Effects of drilling parameters on stress relief performance during mining

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Abstract: This study investigated the effects of borehole diameter and borehole interval on the stress relief performance of coal seams during mining. A discrete element numerical model was established based on the Voronoi and block models, and the stress relief performance was investigated in terms of axial stress, vertical displacement, and plastic zone development using the control variates method. The results showed that a decrease in the distance from the workface was accompanied by an increase in the effects of mining, the stress concentration, and the vertical displacement of the roof. Coal mining had positive effects on fracture propagation in front of the workface. As the borehole interval increased, the density of boreholes in the coal seams decreased, reducing the stress concentration and fracture propagation in front of the workface. The stress relief performance of the boreholes in the coal seams was improved at a borehole interval of 8 m. However, as the borehole diameter increased, the stress concentration near the boreholes decreased, reducing the effects of the workface mining on stress relief through the boreholes. Meanwhile, increasing the borehole diameter decreased the vertical displacement of the roof but exacerbated fracture propagation in front of the workface, which improved the stress relief performance of the boreholes in the coal seams. This study provides a reference for arranging boreholes in coal seams during mining.

Keywords: mining conditions; drilling parameters; high crustal stress; stress relief performance; fracture propagation
1. Introduction

As the mining depth of a coal seam increases, the tunnel’s rock wall environment becomes increasingly complex. As such, the “three highs and one disturbance” phenomenon becomes more serious. This phenomenon primarily includes problems such as rock burst and tunnel deformation, which seriously threaten the safety and production efficiency of underground coal mining (Qi et al. 2020). Stress relief using boreholes is an effective measure for tackling the problem of high crustal stresses encountered during deep coal mining, and the performance of the measure depends on physical and mechanical parameters (e.g., hardness and tensile strength), the burial depth of the coal seam, geological occurrences, and drilling parameters such as the effects of borehole arrangement and borehole diameter (Chen et al. 2019, Tan et al. 2020, Zhu et al. 2024). This study focused primarily on the influence of drilling parameters on stress relief performance during mining; the stress, displacement, and plastic zone evolution at different borehole diameters and borehole intervals were investigated and compared.

In a bid to address various problems encountered in using boreholes to achieve stress relief in coal seams, several scholars have developed and optimized various technologies while studying the corresponding stress relief performances. Zhang et al. proposed an innovative monitoring-while-drilling (MWD) technology using a microseismic system (MS) to monitor vibration signals during drilling (Zhang et al. 2021). Gu et al. proposed the stress relief mechanism of segmented expanded drilling (Gu et al. 2022). Li et al. discussed a stress relief mechanism comprising the combination of variable-diameter boreholes, which showed the potential to enhance the plastic properties of the coal-like specimens (Li et al. 2022). Zhang et al. evaluated the relationship between the stress relief of large-diameter drill holes and the drilling layout by studying the angle of elastic energy dissipation, the stress transmission, and the distribution law of the stress relief zone (Zhang et al. 2020a). Zhang et al. used the permeability related to the stress path to simulate the stress relief performance of a protective layer during the mining of the upper coal seam (Zhang et al. 2018, 2020b). Xu et al. used electromagnetic CT to evaluate the stress relief
performance of boreholes in coal seams (Xu et al. 2022). Bi et al. used numerical simulations to investigate the sealing degree of a tunnel stress relief zone and found the permeability can determine the connection between a borehole’s wall rock fracture and a free surface (Bi et al. 2022). Gao et al. proposed a method for controlling the stress relief gas in a goaf using high directional long drilling holes. They conducted effect tests and obtained the flow process and distribution characteristics of the stress relief air in the goaf based on the distribution characteristics of the stress relief gas fields in mining fracture fields (Gao et al. 2021).

Many researchers have also compared and analyzed the stress relief performance of drilling parameters in different coal seams from different perspectives. Zhao et al. used the large-diameter stress relief model to study the energy dissipation and accumulation characteristics of coal under different mining depths and different stress relief hole spacings (Zhao et al. 2023). Liang et al. used numerical simulations to study the indoor acoustic emission characteristics of boreholes of different diameters (Liang et al. 2021). Zhai et al. used a triaxial loading system and acoustic emission monitoring system to study the discharge behavior of drilling cuttings (Zhai et al. 2018). Cui et al. investigated the characteristics of stress, displacement, strain energy, and plastic zone of a tunnel’s wall rock under different diameters, depths, and spacings of large-diameter boreholes (Cui et al. 2022). Wang et al. used the model for hole mechanics to deduce the connection between drilling and elastic strain energy (Wang et al. 2023). Gu et al. studied the energy evolution and damage behavior of coal samples with holes through acoustic emission tests under uniaxial compression (Gu et al. 2023). Peng et al. thoroughly investigated the effects of borehole arrangement on stress relief performance on rock walls; they obtained the degree of strength reduction, acoustic emission evolution laws, and failure modes for rock samples at different excavation locations, spacings, and tilt angles (Peng and Liu 2021). Cao et al. studied the stress relief characteristics of gassy coal in a deep tunnel and the deformation characteristics of the rock wall (Cao et al. 2022). Xie et al. combined numerical simulation, field monitoring data, and theoretical analysis to detect high stress concentration zones (Xie et al. 2018). Du et al. simulated and
analyzed the high-stress tunnel rock wall response affected by strike-slip stress distribution under different drilling and stress relief parameters (Du et al. 2024).

In summary, researchers have thoroughly investigated the technical mechanisms of using boreholes for stress relief in coal seams. Additionally, the performance of approaches using different drilling parameters has been investigated. These efforts have yielded significant advances. However, the disturbance effects of pressure-relieving boreholes on coal seam mining have not been extensively considered. Therefore, this study focused on the influence of borehole diameter and borehole interval on stress relief performance under deep coal mining conditions. The findings of this study provide theoretical support for optimizing the stress relief parameters of boreholes and enhancing their stress relief performance in coal seams.

2. Geological condition of mine

The 8# coal seam of a mine was the object of this study. The influence of the borehole diameter and borehole interval on the stress relief performance during mining was analyzed using crustal stress and plastic zone displacement and development. Fig. 1 shows the bar chart of the borehole in the coal seams. The physical and mechanical parameters of different rock layers are shown in Table 1. For the convenience of numerical simulations, the coal lines on the floor and roof of the 8# coal seam were ignored.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Bulk density (kg/m³)</th>
<th>Elastic modulus (GPa)</th>
<th>Cohesive force (MPa)</th>
<th>Internal friction angle (°)</th>
<th>Poisson's ratio</th>
<th>Tensile strength (MPa)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mudstone</td>
<td>2500</td>
<td>4.97</td>
<td>0.50</td>
<td>12</td>
<td>0.31</td>
<td>1.00</td>
<td>35</td>
</tr>
<tr>
<td>Coal</td>
<td>1400</td>
<td>1.50</td>
<td>0.30</td>
<td>11</td>
<td>0.38</td>
<td>1.10</td>
<td>18</td>
</tr>
<tr>
<td>Siltstone</td>
<td>2750</td>
<td>4.88</td>
<td>0.55</td>
<td>12</td>
<td>0.29</td>
<td>0.91</td>
<td>54</td>
</tr>
<tr>
<td>Fine sandstone</td>
<td>2650</td>
<td>4.52</td>
<td>0.53</td>
<td>12</td>
<td>0.30</td>
<td>0.98</td>
<td>50</td>
</tr>
<tr>
<td>Sandy mudstone</td>
<td>2550</td>
<td>3.90</td>
<td>0.50</td>
<td>12</td>
<td>0.32</td>
<td>0.92</td>
<td>30</td>
</tr>
</tbody>
</table>
3. Model establishment and monitoring points arrangement

To study the influence of different drilling parameters on the stress relief performance, Universal Distinct Element Code (UDEC) was used to build a discrete element numerical model with dimensions of 40 m × 20 m (see Fig. 2). We compared the stress relief performances of different drilling parameters during mining and monitored the stress relief induced by drilling holes in front of a workface in the plastic zone of the coal seams. The immediate roof and immediate floor were constructed using the Voronoi model, while the other rock formations were constructed using the block model.

As shown in Fig. 2, boreholes were arranged at a certain borehole interval along the advance direction of the workface in the coal seam tunnel. The open-off cut of the workface was 5 m in length, and the advance distance was 4, 8, and 12 m, respectively. The fissure monitoring area was set in front of the advancing mining area in the coal seam, and eight monitoring points (point 1–8) were set equidistant at the point where the coal seam was in contact with the immediate floor. These monitoring points were used to monitor the change in vertical stress on the immediate floor after the drilling stress relief under mining conditions. Meanwhile, eight other monitoring points (point 9–16) were arranged where the coal seam and the direct roof contact were in sequence;
these other monitoring points were used to monitor the change in the vertical
displacement of the direct top after drilling stress relief under mining conditions. Fig.
2 illustrates the specific fracture monitoring area and monitoring points arrangement.

![Figure 2. Initial model and monitoring points layout](image)

4. Setting of drilling parameters for stress relief

The control variates method was used to compare the effect of the borehole
diameter and borehole interval on the stress relief performance of the coal seam. The
stress relief performances of boreholes with diameters of 0.1 m, 0.15 m, and 0.2 m
were compared for an borehole interval of 10 m. The borehole interval and borehole
diameter arrangement are illustrated in Fig. 3. Similarly, the stress relief performances
of boreholes with borehole intervals of 5 m, 8 m, and 10 m were compared for the
borehole diameter of 0.15 m. Fig. 4 illustrates the settings of the borehole interval and
borehole diameter.

![Figure 4. Setting of borehole interval and borehole diameter](image)
5. Stress relief performance of drilling

5.1 Stress relief performance of boreholes under different advancing distances

As this study mainly focused on the stress relief performances of the boreholes during mining, it was necessary to also compare the stress relief performance of the boreholes at different advancing distances of workface. Fig. 5 illustrates the coal seam roof and floor fracture propagation at different advancing distance of the workface at an borehole interval of 10 m and a borehole diameter of 0.15 m. As the coal mining face advanced, the roof gradually collapsed, and the roof and floor fracture propagation areas were gradually enlarged. Because of the pressure-relieving boreholes in the coal seam, the fracture propagation generated by the mining disturbance extended further after drilling, that is, the boreholes in the coal seams promoted the development of mining fractures. The stress relief performance was also
high.

(a) Open-off cut                   (b) Advance distance of 4 m

(c) Advance distance of 8 m       (d) Advance distance of 12 m

Figure 5. Development of fractures at different advance distances

Regarding the impact of the block effect caused by the size of the Voronoi block on the simulation results, due to insufficient computer computing power, the size of the Voronoi block had to be set to be equivalent to the size of the borehole. We once attempted to set the size of the Voronoi block to a smaller size, but when simulating software to generate the block, there was a phenomenon of freezing due to insufficient computer memory. In addition, in the simulation of coalbed methane surface drilling and gas extraction, it is required to set the Voronoi block as small as possible to avoid the influence of block effect on the results. However, in the process of coal mining, the influence of the size of the Voronoi block on the pressure relief effect of mining boreholes can be almost negligible.

Figs. 6 and 7 illustrate the axial stress and vertical displacement of different monitoring points as the workface advanced at a borehole diameter of 0.15 m and an borehole interval of 10 m. As observed in the figure, as the workface advanced, the axial stress on the floor and the vertical displacement of the roof gradually increased. Additionally, the increments of the axial stress and vertical displacement rose as the workface advanced further, until it reached the front of the monitoring points. When the axial stress rapidly decreases and is released, the vertical displacement peaks, and
roof is likely to collapse. A comparison of the axial stress and vertical displacement among different monitoring points showed that the closer the monitoring points were to the workface, the greater the disturbance, the higher the stress concentration, and the larger the roof’s vertical displacement.

Figure 6. Axial stress of coal seam floor under different advancing distances

Figure 7. Vertical displacement of coal seam roof under different advancing distances

5.2 Effects of drilling parameters on stress relief performance

(1) Stress relief performance at different borehole intervals

Figs. 8 and 9 show the axial stress of monitoring point 1 and the vertical displacement of monitoring point 9 as the workface advanced for a borehole diameter of 0.15 m and with varying borehole intervals. As observed, with the continuous advancement of workface, the axial stress at monitoring point 1 gradually increased until it reached the front of monitoring point 1, causing a sharp decrease in axial stress.
until it collapsed. Similarly, the vertical displacement of monitoring point 9 gradually increased until the roof collapse reached the maximum level. Meanwhile, the rate of increase of the axial stress and vertical displacement also gradually rose as the workface advanced. A comparison of the axial stress of monitoring point 1 at different borehole intervals shows that before the workface advanced to 8 m, the rate of increase of the axial stress at monitoring point 1 slowly decreased as the borehole interval increased. This result suggests that as the borehole interval increases, the stress concentration in front of the workface decreases as a result of the reduced density of boreholes in the coal seams. During the workface advancement from 8 m to 12 m, the borehole interval at 8 m underwent the fastest reduction in axial stress: thus, compared with the borehole intervals at 5 m and 10 m, the stress relief performance of the boreholes in the coal seams was optimized at an borehole interval of 8 m. As the borehole interval increased further, a relatively small change in the vertical displacement occurred at monitoring point 9. This result indicates that the stress relief performance varies for different borehole intervals but does not cause any significant changes in the vertical displacement of the coal seam.

![Figure 8. Axial stress of measuring point 1 for different hole spacings](image-url)
**Figure 9.** Vertical displacement of measuring point 1 for different hole spacings

Fig. 10 illustrates the variation in the proportion of fractures that developed in the fracture monitoring area in front of the workface when the borehole diameter was 0.15 m while the borehole interval varied. The figure shows that as the workface advanced, the proportion of fractures in the fracture monitoring area in front of the workface, as well as its growth rate, slowly increased. Additionally, as the borehole interval increased, the proportion of fractures in the fracture monitoring area in front of the workface gradually decreased, which suggests that coal mining promotes fracture propagation in front of a workface. Moreover, the increase in the borehole interval reduced the fracture propagation in front of the workface.

**Figure 10.** Proportion of fracture areas with different hole spacings

(2) Stress relief performance at different borehole diameters

Figs. 11 and 12 illustrate the axial stress and vertical displacement as the
workface advanced when the borehole interval was 10 m while the borehole diameter varied. As observed in the figure, the continuous advancement of the workface was followed by a corresponding gradual increase in the axial stress of monitoring point 1 until the workface reached the front of monitoring point 1, causing a sharp decrease in axial stress until the roof collapsed. The vertical displacement of monitoring point 9 gradually increased until the roof collapsed and reached its peak vertical displacement. Meanwhile, the growth rates of axial stress and vertical displacement also increased as the workface advanced. A comparison of the axial stress curves of monitoring point 1 for different borehole diameters shows that as the borehole diameter increased before the workface advanced to 8 m, the increase in the axial stress of monitoring point 1 gradually decreased. This result suggests that the increase in the borehole diameter reduced the stress concentration in the surrounding boreholes. During the advancement of the workface from 8 m to 12 m, as the borehole diameter increased, the reduction in the axial stress at monitoring point 1 decreased, which suggests that the increase in the borehole diameter can lower the impact of stress relief due to the workface advancement. A comparison of the vertical displacement of monitoring point 9 for different borehole diameters shows that as the borehole diameter increased, no significant vertical displacement occurred at monitoring point 9 for borehole diameters of 0.1 m and 0.15 m, whereas the vertical displacement of monitoring point 1 at a borehole diameter of 0.2 m reduced significantly, which suggests that the increase in borehole diameter limits the vertical displacement of the roof.

Figure 11. Axial stress of measuring point 1 under different diameters
Figure 12. Vertical displacement of measuring point 1 under different apertures

Fig. 13 illustrates the proportion of developed fractures in the fracture monitoring area in front of the workface when the borehole interval was 10 m while the borehole diameter varied. The figure shows that as the workface advanced, the proportion of fractures, in addition to the growth rate, gradually increased. Further, as the borehole diameter increased, the proportion of fractures in the monitoring area gradually increased. This result suggests that coal mining promotes fracture propagation in front of a workface; additionally, the fracture propagation increases as the borehole diameter increases, thus increasing the stress relief performance of the borehole in coal seams.

Figure 13. Proportion of fracture areas with different diameters

6. Conclusions

In this study, the Voronoi and block models were used to create a discrete element numerical model. The model and the control variates method were used to
investigate the effects of borehole diameter (0.1, 0.15, and 0.2 m) and borehole interval (5, 8 and 10 m) on the stress relief performance of boreholes in coal seams during mining. Axial stress, vertical displacement, and plastic zone development were the variables considered. The following conclusions were drawn from the study:

(i) As the workface advanced, the axial stress of the floor and the vertical displacement of the roof gradually increased, and their rates of increase also increased slowly. The axial stress decreased rapidly and was released when the workface advanced near the monitoring points; meanwhile, the vertical displacement peaked, and the roof was likely to collapse. The boreholes in the coal seams aggravated the development of mining fractures, resulting in a significant stress relief performance. The closer the roof to the workface was, the more serious the mining influence, the more obvious the stress concentration, and the greater the roof’s vertical displacement.

(ii) As the borehole interval increased, the density of the boreholes in the coal seams decreased, reducing the stress concentration in front of the workface. Compared with the borehole intervals of 5 m and 10 m, that of 8 cm had the best stress relief performance of the boreholes in the coal seams. Meanwhile, the change in borehole interval had a different effect on the stress relief in the coal seams and caused no significant changes to the vertical displacement of the coal mine. The increase in borehole diameter reduced the stress concentration in areas near the boreholes, thus lowering the impact of the workface advancement on the stress relief of the borehole. Additionally, the increase in the borehole diameter reduced the vertical displacement of the roof.

(iii) The workface advancement was followed by a gradual increase (and rate of increase) in the proportion of propagating fractures in the fracture monitoring area in front of the workface. Coal mining promoted fracture propagation in front of the workface, and the increase in the borehole interval reduced the fracture propagation in front of the workface. Meanwhile, the increase in the borehole diameter exacerbated the fracture propagation in front of the workface, thus increasing the stress relief performance of the boreholes in the coal seams.
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Data Availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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