and rock mass. When the energy concentration reaches a certain degree, it could affect the stability of coal and rock structure system. In combination with mining disturbance, the rapid release of accumulated elastic energy and gas internal energy will eventually result in dynamic disasters.

2.2 | Energy transformation

During the process of dynamic disaster, the gas expansion energy and the elastic energy of coal and surrounding rock are mainly consumed in the transport and crushing of coal, and can be expressed as follows:

$$E_{\text{rock}} + E_{\text{coal}} + E_{\text{gas}} = E_{\text{p}} + E_{\text{m}}$$

where $E_{\text{p}}$ is energy consumption for crushing coal and rock and $E_{\text{m}}$ is energy consumption for the transport of coal and rock.

A typical outburst mainly depends on gas internal energy, whereas a typical rockburst mainly depends on the elastic energy. The main difference between these two types of disasters is the different degree of gas energy participation. In the process of energy transfer of dynamic disaster, when the participation of gas energy $E_{\text{gas}}$ is small and could be ignored, the disaster is classified as a typical rockburst; however, when the participation of $E_{\text{gas}}$ is far greater than $E_{\text{rock}} + E_{\text{coal}}$, the disaster is classified as a typical outburst. Furthermore, when $E_{\text{gas}}$ and $E_{\text{rock}} + E_{\text{coal}}$ are in the same level, the disaster is classified as stress-dominated outburst.\(^6,35\) In deep underground mines, both ground stress and gas pressure remain at a high level. Therefore, it is necessary to simultaneously reduce the elastic energy and gas internal energy to prevent outburst in these areas.

3 | THE REGIONAL OUTBURST PREVENTION METHOD FOR COAL ROADWAY STRIP

3.1 | Zonal disintegration phenomenon in deep roadways

According to the classical elastic-plastic mechanics, the surrounding rock of shallow tunnel can be divided into fractured zone, plastic zone, and elastic zone from the inside to the outside. However, the failure distribution characteristics of surrounding rock in deep roadway are quite different.\(^36,37\) At great depth, fractured zones and nonfractured zones occur alternately in the surrounding rock masses (Figure 2). This phenomenon, termed zonal disintegration, cannot be fully explained by the traditional continuum mechanics theory.

It is indicated that zonal disintegration is a regular behavior of the surrounding rock in deep high-stress roadway,\(^32,38\) which presents another new equilibrium form of surrounding rock that is different from the shallow roadway. A field investigation\(^31\)
also indicated that four fractured zones exist in the surrounding rock of roadway at a depth of 1 km. The failure range of surrounding rock is about 8 m, which is much larger than the loose zone of the shallow roadway. In shallow roadway, the plastic zone of shallow roadway can support the ground stress of surrounding rock. Therefore, there is only one fractured zone in surrounding rock. However, in deep roadway, because the initial stress is higher than the uniaxial compression strength of the rock, the surrounding rock presented a different behavior from the shallow roadway after excavation. Several fractured zones occurred in surrounding rock under the high-stress condition. To reveal the mechanism of the zonal disintegration phenomenon, a lot of studies were conducted with theoretical analysis and physical simulation experiment.

So far, although the mechanism of zonal disintegration is still not explicitly revealed, some important insights and understanding about the occurrence condition the phenomenon are obtained. Firstly, the initial stress of rock, especially the horizontal stress, should be high. Only when the in situ stress is greater than the uniaxial compressive strength (UCS) of rock, the zonal disintegration would occur. When the in situ stress is less than the UCS of rock, only one fractured zone occurs like the condition in shallow roadway as shown in Figure 2A. The stress is the key factor determines the number of the fractured zones. Secondly, the surrounding rock shows a feature of brittle failure under the complex excavation unloading conditions. Zonal disintegration is considered a result of rock mass splitting along the direction of maximum tangential stress caused by the radial tensile stress or strain due to the high tangential and axial stress. Thirdly, the radial dynamical stress plays an important role in the formation of the zonal disintegration as well as the high static stress. Because the radial tensile effect created by the dynamical unloading stress, the excavation method and speed will significantly influence the fracturing distribution of surrounding rock.

Obviously, the stress of surrounding rock in fractured zone is relieved and lower than that in nonfractured zone. It is believed that the stress of surrounding rock in fractured range is non-monotonically distributed as shown in Figure 2B when zonal disintegration occurs. Theoretical analysis also showed that the stress distribution of surrounding rock presents a feature of multipeak wave at great depth. Therefore, the stress-relief range of surrounding rock is much larger than that of shallow roadway. Meanwhile, because the permeability of coal or rock in low-stress condition is higher than that in high-stress condition, the range of increased permeability of surrounding rock in deep roadway would be larger than in shallow roadway. Therefore, as for outburst prevention, the fracture and stress distribution characteristics of surrounding rock in zonal disintegration could be utilized to relieve stress and increase permeability.

3.2 Regional outburst prevention method for coal roadway strip

According to the energy source analysis of dynamic disasters, the outburst prevention method in deep mines should reduce both internal energy of gas and elastic energy of coal or rock mass. To reduce gas pressure and content in coal seam, the conventional prevention method drains the gas from the coal seam strip through cross-boreholes from floor roadway. For the convenience of borehole drilling, the floor roadway for gas extraction is usually designed to be located below coal seam with a distance more than 20 m in vertical direction, and about 15-30 m away from the coal roadway strip in horizontal direction. The spatial distance between conventional floor roadway and coal strip is greater than the stress-relief range of floor roadway. Therefore, it is difficult to achieve the stress-relief effect on coal seam for a conventional floor roadway.

Based on zonal disintegration of surrounding rock in deep roadway and its stress-relief effect, an improved outburst prevention method through stress-relief floor roadway is proposed in this paper. The prevention principle and flowchart are shown in Figure 3. First, based on the depth and geological structure of coal seam, we adjust the spatial design of the floor roadway to reduce the distance between coal heading strip and the floor roadway, so that the coal strip of heading is within stress-relief range of the floor roadway. Thus, the ground stress of coal within the roadway strip would be reduced, and the permeability of coal strip would also be improved. Second, to reduce the gas internal energy, cross-boreholes are drilled from the floor roadway to drain the coal
seam gas. Upon implementing these two measures for energy release, the outburst risk of the heading face in the roadway strip will be regionally eliminated.

4 | IN-SITE INVESTIGATION SCHEME

To evaluate the outburst prevention effect of the proposed method, the deformation and failure characteristics of surrounding rock of two stress-relief floor roadways (702 and 213) and the gas extraction effect of the upper coal seam strip are investigated in the Qujiang coal mine, Jiangxi Province in China.

4.1 | Overview of investigation site

The Qujiang coal mine is highly susceptible to outbursts. The ground elevation of this mine is +20 to +90 m, with a mining depth of 650-1000 m. Thickness of the current mining seam (B4) ranges from 1.7 m to 2.4 m, and the dip angle of the seam ranges from 8° to 13°. The hardness coefficient (f) of coal is 0.3 ~ 0.8, and the coal strength is low. The maximum gas pressure of coal seam is 9.2 MPa, and the gas content is 13.5-25.3 m³/t. The permeability of B4 seam is low (1.7 × 10⁻⁵-0.74 m²/MPa² d). The 702 and 213 floor roadways are located about 9 m below the planned coal roadway. The gas geology parameters of the test sites are presented in Table 1.

4.2 | Investigation scheme

1. To investigate the deformation and failure characteristics of surrounding rock of stress-relief floor roadway, three measurement groups are arranged at positions with different distance from the heading face of stress-relief floor roadway. The specific positions of these measurement groups are presented in Table 2. Each measurement group
contains five observation cross-boreholes with different directions, covering a range of 15 m on both sides of coal roadway, as shown in Figure 4. First, the YTJ20-type camera system is inserted into the cross-borehole to observe the failure characteristics of surrounding rock. Second, six gauging points are arranged in each cross-borehole equipped with a DW-6 multipoint extensometer to observe the displacement of the surrounding rock at different depths.

2. To investigate the permeability variation of coal seam in the stress-relief range of the floor roadways, the radial gas flow method is used to calculate seam permeability through cross-boreholes. The arrangement of measurement groups is similar to that for failure investigation, and detailed information about this arrangement and cross-borehole is presented in Table 2.

3. To investigate the effective gas extraction radius of boreholes, a statistical analysis method of borehole gas flow is adopted to calculate the extraction radius of cross-boreholes before and after stress relief in the test site. These cross-boreholes for extraction radius calculation at stress-relief area are the same ones for permeability measurement.

4. To investigate the outburst prevention effect in coal roadway strip, first, the gas extraction amount and concentration of boreholes are analyzed, and the residual gas content of seam strip is measured. Second, during the driving process of the coal roadways, the variation of outburst risk prediction indexes, including gas desorption index of drilling cuttings ($K_1$) and amount of drilling cuttings ($S$), is tracked and recorded.

5. **RESULTS AND ANALYSIS**

5.1. **Deformation and failure characteristics of surrounding rock of floor roadway**

5.1.1. **Failure characteristics of surrounding rock of floor roadway**

To record the failure characteristics of the surrounding rock of floor roadway in the investigation site, the YTJ20 instrument was inserted into each borehole to observe its damage condition. A steel ruler was used to calibrate the depth of fractures, with a guide rod to push the camera into borehole to record the fracture characteristics of the surrounding rock. Figure 5 presents some inner view pictures of boreholes obtained by YTJ20-type camera, and the fracture characteristics of boreholes can be clearly distinguished.

For analysis of the regional failure characteristics of the surrounding rock, the fractured zones of surrounding rock in
boreholes are depicted according to the image data obtained from the observation into boreholes. The fractured area with an interval no more than 0.2 m is treated as a fractured zone. Each fractured zone is connected with a polysemy line and filled with a cross grid. Figures 6 and 7 show the failure zone distribution of surrounding rock in different locations of the 702 and 203 floor roadways in test sites.

As can be seen from Figures 6 and 7, four fractured zones and nonfractured zones are alternatively distributed in the surrounding rock of floor roadways, which indicates that zonal disintegration phenomenon occurred in the investigation sites. Besides, from the surface to the deep of surrounding rock, the damage degree gradually weakens, while the width of the fractured zone is gradually reduced. The first fractured zone, which ranges from the surface to the depth of 1.5 m, is the zone most seriously damaged. It is considered to be the traditional loose zone of the roadway surrounding rock in shallow roadways. In the second fractured zone, the surrounding rock with a large amount of fractures is also damaged seriously. The third fractured zone is mainly composed of fractures and fissures, and the damage degree of the surrounding rock in this zone is relatively lower. Further, in the fourth fractured zone, no obvious fragmentation of surrounding rock exists in the zone which is composed of fissures.

In addition, the maximum depth of the fractured zones of the surrounding rock around the 702 and 213 floor roadways is 7.8 m and 6.5 m, respectively, which indicates that the fractured range of deep roadway is larger than that of shallow roadway (the loose zone). Because of the in situ stress in fractured range is relieved, it is implied that the stress-relief range of roadway surrounding rock in deep mines is larger than that in shallow mines. Moreover, through comparing the maximum damage range of different groups, it can be found that the depth of fractured zone gradually increases with the increase of distance between the observation group site and the heading face. In other words, the longer the roadway excavation time, the more serious the damage degree of the surrounding rock. This is because the elastic energy of surrounding rock is released over time. With more deformation time, more elastic energy of surrounding rock would be released, which would lead to more significant stress-relief effect.

**5.1.2 | Deformation characteristics of surrounding rock of floor roadway**

After the observation of the zonal disintegration of the surrounding rock, a DW-6 multipoint displacement extensometer is installed in every observation borehole to measure the displacement variation at different depths of surrounding rock of the 702 and 213 floor roadways. The displacement distribution of surrounding rock at different measurement groups of roadways (1 month later) are shown in Figures 8 and 9. It should be noted that the measured data are the displacement of surrounding rock for 1 month after the extensometer installation in boreholes. In other words, because most of the deformation has occurred before the measurement, the recorded data are only part of the displacement since the excavation of roadway. Therefore, the analysis on displacement distribution characteristics is more meaningful than the displacement value.

As can be seen from Figures 8 and 9, from the surface to the deep of surrounding rock, the displacement in all boreholes presents an interval distribution of wave peak and trough, which is obviously different from the monotonic variation of deformation in shallow surrounding rock. It is indicated that this nonmonotonic distribution is related to the zonal disintegration phenomenon. The peak position of displacement is the fractured zone of surrounding rock, and the trough position of displacement is the nonfractured zone. The correlation phenomenon can also be observed in physical simulations of zonal disintegration in laboratory.41,42

Figure 10 shows the maximum displacement of the surrounding rock in different directions in the test site. It can be found that the displacement in vertical direction borehole is larger than that in side direction boreholes. It is implied that the largest deformation and failure of surrounding rock occurred right above the floor roadway. Figure 11 shows the maximum displacement of the surrounding rock at 3 different measurement groups of floor roadways. The specific...
positions of three measurement groups in the 702 and 213 floor roadways are presented in Table 2. Obviously, with the increase of distance from the heading face of floor roadway, the displacement of surrounding rock shows an increasing trend. It indicates that the deformation of surrounding rock has a time-dependent rheological effect.

5.2 | Coal seam permeability

The permeability of coal seam is measured with the gas radial flow method. Figure 12 shows the variation of coal seam permeability at different positions before and after stress relief above the floor roadways. It can be found that the highest coal seam permeability occurs above the floor roadway, followed by the 2#, 4#, 1#, and 5# boreholes. Besides, the coal seam permeability increases with the increase of distance from the heading face (Groups 3#, 2#, and 1#), indicating that the stress-relief effect of the coal seam above the floor roadway increases gradually over time.

Figure 13 shows the permeability enhancement coefficient of coal seam at different positions after the stress relief above the floor roadway, which represents the ratio of permeability of coal seam after stress relief to that of the original coal seam. The permeability of coal seam right above the 702 and 213 floor roadways is the highest, and the permeability of coal seam on both sides gradually decreases with the distance increasing from the central line of the floor roadways. The permeability of coal seam above the 702 floor roadway is 43 times higher than that of the original seam, whereas the permeability of coal seam on both 7.5 m and 15 m sides of the 720 floor roadway is 32 and 11 times higher than the original coal seam.

5.3 | The effective extraction radius of cross-boreholes

Figure 14 shows the variation of the average daily gas extraction amount at different positions of coal seam above the 702 and 213 floor roadways, which obeys the negative exponential decay trend. It is noted that the radius of gas extraction borehole is 75 mm and the negative pressure for gas extraction is 13 kPa.

Figure 15 shows the variation of the effective extraction radius of boreholes at different positions of coal seam above the 702 and 213 floor roadways in test site. It can be found that the largest effective extraction radius of boreholes of coal seam occurred at 3# borehole, followed by those at 2#, 4#, 1#, and 5# boreholes.

Table 3 lists the effective extraction radius of coal seam above the 702 and 213 floor roadways, and Figure 16 shows the improvement rate of the effective extraction radius of coal seam before and after stress relief. In the stress-relief
range of the 213 floor roadway, the effective extraction radius of coal seam is improved by 15%-45%. In addition, the improvement rate of the effective extraction radius of coal seam decreases in the order of 4#, 2#, 1#, and 5# boreholes. The largest improvement of effective extraction radius occurred at 3# borehole.

### 5.4 | Outburst prevention effect of coal roadway strip

#### 5.4.1 | Gas extraction effect of coal roadway strip

Figure 17 shows the variation of gas extraction quantity and concentration through cross-boreholes of the coal seam above the 702 and 213 floor roadways. For the coal seam above the 702 floor roadway, the maximum gas extraction concentration is about 14%, and the maximum daily gas extraction quantity is about 2130 m³/d. After 90 days, the gas content in the coal roadway strip has been extracted by 49%-58%, and the residual gas content is reduced to 3.7-4.2 m³/t. This indicates that the gas extraction efficiency was improved significantly after stress relief via the two stress-relief floor roadways.

#### 5.4.2 | Outburst prevention effect of coal roadway strip

After stress relief and gas extraction, the outburst risk prediction indexes $K_1$ and $S$ of the heading face of coal seam are significantly reduced. During the driving period, the gas desorption index value of drilling cuttings is 0.1-0.4 mL/g min$^{1/2}$, which is less than the critical value of 0.5 mL/g min$^{1/2}$; the amount of drilling cuttings is 2.5-3.9 kg/m, which is also less than the critical value of 6.0 kg/m, as shown in Figure 18. In addition, the tunneling speed of coal roadway in the test site has improved from 40 m per month to 100 m per month, which realized the safe and rapid tunneling of the deep coal roadway.
In shallow seams, the ground stress is generally low and gas is the main outburst causing factor. Therefore, the most effective outburst prevention method in such seams is gas extraction. However, in deep seams, both the gas and ground stress play an important role in outburst occurrence. Therefore, stress relief and gas extraction are both key prevention steps in deep mines. Based on zonal disintegration characteristics of deep

**FIGURE 9** Displacement variation of surrounding rock of the 213 floor roadway

**FIGURE 10** Maximum deformation of surrounding rock of boreholes with different directions above the floor roadway in the test site (“−” and “+” represent the upside and downside of the roadway)

**FIGURE 11** Maximum deformation of the surrounding rock in different positions of roadway

6 | DISCUSSION

In shallow seams, the ground stress is generally low and gas is the main outburst causing factor. Therefore, the most effective
surrounding rock, an improved regional strip outburst prevention method, called strip stress relief combined with gas extraction through stress-relief floor roadway, is proposed in this paper, which can not only reduce the elastic energy of coal and rock, but also decrease the gas internal energy, so as to realize the outburst prevention of coal roadway strip in deep mines.

Generally, most studies on zonal disintegration mainly focused on the failure and stability of the tunnels or roadways at great depth. The ultimate purpose of those studies is to provide theoretical basis for supporting structure design to reduce the range of zonal disintegration and promote the stability of surrounding rock. However, this study goes to another direction and tries to utilize fracturing distribution characteristics of zonal disintegration into outbursts prevention for its stress-relief effect on surrounding rock. It provides a new pathway for regional stress-relief and permeability

**Figure 12** Variation of coal seam permeability at different positions above the floor roadways (“s−” and “+” represent the upside and downside of the roadway)

**Figure 13** The permeability of coal seam at different position above the 702 and 213 floor roadways (“−” and “+” represent the upside and downside of the roadway)

**Figure 14** Average daily quantity of single-borehole gas extraction
enhancement of coal seam strip. Compared with the traditional gas extraction by cross-bores, the improved regional outburst prevention method could eliminate the risk of stress-dominated outbursts in deep mines.

Field investigation results in the paper show that four typical fractured zones are distributed in the surrounding rock of deep floor roadway, with the maximum depth of the fractured zone being 7.8 m. It is similar to the zonal

**FIGURE 15** The variation of the effective extraction radius of boreholes at different positions of coal seam above the 702 and 213 floor roadways

**TABLE 3** Statistics of effective extraction radius of coal seam above the 702 and 213 floor roadways in test site

| Test site     | Time (d) | 5# borehole (m) | 4# borehole (m) | 3# borehole (m) | 2# borehole (m) | 1# borehole (m) | Original coal seam (m) |
|---------------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------------|
| 702 floor roadway | 15       | 1.3             | 1.4             | 1.4             | 1.2             | 1.2             | 1.1                    |
|                | 30       | 1.7             | 1.8             | 1.8             | 1.6             | 1.6             | 1.5                    |
|                | 60       | 2.0             | 2.1             | 2.2             | 2.0             | 1.9             | 1.8                    |
|                | 90       | 2.2             | 2.3             | 2.4             | 2.1             | 2.2             | 2.0                    |
| 213 floor roadway | 15       | 1.4             | 1.5             | 1.6             | 1.4             | 1.4             | 1.1                    |
|                | 30       | 1.8             | 1.9             | 2.0             | 1.9             | 1.8             | 1.5                    |
|                | 60       | 2.1             | 2.2             | 2.4             | 2.2             | 2.2             | 1.8                    |
|                | 90       | 2.3             | 2.4             | 2.5             | 2.3             | 2.3             | 2.0                    |

**FIGURE 16** Improvement rate of the effective extraction radius of coal seam before and after stress relief
disintegration of the surrounding rock at 1 km depth in the Huainan Mining Area. This finding further indicates that the zonal disintegration is a general feature of fracturing for deep surrounding rock. Moreover, the deformation and failure of deep surrounding rock have a strong time rheological effect. The longer the time of roadway deforms, the larger the fractured zone and the higher the failure degree. The coal seam permeability within the stress-relief range of the floor roadway was improved significantly (with increment of 15%-45%), while the gas extraction concentration and quantity were both enhanced to high levels, shortening the gas extraction period. These results show that the floor roadway with short distance to coal seam has a stress relief and permeability enhancement effect on the upper seam strip.

Obviously, the shorter the distance between floor roadway and coal seam, the better the effects of stress relief and permeability enhancement on the coal seam. However, there are some potential risks in floor roadway driving close to a coal seam, such as outburst induced by unexpected uncovering of coal seam, the instability of the floor, and gas emission overrun. According to the Chinese coal mine safety regulations, the rock roadway should be at least 7 m away from the coal seam. In the investigation site, the distance between the floor roadway and the coal seam is about 9 m. Obviously, in the areas with abnormal geological structures such as faults, folds, or igneous rock intrusion, the distance between the floor roadway and the coal seam should be increased appropriately to ensure the safety of floor roadway driving. In that case, however, the stress-relief effect of the floor roadway on the coal seam will inevitably decline. Thus, in that case, local drilling and stress-relief methods including hydraulic cutting, hydraulic flushing, and hole cutting should be adopted to reduce the stress of coal in roadway strip.

It can be concluded that the zonal fracturing range and stress-relief degree of deep surrounding rock are the key factors influencing outburst prevention effect of the proposed method. Studies have shown that many factors affect the zonal fracturing shape and range of surrounding rock around deep roadways, such as vertical stress, axial stress, rock properties, and tunneling method and speed. However, the insights into mechanism underlying zonal disintegration of surrounding rock still remain ambiguous, and it is difficult
to clarify the quantitative relationship between the range of zonal disintegration of surrounding rock and the influencing factors such as stress distribution, geological condition, and dynamic loads. Therefore, the method proposed in this paper remains to be fully explored, and it is difficult to accurately calculate the range of coal seam stress relief according to the theories on zonal disintegration in present. With the progress of quantitative mechanism research on zonal disintegration, the core quantitative relationship of zonal disintegration occurrence and development conditions will be gradually revealed, and the analysis of the stress-relief range and degree of seam can be gradually improved to accurate quantification that will promote the progress of the proposed outburst prevention method.

7 | CONCLUSIONS

1. The elastic energy of coal and rock and the gas internal energy are the main energy sources of stress-dominated outburst in deep mines. The outburst prevention method for deep seams should simultaneously reduce both the elastic energy of coal and rock and the gas internal energy. Based on zonal disintegration characteristics of deep surrounding rock, an improved regional strip outburst prevention method, called strip stress relief combined with gas extraction through the stress-relief floor roadway, was proposed to eliminate the risk of outburst for coal roadway strip in deep mines.

2. The zonal disintegration phenomenon, which occurred in the surrounding rock of the investigation sites, induced the stress-relief effect on the upper coal seam. Fractured zone and nonfractured zone were alternatively distributed in the surrounding rock of deep floor roadways, the damage degree of surrounding rock weakened gradually, and the width of fractured area reduced gradually. The displacement of surrounding rock also presented the characteristics of alternative distribution of wave crest and trough. Moreover, the deformation and failure of surrounding rock presented a time-dependent rheological behavior. With increase of the distance from the driving face, the deformation and fracture range of surrounding rock increased gradually.

3. Under the stress-relief effect of the floor roadway, the permeability and extraction radius of seam strip were greatly increased. The seam permeability of measurement point right above the stress-relief floor roadway was 43 times higher than that of original seam, respectively, and 32 and 11 times higher at the 7.5 and 15 m side measurement points of the 720 roadway. The effective gas extraction radius of coal seam within the stress-relief range is improved by 15%-45%. In addition, the amount and concentration of daily gas extraction in the coal seam strip improve greatly, indicating that the gas extraction efficiency was enhanced significantly in the stress-relief strip of the roadway.

4. During the tunneling period of coal roadways, the values of outburst risk prediction indexes $K_1$ and $S$ of the working face were lower than the critical value, and the tunneling speed of the coal roadway improved from 40 m per month to 100 m per month. This indicates that the method proposed for prevention of regional outbursts in roadway strip can simultaneously reduce the ground stress and the gas content, and can effectively eliminate the outburst risk of coal roadway in deep mines.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, and the manuscript is approved by all authors for publication.

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