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*Research Article*

# Research on Permeability Enhancement Model of Pressure Relief Roadway for Deep Coal Roadway Strip

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Aiming at the problem of permeability enhancement in deep coal roadway strip, it proposed a pressure relief roadway permeability enhancement model, and the model was verified through experiments, theoretical calculations, and field tests. The experiment reveals that the unloading of gas-containing coal can achieve the effect of permeability enhancement. Theoretical calculation shows that with the increase of the distance from the coal seam, the overlying coal seam's permeability enhancement multiple and the width of the significant permeability enhancement zone gradually decrease, and the width of the general permeability enhancement zone gradually increases and then stabilizes. Field tests show that the pressure relief roadway is arranged 9 m directly below the coal seam; the overlying coal strata has a significant pressure relief and permeability enhancement effect. This research can provide reference value for the high-efficiency permeability enhancement in the deep coal roadway strip.

## 1. Introduction

With the increase of coal mining depth, most of the deep coal seams have the characteristics of low gas permeability [1–4], which has seriously affected the gas drainage of deep coal seams, especially in the coal and gas outburst areas of coal roadways. Gas drainage is difficult [5–8], long time for drainage to reach the standard [9, 10], and low drainage efficiency [11, 12]. For this reason, domestic and foreign studies have successively proposed hydraulic flushing [13–16], hydraulic slitting [3, 17, 18], hydraulic fracturing [19, 20], $CO_2$ fracturing [21–23], and high-pressure gas blasting [24]; these permeability enhancement technologies can increase the permeability of the coal seam, but there are still some shortcomings. For example, deep hole loosening blasting has disadvantages such as complex technology, hydraulic fracturing, which is prone to local stress concentration, and hydraulic slitting with a small pressure relief range. Therefore, it is an urgent to realize high-efficiency coal seam drainage and effective outburst prevention research on pressure relief and permeability enhancement in deep coal seams with high ground stress and low permeability.

In recent years, scholars at home and abroad have conducted a large number of studies on the failure characteristics of deep surrounding rocks through field investigation [25, 26], theoretical analysis [27–31], laboratory experiments [32, 33], numerical simulation [34–37], and other methods and found that deep surrounding rocks will appear zonal disintegration [38, 39], and studies have shown that the damage range of the zonal disintegration of the deep roadway surrounding rock is much larger than that of the shallow. From the perspective of roadway surrounding rock control, the damage and deformation of surrounding rock should be minimized. From the perspective of deep coal seam permeability enhancement, the regional fracture characteristics of deep surrounding rock not only have the effect of reducing the in-situ stress of the coal rock, but also can play a role permeability enhancement in the coal.

Therefore, the author proposes to arrange the coal roadway to be excavated within the pressure relief influence range of the pressure relief roadway. So it can relieve the overlying coal and rock layer the ground stress and increase the coal seam permeability in advance. It is expected to provide a reference for the permeability enhancement of coal roadway strip.

## 2. Permeability Enhancement Model of Pressure Relief Roadway

*2.1. Model Principle.* Coal roadway strip area generally uses floor rock roadway to gas drainage to prevent coal and gas outburst. Traditional floor rock roadways are usually arranged internally and externally horizontal distance 20~30 m below the coal roadway to be excavated (the internal and external horizontal distance is generally 15~25 m). It cannot be formed with a pressure relief and permeability enhancement effect to the overlying coal seam. Studies have shown that the surrounding rock of deep roadway will have zonal disintegration, and the fracture zone of surrounding rock in shallow roadway is only the first fracture zone of zonal disintegration in deep roadway, that is, the range of deep surrounding rock fracture is obviously larger than that of shallow [40–42].

Based on this, the author proposes to change the layout of the traditional floor rock roadway, arrange it directly under the coal roadway to be excavated, and appropriately reduce the distance between the pressure relief roadways and coal roadway. So it not only can relieve the pressure of the overlying coal seam, but also can increase the gas permeability of the coal seam. Floor rock roadway arranged in such a way is called "pressure relief roadways." After undergoing mechanical action by the excavation of the pressure relief roadway, it can reduce the stress of the surrounding rock over the pressure relief roadway and increase the gas permeability of the overlying coal seam. The author proposes that the surrounding rock stress that decreases more than 5% is called the surrounding rock stress relief zone, and the area where the coal seam permeability coefficient increases is called the coal seam pressure relief and permeability enhancement zone. According to the degree of coal fracture and the increase of coal seam permeability, the coal seam pressure relief and permeability enhancement zone can be divided into significant permeability enhancement zone $X_1$ and general permeability enhancement zone $X_0$.

Therefore, the author proposes the permeability enhancement model of pressure relief Roadway for deep coal roadway strip (shown in Figure 1). It is to study the impact range and effect of permeability enhancement on the overlying coal seam, when the pressure relief roadway is different distance from the seam. It is expected that the pressure relief roadway can be used to relieve pressure and increase the permeability of the coal seam in the coal roadway strip area. It can provide a new method for safe, economical, and efficient permeability enhancement and drainage in the deep coal road strip area.

*2.2. Model Parameters*

*2.2.1. Location of the Pressure Relief Roadway.* Figure 2 shows the calculation model of the surrounding rock plastic zone after the pressure relief roadway and coal roadway are excavated successively. $H_y$ and $h_m$ are the failure depths of the rock mass after the pressure relief roadway and coal roadway are excavated successively. After the pressure relief roadway and the coal road have been excavated successively, the overlying coal and rock layers have been subjected to twice pressure relief. In order to ensure the stability of the surrounding rock of the roadway and prevent coal and gas outburst, the pressure relief roadway and the upper coal seam should be prevented from forming a through failure zone. Then, the reasonable formula of the distance between the pressure relief roadway and the coal seam is

$$\Delta h \geq h_y + h_m. \tag{1}$$

After sorting out, the calculation formula changes to

$$\begin{cases} h_y = \delta \cdot R_y - (M - H) \\ h_m = \delta \cdot R_m - \dfrac{M}{2} \end{cases}. \tag{2}$$

In Formula (2), $\delta$ is the superposition coefficient of the secondary pressure relief effect, which can be calculated through on-site monitoring statistical analysis or simulation calculation. $R_y$ is the plastic zone radius of the pressure relief roadway, m. $R_m$ is the plastic zone radius of the coal roadway, m.

Combining Formulas (1) and (2), the criterion for the reasonable distance between the pressure relief roadway and the coal seam can be obtained as

$$\Delta h \geq \delta \cdot \left(R_y + R_m\right) - \left(\frac{3}{2}M - H\right). \tag{3}$$

*2.2.2. Scope of the Permeability Enhancement Zone.* Figure 3 shows the zoning characteristics of the surrounding rock formation of the roadway after the excavation of the pressure relief roadway, that is, the surrounding rock can be divided into the fracture zone, the plastic zone, the elastic zone, and the original rock stress zone.

Assuming that the radius of the stress relief zone is $r'$ (that is, the radius of the area where the stress reduction is not less than 5%), it can be seen from Figure 3 that when the stress reduction of the coal seam is 5%, it is located in the elastic zone. In polar coordinates, the vertical stress calculation formula is

$$\sigma_r = p_0 - \left(p_0 - \sigma_R^p\right)\left(\frac{R_p}{r'}\right)^2 = 0.95p_0. \tag{4}$$

In Formula (4), $\sigma_r$ is the vertical stress in polar coordinates. $R_p$ is the radius of the plastic zone. $P_0$ is the original

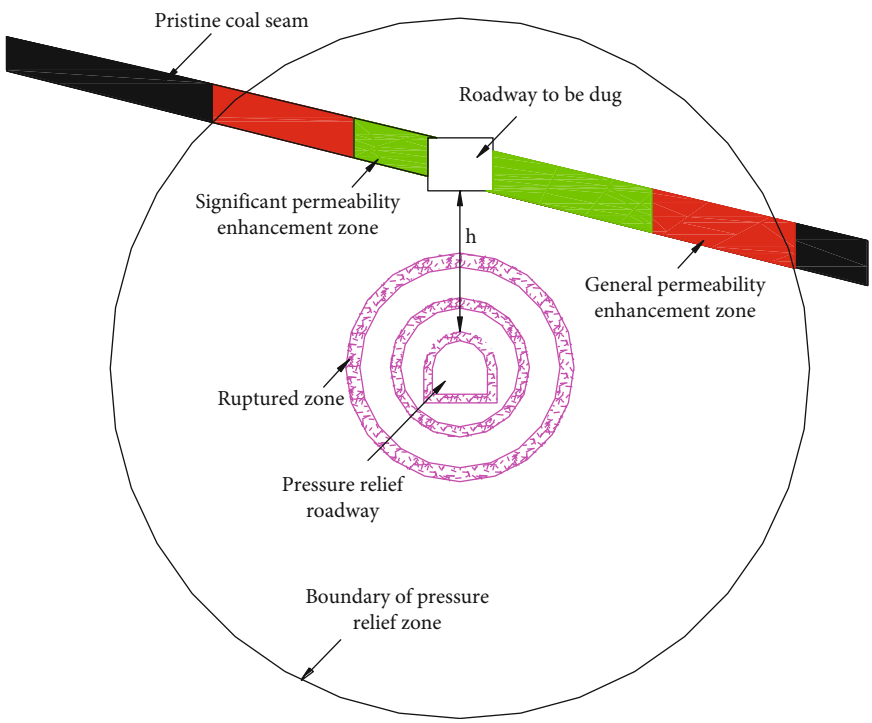



Figure 1: The model of pressure relief roadway for deep coal roadway strip.

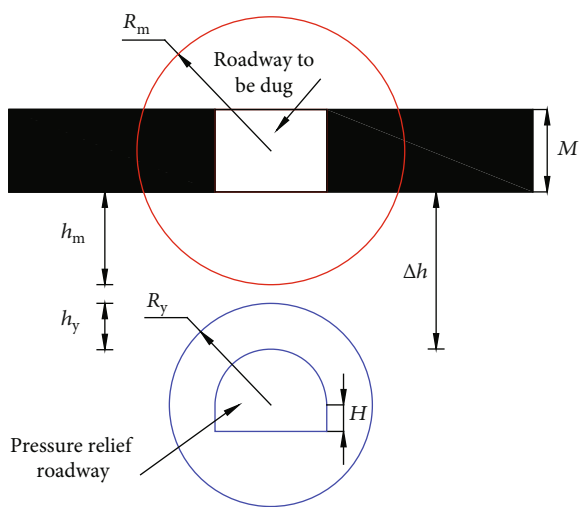



Figure 2: Calculation model of pressure relief roadway position.

rock stress. $\sigma_R^p$ is the vertical stress in the plastic zone.

$$r' = 2\sqrt{5}R_p\sqrt{1-\frac{\sigma_R^p}{p_0}}. \tag{5}$$

Combining the stress calculation formula and geometric relationship, the vertical stress calculation formula in the Cartesian coordinate system is

$$\sigma_y = p_0 - \frac{\left(p_0-\sigma_R^p\right)R_p^2}{\left(h^2+x^2\right)^2}\left(h^2-x^2\right). \tag{6}$$

In Formula (6), $h$ is the normal distance from the coal seam floor to the center of the roadway, m. $x$ is the distance in the horizontal direction, m. $\varphi$ is the angle between the radius $r$ and the vertical direction, °. $\sigma_y$ is the vertical stress in the Cartesian coordinate system, MPa.

After the excavation of the pressure relief roadway, the adsorbed gas becomes free gas in the upper coal seam and increases the gas stress in the coal seam. According to the coal sample unloading experiment, it can be seen that as the coal gas content increases, its uniaxial compressive strength will decrease. Its relationship conforms to the following formula:

$$\sigma_c = A_2 + B_2 \cdot p. \tag{7}$$

In Formula (7), $\sigma_c$ is the uniaxial compressive strength. $A_2$ and $B_2$ are parameters related to coal.

From the unified strength criterion:

$$\frac{\alpha_c}{1+b}\left(\sigma_x + b\sigma_z\right) - \sigma_y = \alpha\sigma_c. \tag{8}$$

In Formula (8), $\alpha$ is the ratio of the tensile strength of the rock. $b$ is the influence coefficient of the intermediate principal stress. $\sigma_x$, $\sigma_y$, and $\sigma_z$ are the stresses in the $X$, $Y$, and $Z$ directions, respectively, MPa.

Substituting Formulas (6) and (7) into Formula (8), and substituting pressure relief roadway layout conditions and related parameters of the overlying coal seam, it can obtain the width of the significant coal seam permeability enhancement zone $X_1$ and the width of the general coal seam permeability enhancement zone $X_0$.

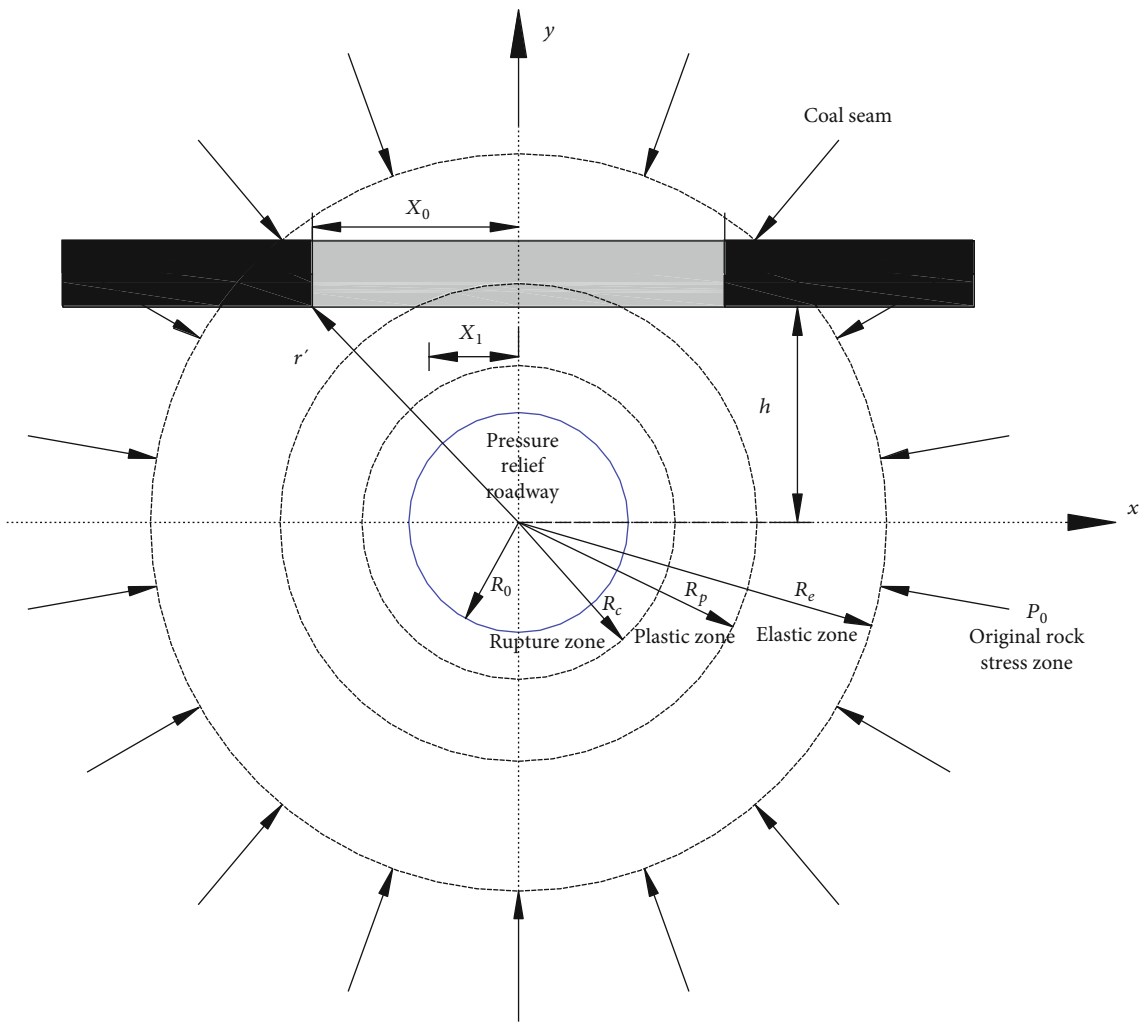



Figure 3: Calculation model of coal seam permeability enhancement.

(a) Press-formed test piece (b) Glued test piece

Figure 4: Physical image of rectangular coal briquette specimen.

Figure 5: Diagram of gas-solid coupling experiment device.

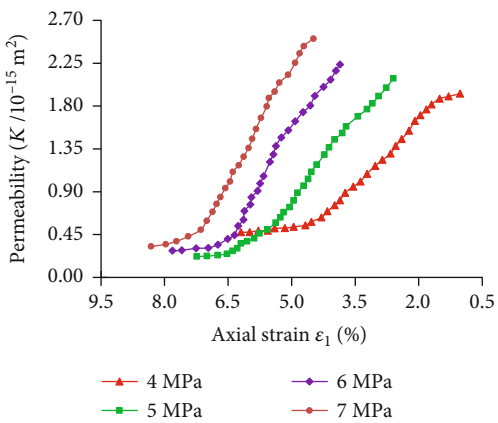



Figure 6: Axial unloading mechanics-permeability characteristic curves of different confining pressure specimens.

Table 1: The permeability enhancement effect of coal seams with different $\Delta h$.

| Distance from the center of the roadway $\triangle h$/m | Significant permeability enhancement zone $X_1$/m | General permeability enhancement zone $X_0$/m | Gas permeability increase multiple |
|---|---|---|---|
| 7 | 4.3 | 12.1 | 11.1~239.3 |
| 9 | 3.5 | 15.4 | 6.7~89.2 |
| 12 | 1.2 | 20.5 | 3.6~37.1 |
| 15 | 0.3 | 20.7 | 2.4~9.1 |
| 18 | 0 | 20.5 | 1.2~5.5 |
| 21 | 0 | 20.4 | 0.8~1.6 |

## 3. Model Verification

According to the principle of the model, the location of the pressure relief roadway and the range of the permeability enhancement zone are the main parameters of the model. Therefore, it proposed a method for determining the location of the pressure relief roadway and the range of the permeability enhancement zone, which provides a theoretical basis for the model.

*3.1. Unloading Seepage Experiment of Gas-Containing Coal.* In the unloading seepage experiment of gas-containing coal, it adopts the steady-state method to test the pressure relief and the change law of permeability in the cuboid standard coal sample, when the gas pressure of 1.5 MPa and different confining pressures ($\sigma_2 = \sigma_3 = 4$ MPa, 5 MPa, 6 MPa, and7 MPa).

The experimental raw coal was taken from coal seam $B_4$ of Qujiang Coal Mine in Fengcheng City, Jiangxi Province, China. There are three steps in coal sample preparation. First, the fresh coal sample of $B_4$ coal seam in Qujiang Coal Mine is pulverized and ground on a pulverizer, screened out the same amount of 20-40 mesh and 40-80 mesh coal powder sample base material, mixed with water evenly, and placed into the sample forming device. Secondly, it is pressed on a 100 t press for 30 minutes to form a rectangular parallelepiped standard coal specimen with a size of 100 mm × 100 mm × 200 mm (as shown in Figure 4). Thirdly, put it in a drying oven at 80 °C and dry it for 24 hours and then wrap it with insurance film for later use.

The experiment used 0.01 N/s to continuously apply axial pressure to 80% of the coal sample's compressive strength and then unload the axial pressure at 0.01 N/s until the coal body was damaged. Figure 5 is a diagram of the gas-solid coupling experiment device. Figure 6 shows the axial pressure unloading mechanics-permeability characteristic curves of different confining pressure specimens.

It can be seen from Figure 6 that during the process of fixed confining pressure and axial stress unloading, when the confining pressure increases from 4 MPa to 7 MPa, the permeability of the coal sample gradually increases, but the increase rate decreases, and the permeability $K$ increases from $1.93 \times 10^{-15}$ m$^2$ to $2.51 \times 10^{-15}$ m$^2$, the increase rate is 30.05%. Experiments show that with the increase of


Figure 7: Geographical location of Qujiang Coal Mine.

Table 2: Test content and test method.

| Test content | Test parameter | Drilling diameter (mm) | Drilling depth (m) | Test method | Remarks |
|---|---|---|---|---|---|
| Effect of surrounding rock relief | Destruction | 32 | 9 | YTJ20 rock detection recorder | |
| | Displacement | 32 | 9 | DW-6 multipoint displacement meter | 6 test points per drill hole |
| Effect of gas extraction | Coal permeability | 75 | 9~21 | Radial flow method [44] | Compare with the original coal seam |
| | Excavation diameter | 75 | 9~21 | Statistical analysis [45] | |

confining pressure, the axial pressure unloading permeability increases significantly, revealing that unloading can effectively increase the permeability of coal samples.

### 3.2. Theoretical Calculation of Coal Seam Permeability Enhancement Effect

*3.2.1. Calculation Method.* According to the axial stress unloading experiment of the gas-containing coal sample under the conditions of 4 MPa confining pressure and 1.5 MPa gas pressure, it obtained the fitting formula of gas permeability $K$ and $\sigma_1 - \sigma_3$:

$$K = A_3 \cdot e^{B_3 \cdot (\sigma_1 - \sigma_3)}. \tag{9}$$

In the formula, $A_3$ and $B_3$ are parameters related to coal body, stress and gas.

From the surrounding rock stress analysis, when $x < h$, the first principal stress is $\sigma_x$, and the third principal stress is $\sigma_y$; when $x > h$, the first principal stress is $\sigma_y$, and the third principal stress is $\sigma_x$. Therefore, the formula for permeability

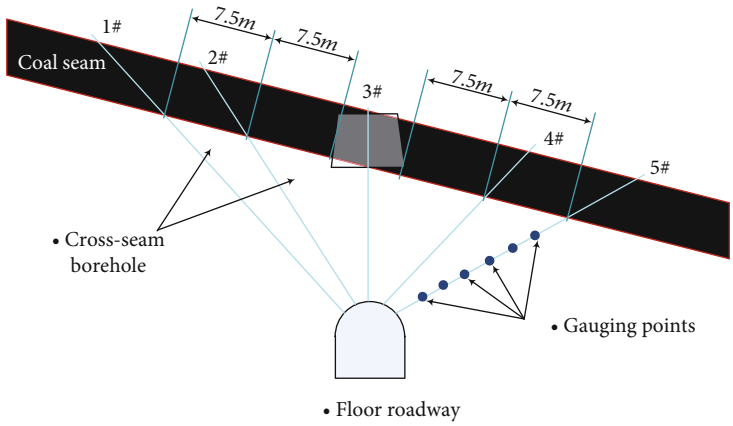
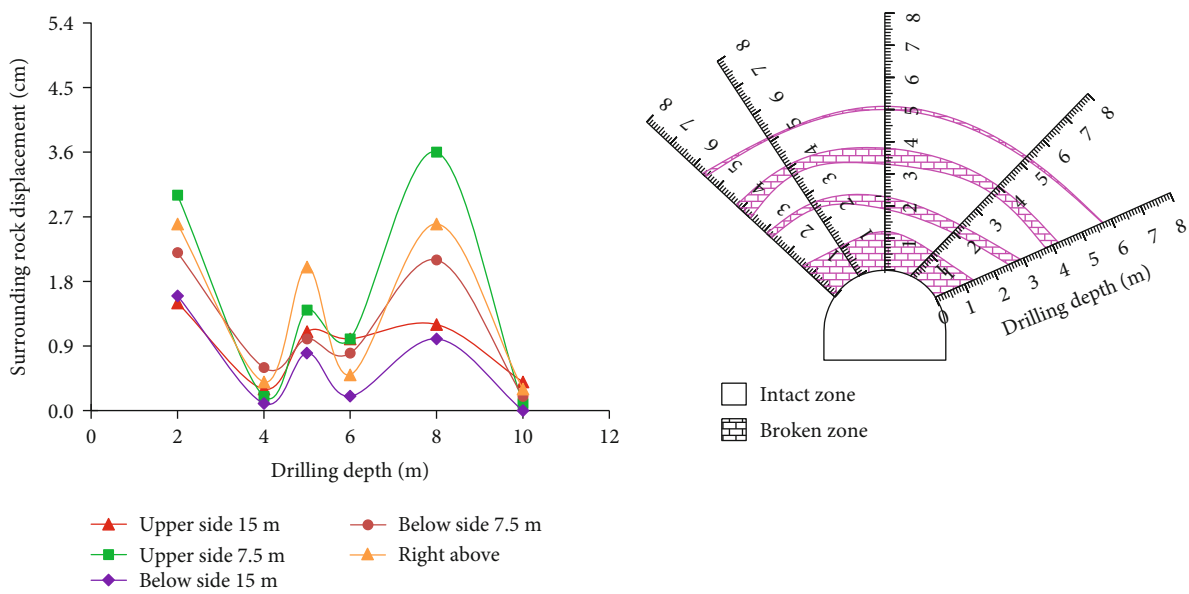



Figure 8: Test scheme.




(a) Displacement

(b) Surrounding rock failure

Figure 9: Pressure relief effect of surrounding rock in 213 pressure relief roadway.

$K$ and $\sigma_1 - \sigma_3$ can be sorted as

$$\begin{cases} K = A_3 \cdot e^{\left(2B_3 \cdot \left(p_0 - \sigma_R^p\right)\left(h^2 - x^2\right)R_p^2\right) / \left(\left(h^2 + x^2\right)^2\right)}, x < h \\ K = A_3 \cdot e^{-\left(2B_3 \cdot \left(p_0 - \sigma_R^p\right)\left(h^2 - x^2\right)R_p^2\right) / \left(\left(h^2 + x^2\right)^2\right)}, x > h \end{cases}. \quad (10)$$

The gas permeability of a coal seam is usually expressed by the gas permeability coefficient of the coal seam, and the relationship between the gas permeability coefficient of the coal seam and the permeability of a confined coal sample is as follows [43]:

$$\lambda = \frac{K}{2\rho p_n}. \quad (11)$$

In Formula (11), $\lambda$ is the coal seam permeability coefficient, $m^2/(MPa^2 \cdot d)$; $\rho$ is the absolute viscosity of gas ($CH_4$), $1.08 \times 10^{-8}$ N·s/cm$^2$; and $P_n$ is a standard atmospheric pressure, 0.1013 MPa.

Substituting Formula (10) into Formula (11), the relationship between the coefficient of coal seam permeability and the change in stress conditions can be obtained as

$$\begin{cases} \lambda = \dfrac{A_3}{2\rho p_n} \cdot e^{\left(2B_3 \cdot \left(p_0 - \sigma_R^p\right)\left(h^2 - x^2\right) \cdot R_p^2\right) / \left(\left(h^2 + x^2\right)^2\right)}, x < h \\ \lambda = \dfrac{A_3}{2\rho p_n} \cdot e^{-\left(2B_3 \cdot \left(p_0 - \sigma_R^p\right)\left(h^2 - x^2\right) \cdot R_p^2\right) / \left(\left(h^2 + x^2\right)^2\right)}, x > h \end{cases}. \quad (12)$$

*3.2.2. Enhancement Effect of Coal Seam Permeability.* Assuming that the coal seam confining pressure is 4 MPa and the gas pressure becomes 2 MPa after pressure relief,

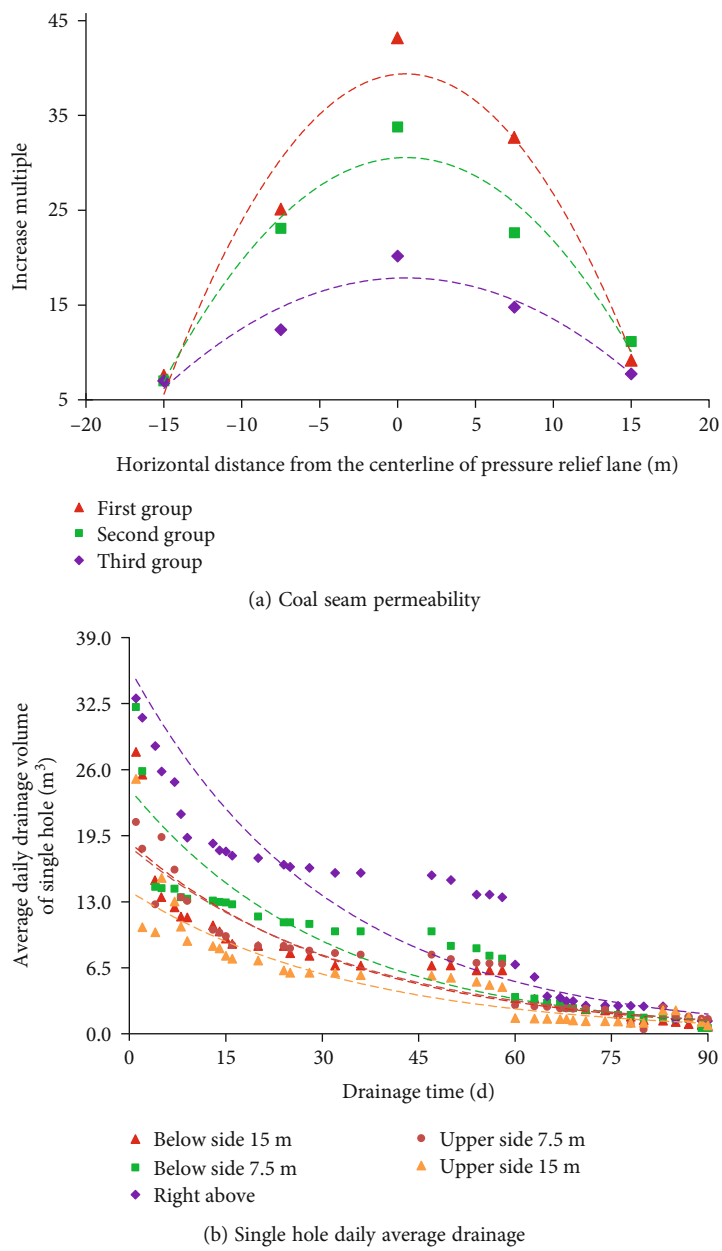



Figure 10: The permeability enhancement effect of the overlying coal seam above 213 pressure relief roadway.

regardless of the rheological effect of pressure relief of the roadway, substituting the rock formation conditions and the relevant parameters the 213 pressure relief roadway of Qujiang Coal Mine into the relevant formula, it can obtain $\sigma_R^P$=7.72 MPa⊠$K_0 = 2.4407 \cdot e^{-0.089\cdot(\sigma_x-\sigma_y)}$. It can obtain the effective pressure relief distance and the effect of increasing the permeability of the upper coal seam, when the distance between the coal seam and the floor roadway center is different $\Delta h$. It is shown in Table 1.

It can be seen from Table 1 that as the distance between the pressure relief roadway and the coal seam increases, the width of the significant enhancement zone and the coal seam permeability enhancement multiple are gradually reduced, and the width of the general enhancement zone gradually increases and then stabilizes.

When the layer spacing is 7 m, the maximum widths of the significant and general permeability enhancement zones are 12.1 m and 4.3 m, respectively, which are 5.4 times and 1.9 times the radius of the roadway; the maximum widths of the significant and general permeability enhancement zones are coal seam permeability enhancement multiples which are, respectively, 239.3 times and 11.1 times that of the original coal seam.

When the interlayer spacing is 18~21 m, the significant coal seam permeability enhancement zone is 0, the general coal seam permeability enhancement zone is 9.1 times the radius of the roadway, and the maximum coal seam permeability enhancement multiples of the significant coal seam permeability enhancement zone and the general coal seam permeability enhancement zone are 5.5 times and 1.6 times

of the original coal seam, that is, the overlying coal seam's permeability enhancement effect is not significant.

### 3.3. Field Test of the Coal Seam Permeability Enhancement

*3.3.1. Test Scheme.* Based on the abovementioned experiments and theoretical calculations, field tests were carried out. It tests the effect of permeability enhancement of the overlying coal seam. The test site is also the Qujiang Coal Mine in Fengcheng City, Jiangxi Province, China. Figure 7 shows the geographical location of the Qujiang Coal Mine. The 213 pressure relief roadway is arranged 9 m directly below the roadway to be excavated, which is about 1000 m in ground buried depth. The measured coal seam permeability coefficient of the test area is 0.002 $m^2/MPa^2$•d, which is a deep low-permeability coal seam.

The test content is the pressure relief effect of the surrounding rock and the permeability enhancement effect of the coal seam. The test area is 15 m from the upper and lower sides of the overlying coal rock above the 213 pressure relief roadway. As shown in Table 2. Figure 8 shows the layout of the test boreholes, with 5 test boreholes arranged for each parameter.

*3.3.2. Enhancement Effect of Coal Seam Permeability.* Figure 9 is the pressure relief effect of the overlying strata above the 213 pressure relief roadway. Figure 10 is the coal seam's permeability enhancement effect above the 213 pressure relief roadway. It can be seen from Figure 9(a) that the maximum displacement of the surrounding rock of the roadway is 3.6 cm, and the displacement of the surrounding rock shows the phenomenon of "wave crest" and "wave trough" alternately. The same law is also obtained in laboratory physical simulation [46, 47]. It can be seen from Figure 9(b) that the surrounding rock of the roadway appears divided into zones, that is, four fracture zones appear from the outside to the inside of the roadway, and the maximum influence range of the fracture zone is 5.7 m. It can be seen from Figure 10(a) that the permeability coefficient of the pressure relief coal seam is 7.0-43.2 times higher than that of the original coal seam. It can be seen from Figure 10(b) that the maximum single-hole daily average drainage is 31.1 $m^3$/d, which is 3 times larger than the original coal seam (maximum 7.7 $m^3$/d). It shows that the overlying coal and rock layers of the 213 pressure relief roadway have a significant effect on pressure relief and permeability enhancement. The test results are consistent with the aforementioned research rules (although there are other objective factors in the test area), verifying that the model is feasible and effective for pressure relief and permeability enhancement.

## 4. Discussion

Based on the zonal disintegration of the surrounding rock in the deep roadway, it is proposed to arrange the pressure relief roadway directly under the coal roadway to be excavated to increase the pressure relief of the overlying coal seam. The coal seam pressure relief and permeability enhancement model is carried out at the appropriate position directly below the roadway, which realizes the safe, economical, and efficient permeability enhancement of the deep seam coal roadway strip area. However, the research still needs to be improved. First, there is a time rheological effect in the pressure relief zone of the pressure relief roadway [48], so the time rheology effect on the overlying coal roadway needs further study. Second, this model only studies the experimental results under specific conditions, and the pressure relief and permeability enhancement effects under different gas geological conditions (such as coal seam dip, coal thickness, lateral pressure coefficient, buried depth, and geological structure) need further research. Third, this model only studies the pressure relief and permeability enhancement effects of single factors such as ground stress and gas, and the coupling effect of the two needs to be further studied.

## 5. Conclusion

(1) Based on the zonal disintegration of the surrounding rock in the deep roadway, the area is defined as the stress relief area of the surrounding rock above the pressure relief roadway, where the stress reduction is more than 5%. It is defined the pressure-relief and permeability enhancement area of the overlying coal seam. It constructed a permeability enhancement model of pressure relief roadway for the of deep coal roadway strip, which provides a new method for deep coal roadway strip pressure relief and permeability enhancement

(2) The unloading seepage experiment of gas-containing coal shows that unloading can effectively increase the permeability of the coal sample. Calculations show that with the increase of the distance from the coal seam, the overlying coal seam's permeability enhancement multiple and the significant permeability zone width gradually decrease and the width of the permeability enhancement generally zone gradually increases and then tends to be stable. When the pressure relief road is 7 m away from the coal seam, the widths of the significant and general enhancement zones are, respectively, 5.4 and 1.9 times the radius of the roadway. When the pressure relief roadway is 18-21 m away from the coal seam, the widths of the significant and general enhancement zones are 0 times and 9.1 times the radius of the roadway, respectively. It provides a theoretical basis for the location of the pressure relief roadway

(3) Field tests show that when the pressure relief roadway is located 9 m directly below the coal seam, the overlying coal strata has a significant pressure relief and permeability enhancement effect. The maximum displacement is 3.6 cm of the surrounding rock of the pressure relief roadway, the maximum influence range of the fracture zone is 5.7 m, and the coal seam permeability coefficient is increased by 7.0~43.2 times, and the maximum daily average drainage volume of a single hole has increased by 3 times. It has

realized safe, economical, and efficient permeability enhancement and drainage in the deep coal seam strip area, which provides a certain reference for the permeability enhancement of the coal road strip area in similar coal seams

## Data Availability

All data included in this study are available upon request from the corresponding author.

## Conflicts of Interest

The authors declared that they have no conflicts of interest to this work.

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