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Effect of Pressure Relief Hole Spacing on Energy Dissipation in Coal Seam at Various Mining Depths

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Abstract: The large diameter pressure relief borehole is one of the most effective technical means to prevent and control rockburst during deep mining. Based on the engineering background of rockburst mines, the mechanical model of coal energy dissipation of large diameter pressure relief holes is established by theoretical analysis, and the approximate formula for calculating energy dissipation of coal is obtained. Combined with numerical simulation methods, the energy accumulation and dissipation laws of coal under various mining depths and the various spacings of pressure relief holes is studied. The results show that the upper and lower ends of the pressure relief holes have the highest degree of energy dissipation and the largest range of energy dissipation. While the energy dissipation effect on the left and right sides of the pressure relief holes is poor, a high accumulation of elastic strain energy occurs at a certain distance on the left and right sides of the relief holes. The dissipated energy of the coal seam increases continuously with the increase in mining depth and the decrease in spacing of pressure relief holes. The dissipated energy rises especially suddenly when the hole spacing changes from 1.0 m to 0.5 m. For coal seams with high rockburst risk, the spacing of pressure relief holes can be set to be less than or equal to 0.5 m, which can greatly improve the energy dissipation effect of coal seams. The studies can provide a theoretical basis for the optimization parameters of pressure relief holes for rockburst prevention.

Keywords: pressure relief holes; mining depth; dissipated energy; numerical simulation; rockburst

Citation: Zhao, H.; Pan, Y.; Lyu, J.; Peng, Y.; Li, S. Effect of Pressure Relief Hole Spacing on Energy Dissipation in Coal Seam at Various Mining Depths. *Sustainability* **2023**, *15*, 3794. https://doi.org/10.3390/su15043794

Academic Editor: Adam Smoliński

Received: 1 January 2023
Revised: 29 January 2023
Accepted: 17 February 2023
Published: 19 February 2023

1. Introduction

With the increase in mining depth of coal seams year by year, dynamic coal rock phenomena occur frequently, and can even evolve into rockburst disasters, which cause extensive damage to the surrounding rock of roadways [1–9]. For coal seams at risk of rockburst, localized hazard relief measures are often used for effective prevention and control [10–13]. Among them, a large diameter borehole for pressure relief is one of the most effective technical means to prevent rockburst, and is simple and practical [10]. Many experts and scholars at home and abroad have carried out research on the influence of parameters such as size and spacing of pressure relief boreholes on the effect of rockburst prevention. Wang Aiwen et al. [14] performed uniaxial compression tests on prefabricated borehole specimens and used acoustic emission and digital image correlation monitoring technology to analyze the burst tendency, deformation failure, and energy accumulation and release of borehole specimens. Additionally, it is believed that the borehole pressure relief can reduce the accumulated strain energy before the peak, and reduce the energy release per unit time after the peak, making the sample less prone to dynamic damage. Qi Qingxin et al. [10,13,15] considered that large diameter boreholes are more suitable for stress relief of large areas in part of the stope, which also can reduce elastic energy accumulation. According to the research results of Jia Chuanyang et al. [16], the stress release caused by crack extension and penetration in the coal surrounding the boreholes is the main reason for the pressure relief effect of the boreholes. The larger the hole diameter and depth, and the smaller the hole spacing, the better the pressure relief effect is. Li Yunpeng et al. [17] proposed a distributed optical fiber technology to evaluate the effect of boreholes for pressure relief, and divided the process of pressure relief into four stages: fracture development, ultimate equilibrium, hole collapse, and crushed coal compaction. Liu Honggang et al. [18] studied the action principle of boreholes for pressure relief and the damage–failure process of the surrounding rock of the roadway, and considered that a reasonable arrangement of pressure relief boreholes can make the roadway side wall produce structural pre-cracking and transfer the surrounding rock stress to deeper areas. Ge Decheng et al. [19] studied the reasonable spacing of pressure relief holes of coal with different strengths and discovered a linear relationship between reasonable pressure relief hole spacing and coal strength. Tong-bin Zhao [20], Bin Huang [21], and other researchers have studied the pressure relief mechanism of boreholes and its reasonable parameters using uniaxial experiments, numerical simulations, and other methods. In particular, Tong-bin Zhao [20] found that the bursting energy index decreases with an increase on the drilling diameter or the number of drilling holes in one row, but that increasing the number of drilling rows did not lead to an obvious change in bursting energy index. Fan Feng et al. [22] applied numerical simulations to investigate the failure characteristics and crack extension process of central holes of various shapes. The above studies have analyzed the mechanism and influencing factors of boreholes for pressure relief from the perspective that the deformation and failure of boreholes can reduce the stress of coal, which has a certain significance for guiding engineering practice. However, the degree of energy dissipation in the coal seam varies under the conditions of various mining depths and various hole spacings. Additionally, the pressure relief holes not only dissipate the elastic strain energy of the coal seam, but also cause the energy to transfer and accumulate to the lateral coal of pressure relief holes. Correctly understanding the effect of pressure relief hole spacing on coal seam energy dissipation at various mining depths is an important basis from which to guide engineering practice.

For this study, rockburst mines were taken as the engineering background and a combination of theoretical analysis and numerical simulation was used to carry out a study on the dissipated energy effect of pressure relief holes based on various mining depths and pressure relief hole spacings. The study can reveal the law of energy dissipation in coal seams by the various spacing of pressure relief holes at various mining depths, which can provide a theoretical basis for parameter optimization of pressure relief holes for rockburst prevention.

2. Energy Dissipation Mechanism of Pressure Relief Holes

The deep coal seam is an environment with a complex and intense stress field, which causes the deep coal-rock to accumulate a large amount of elastic strain energy. If pressure relief holes with a large diameter are employed in the coal seam, it can cause loose damage to the coal around the hole. The stress around the holes decreases and transfers to a distant site, dissipating the accumulated elastic strain energy to a certain extent and reducing the possibility of rockburst in the coal mine [23,24].

As shown in Figure 1, $\boldsymbol{P}$ is the vertical load and λ indicates the coefficient of lateral pressure. After the formation of large diameter pressure relief holes, a part of elastic strain energy stored in the coal around the holes is released into the free space in the form of deformation and failure, another part is consumed by plastic deformation, and the remaining part is still stored in the coal [7,25]. The energy released and consumed during the deformation and failure process of the coal is known as dissipated energy.

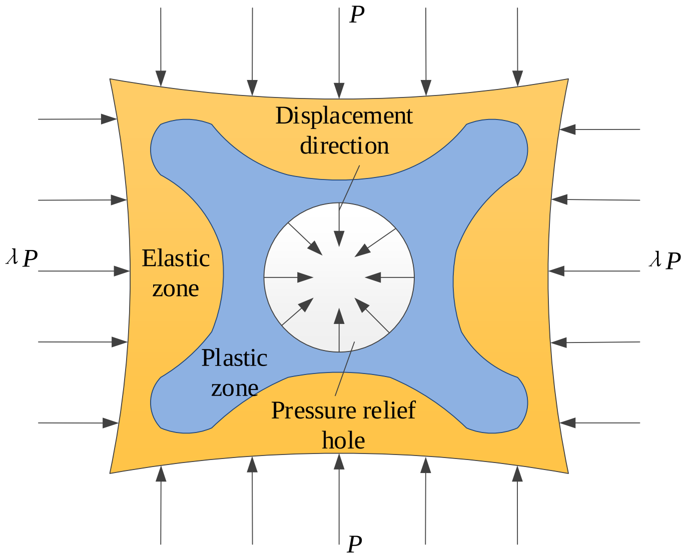


Figure 1. Schematic diagram of large diameter borehole for pressure relief.

We take the pressure relief hole and its surrounding coal as the study system. It is assumed that the system does not exchange heat with the outside world during the action of external force, which means it is a closed system. The total input energy generated from the work done by the external force is U. Equation (1) is shown according to the first law of thermodynamics:

$$U = U^d + U^e \tag{1}$$

where U^d is dissipated elastic strain energy during the process of deformation and failure of coal, and U^e indicates releasable residual elastic strain energy.

The dissipated energy U^d during the process of deformation and failure of coal is shown in Equation (2):

$$U^d = U - U^e \tag{2}$$

Under the triaxial stress state, the work done by the external force acting on coal is shown in Equation (3):

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + \int_0^{\varepsilon_2} \sigma_2 d\varepsilon_2 + \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3 \tag{3}$$

where σ_1, σ_2, σ_3 are the principal stresses in three directions, respectively, and $\sigma_1 > \sigma_2 > \sigma_3$. The terms ε_1, ε_2, ε_3 indicate the principal strains of three principal stress directions, respectively.

The releasable elastic strain energy U^e is calculated according to the theory of strain energy under complex stress state as shown in Equation (4):

$$U^e = \left(\frac{1}{2}\sigma_1\varepsilon_1^e + \frac{1}{2}\sigma_2\varepsilon_2^e + \frac{1}{2}\sigma_3\varepsilon_3^e\right)\cdot V \tag{4}$$

where ε_1^e, ε_2^e, ε_3^e are the elastic strains in three directions of principal stress, respectively, and V is element volume.

If the coal is homogeneous and the elastic modulus remain the same during the whole process of deformation and failure, the releasable elastic strain energy U^e of the coal element can be further calculated as shown in Equation (5) with a generalized Hooke's law:

$$U^e = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right]\cdot V \tag{5}$$

where E is the loading and unloading elastic modulus of coal, and ν indicates the Poisson's ratio of coal.

When the accumulated elastic strain energy exceeds its energy storage limit, the coal will fail with energy dissipation. Therefore, the energy dissipation can be approximately characterized by the change in elastic strain energy before and after the pressure relief hole construction in the coal seam. We can divide the coal seam into element grids and use the finite element analysis approach to carry out the numerical simulation. Any finite element software can analyze the energy accumulation and dissipation directly or indirectly. Therefore, the FLAC3D platform is chosen to analyze such problems. If the work done by the external force on coal is completely converted into elastic strain energy before the construction of pressure relief holes, the dissipated energy U^d after the construction can be calculated as shown in Equation (6):

$$U^d = \sum\left(U^e_{i,0} - U^e_{i,1}\right) \tag{6}$$

where $U^e_{i,0}$ is the elastic strain energy accumulated in the i-th element before the construction of pressure relief holes, and $U^e_{i,1}$ represents the elastic strain energy accumulated in the i-th element after the construction of pressure relief holes.

3. Effect of Pressure Relief Hole Spacing on Energy Dissipation at Various Mining Depths

3.1. Numerical Model

Taking the mine with a mining depth of 400~1200 m as the engineering background and based on the characteristics of medium-thickness coal seams, the FLAC^{3D} numerical simulation software was used to establish a three-dimensional numerical model. The size of the coal seam model was length × width × height = 10.0 m × 1.0 m × 2.5 m. The number of model elements was about 692,640. The mining depth of the coal seam was set as 400 m, 600 m, 800 m, 1000 m, and 1200 m, and the pressure relief hole spacing of the coal seam at each depth was 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m. The diameter of the pressure relief holes was 150 mm, and the vertical distance between the center of the pressure relief holes and the coal seam floor was 1.5 m. A total of twenty-five kinds of numerical calculation models were created to analyze energy dissipation after the construction of pressure relief holes in coal seams under different mining depths. The three-dimensional numerical model is shown in Figure 2. The bottom surface of the model was fixed, the top surface imposed a self-weight load, and the other four surfaces were constrained by their normal displacements. The yield criterion of Mohr–Coulomb was selected for the model. In geotechnical engineering, the application of 2.5 MPa is generally equivalent to the dead weight of a 100 m deep stratum. Therefore, the applied load can be simulated as the dead weight of the stratum's buried depth. The physical and mechanical parameters of coal were based on the engineering background of rockburst mines. However, there is a certain increase or reduction compared with the original data. The change in parameters does not affect the understanding of the law of energy accumulation and release. The detailed numerical simulation scheme and physical and mechanical parameters of coal are shown in Tables 1 and 2.

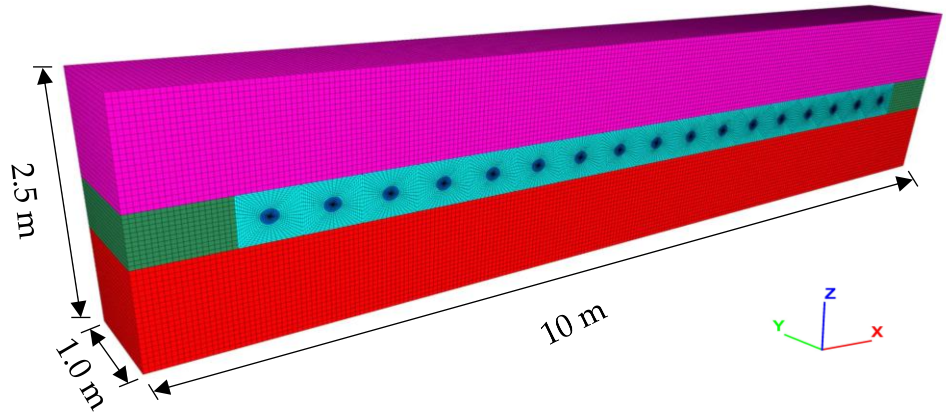


Figure 2. Three-dimensional numerical model.

Table 1. Numerical simulation scheme.

No.	Mining Depth (m)	Spacing of Pressure Relief Holes (m)	Model Size (m)	Top Load (MPa)
1	400	0.5	10.0 × 1.0 × 2.5	10.0
2	400	1.0	10.0 × 1.0 × 2.5	10.0
3	400	1.5	10.0 × 1.0 × 2.5	10.0
4	400	2.0	10.0 × 1.0 × 2.5	10.0
5	400	2.5	10.0 × 1.0 × 2.5	10.0
6	600	0.5	10.0 × 1.0 × 2.5	15.0
7	600	1.0	10.0 × 1.0 × 2.5	15.0
8	600	1.5	10.0 × 1.0 × 2.5	15.0
9	600	2.0	10.0 × 1.0 × 2.5	15.0
10	600	2.5	10.0 × 1.0 × 2.5	15.0
11	800	0.5	10.0 × 1.0 × 2.5	20.0
12	800	1.0	10.0 × 1.0 × 2.5	20.0
13	800	1.5	10.0 × 1.0 × 2.5	20.0
14	800	2.0	10.0 × 1.0 × 2.5	20.0
15	800	2.5	10.0 × 1.0 × 2.5	20.0
16	1000	0.5	10.0 × 1.0 × 2.5	25.0
17	1000	1.0	10.0 × 1.0 × 2.5	25.0
18	1000	1.5	10.0 × 1.0 × 2.5	25.0
19	1000	2.0	10.0 × 1.0 × 2.5	25.0
20	1000	2.5	10.0 × 1.0 × 2.5	25.0
21	1200	0.5	10.0 × 1.0 × 2.5	30.0
22	1200	1.0	10.0 × 1.0 × 2.5	30.0
23	1200	1.5	10.0 × 1.0 × 2.5	30.0
24	1200	2.0	10.0 × 1.0 × 2.5	30.0
25	1200	2.5	10.0 × 1.0 × 2.5	30.0

Table 2. Physical and mechanical parameters of coal.

Lithology	Density ρ (kg/m^3)	Elastic Modulus E (GPa)	Poisson's Ratio μ	Internal Friction Angle (°)	Cohesive Forces (MPa)	Tensile Strength σ_b (MPa)
coal	1335	0.532	0.255	37.29	1.205	0.635

3.2. Energy Variation Law around Pressure Relief Holes at Various Mining Depths

Using Equation (6), the energy dissipation of coal before and after the construction of the pressure relief holes can be approximately estimated. A positive value represents energy dissipation of coal, while a negative value represents energy accumulation of coal. As shown in Figure 3, at mining depths of 400 m, 600 m, 800 m, 1000 m, and 1200 m, when the pressure relief hole spacing is selected as 1 m, the energy dissipation law of coal is analyzed as follows: (1) The upper and lower ends of coal near the pressure relief holes have the highest energy dissipation degree and the largest dissipation range. (2) As the mining depth increases, the energy dissipation degree of coal at the upper and lower ends of the hole increases gradually. (3) The energy dissipation range on the left and right sides of the pressure relief holes are quite small. There are energy accumulation areas on the left and right sides far away from the pressure relief hole wall within a certain range, and the degree of energy accumulation is the highest. (4) With the gradual increase in mining depth, the energy accumulation degree also increases gradually in this area.

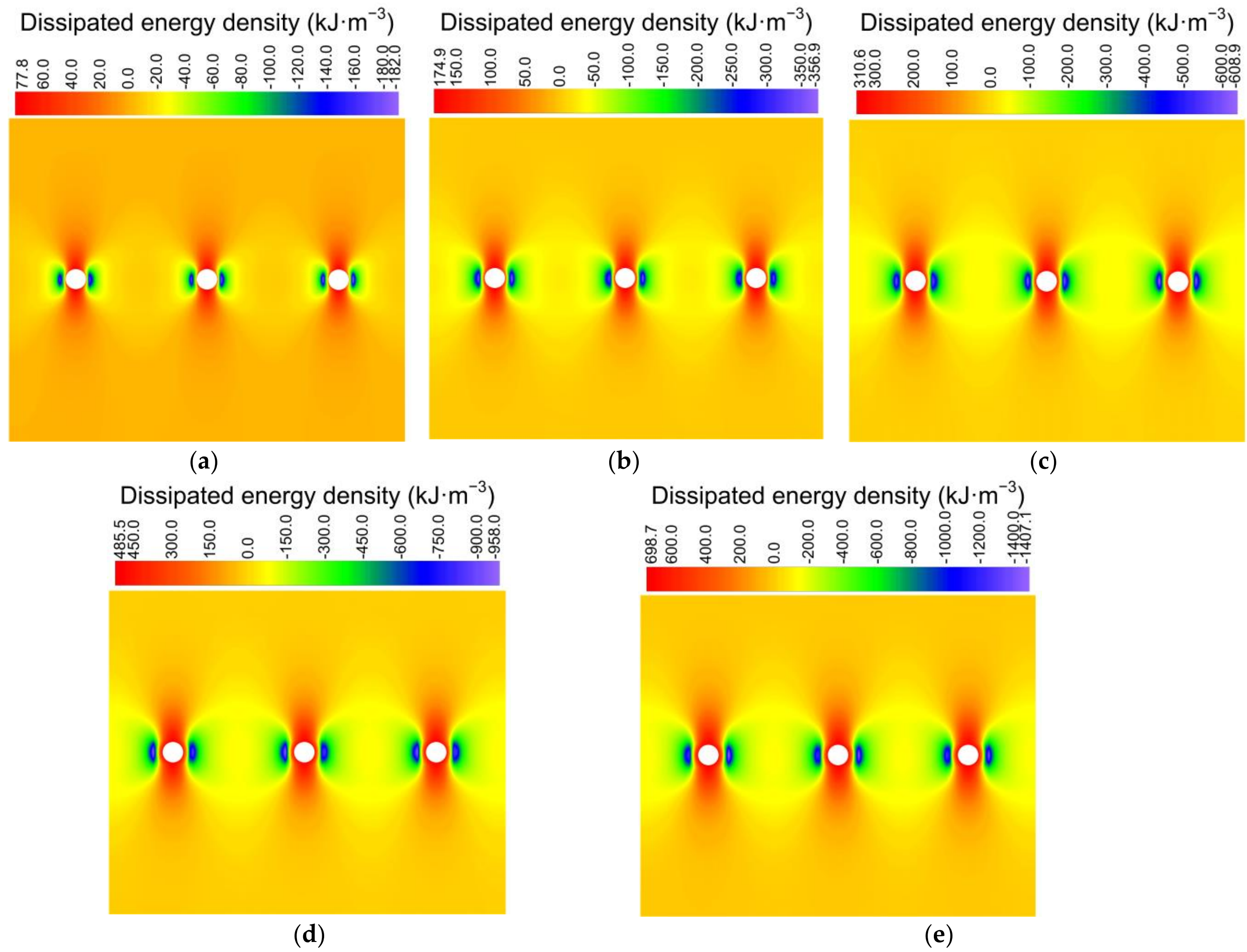


Figure 3. The dissipated energy density nephogram of pressure relief holes under various mining depths: (**a**) 400 m; (**b**) 600 m; (**c**) 800 m; (**d**) 1000 m; (**e**) 1200 m.

3.3. Coal Body Energy Variation Law under Various Spacings of Pressure Relief Holes

The pattern of energy dissipation from pressure relief hole to coal seam was similar under different mining depths. Therefore, the different pressure relief hole spacings under 600 m mining depth were selected as the analysis object. As shown in Figure 4, the energy dissipation law of coal was analyzed as follows under the conditions of 600 m mining depth and 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m pressure relief hole spacings.

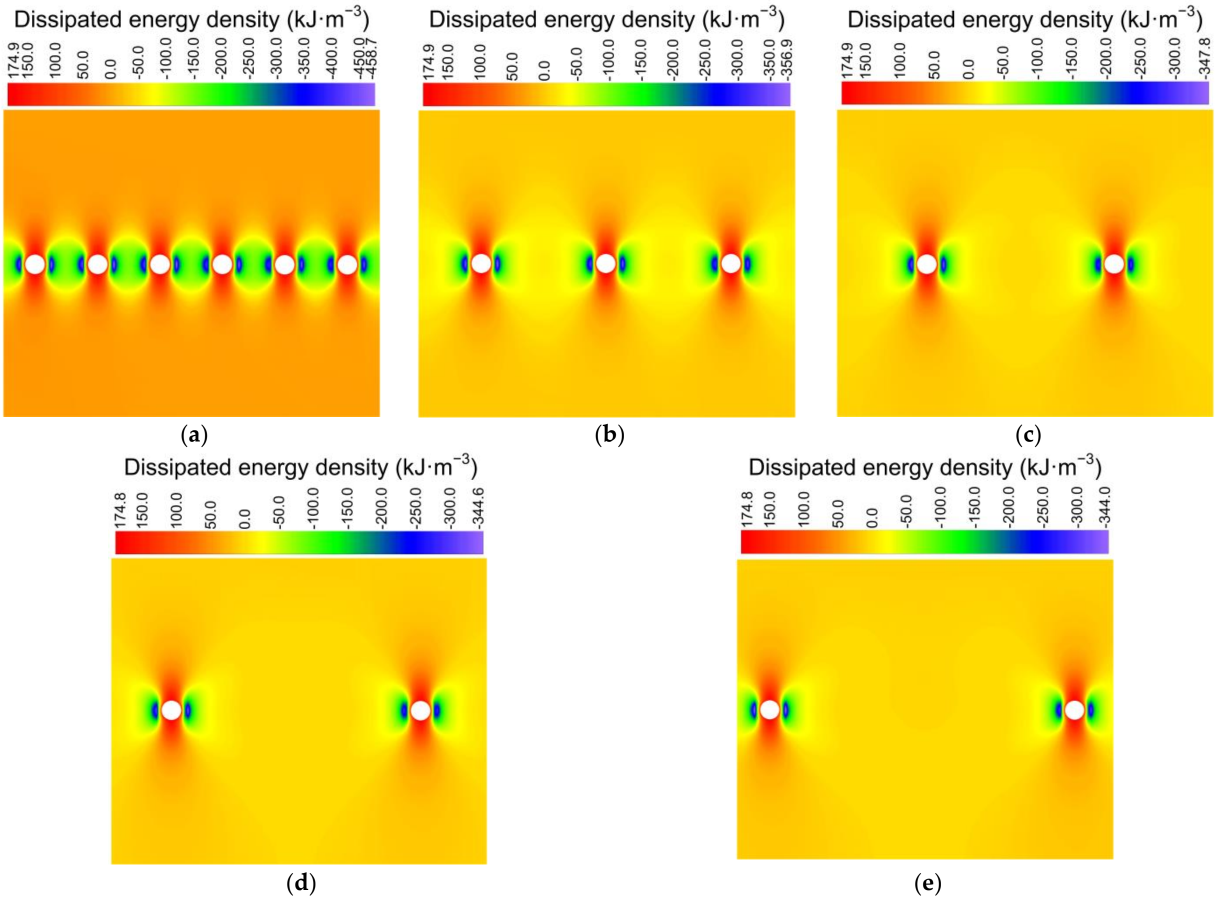


Figure 4. The dissipated energy density nephogram at various spacings of pressure relief holes: (**a**) 0.5 m; (**b**) 1.0 m; (**c**) 1.5 m; (**d**) 2.0 m; (**e**) 2.5 m.

(1) With the increase in pressure relief hole spacing, the energy dissipation degree of coal at the upper and lower ends near the hole remained largely unchanged. (2) When the spacing is 0.5 m, the energy accumulation degree on the left and right sides of the holes is the highest, which is 1.3 times higher than the other four spacings. However, the energy accumulation on the left and right sides of the pressure relief holes at the other four intervals has little change. (3) The energy accumulation degree decreases constantly as the spacing increases generally. The reason is that the superposition effect of energy accumulation between adjacent pressure relief holes is weakened with the increase in the spacing of adjacent holes. (4) With the increase in the spacing of pressure relief holes, the number of pressure relief holes will decrease correspondingly in the same size of coal, which leads to a weakened energy dissipation effect of the pressure relief holes on the coal seam. (5) If the spacing of pressure relief holes is small, though the energy accumulation degree between two holes increases, the total number of pressure relief holes increases in the condition of a specific size. It means that the effect of energy dissipation on coal is also enhanced in general.

3.4. Relationship between Mining Depth, Spacing of Pressure Relief Holes and Dissipated Energy

Based on twenty-five groups of numerical simulation results under the combinations of five kinds of mining depth and five kinds of pressure relief hole spacing, the least square method was applied to fit the dissipated energy data, and the functional relationship between the mining depths of the coal seam, the spacing of pressure relief holes, and the dissipated energy was obtained. The details are shown in Figures 5 and 6.

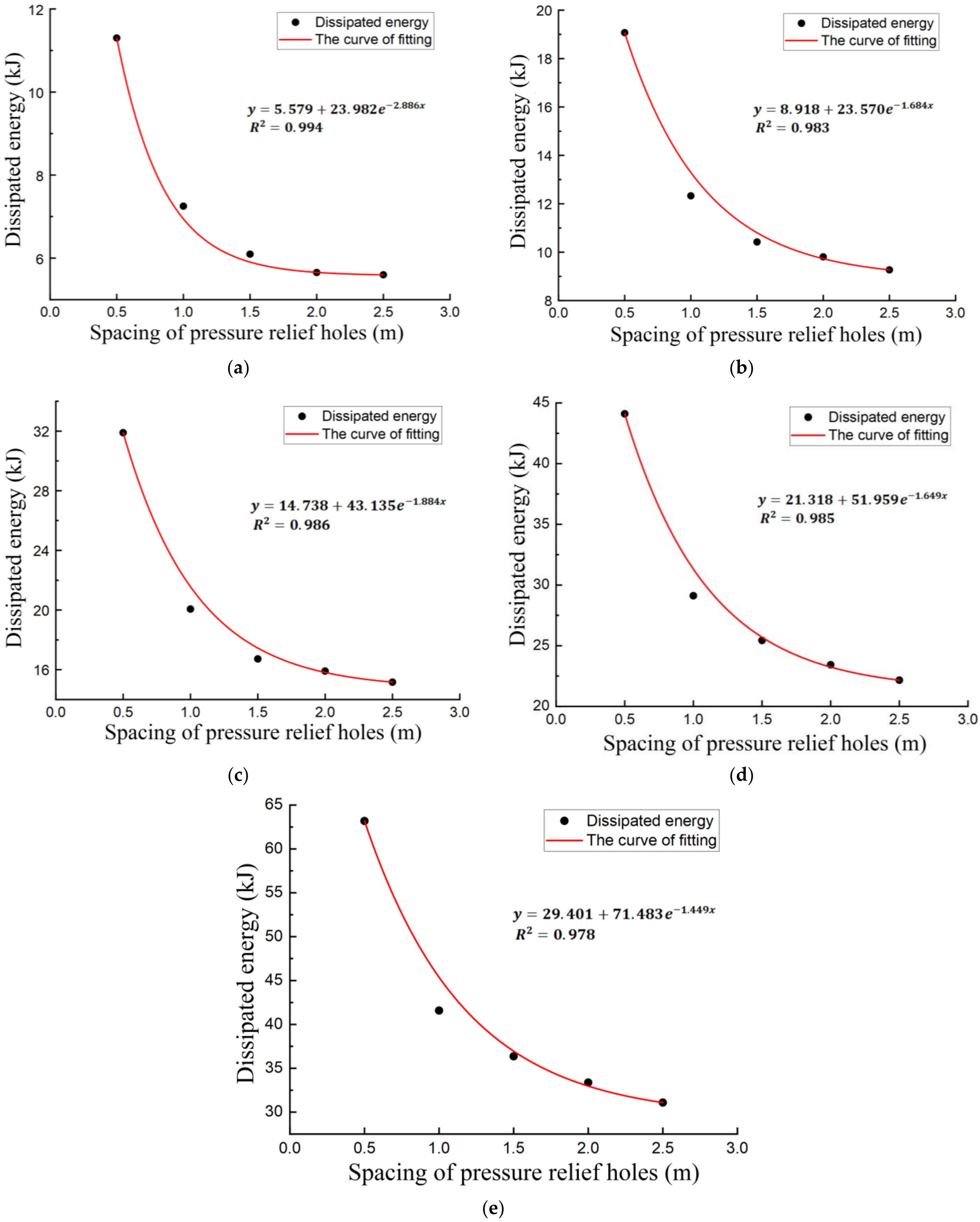
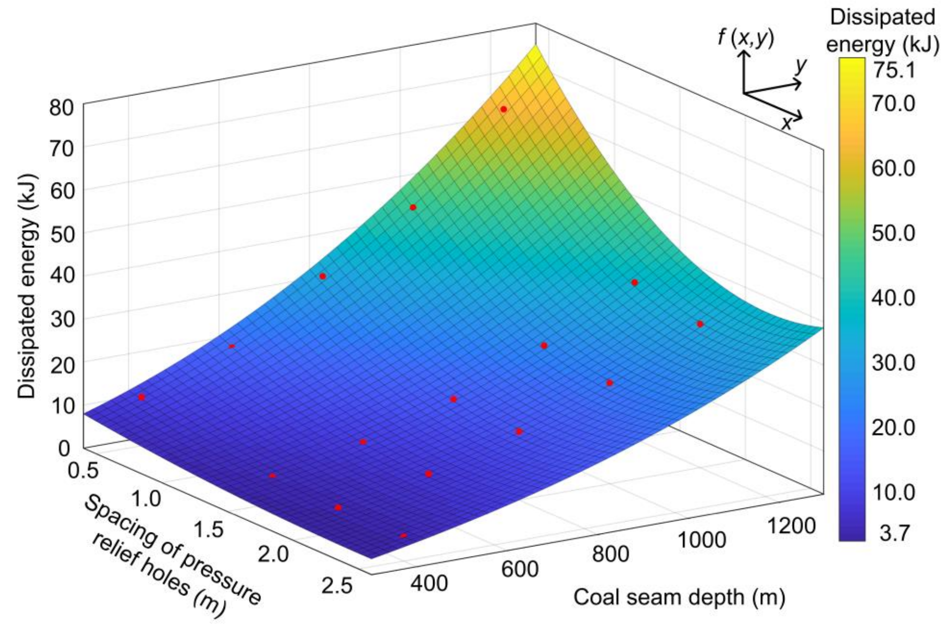


Figure 5. Fitting relationship between spacing of pressure relief holes and dissipated energy at various mining depths: (**a**) 400 m; (**b**) 600 m; (**c**) 800 m; (**d**) 1000 m; (**e**) 1200 m.



$$f(x,y) = 16.27 - 5.128x + 10.32y + 3.485x^2 - 3.047xy + 2.331y^2 + 1.713x^2y - 0.5135xy^2 + 0.1489y^3$$
$$R^2 = 0.989$$

Figure 6. Fitting relationship between coal seam depth, spacing of pressure relief holes and dissipated energy.

As shown in Figure 5, the dissipated energy of coal seam decreased with the increase in spacing of the pressure relief holes under the same mining depth. The larger the spacing, the smaller the decreasing range of dissipated energy. Figure 6 shows that the dissipated energy increased continuously with the increase in mining depth and the decrease in pressure relief hole spacing. In particular the dissipated energy rose suddenly when the spacing changed from 1.0 m to 0.5 m. In fact, the pressure relief holes not only dissipated the elastic strain energy of the coal seam, but also caused the energy to transfer and accumulate to the holes' axial and lateral coal. However, the energy dissipated by the relief holes was greater than the energy transferred and gathered generally.

4. Discussion on the Spacing of Pressure Relief Holes in Coal Seam of Rockburst Hazard

Typically, the spacing of pressure relief holes is 3 m for a coal seam with weak rockburst risk, 2 m for a coal seam with medium rockburst risk, and 1 m for a coal seam with high rockburst risk. The diameter of the pressure relief holes is 120–150 mm and the depth of holes is around 20 m [26]. In this numerical model, the depth of pressure relief holes was 1 m. When converted into a hole depth of 20 m, taking a mining depth of 800 m as an example, the dissipated energy of the coal seam was 400 kJ if the hole spacing was 1 m. Additionally, the dissipated energy of the coal seam was 640 kJ if the hole spacing was 0.5 m. The microseismic monitoring of underground mines shows [27] that when the microseismic energy is 1~100 kJ, a small amount of coal rock is thrown out and local damage such as wall caving and floor heave occurs. When the microseismic energy is 100–1000 kJ, the damage degree of coal rock is sharp, a large amount of coal rock is thrown out with strong air waves, and the roadway collapses and supports fail. When the microseismic energy is greater than 1000 kJ, it could destroy dozens of meters or even hundreds of meters of roadway and damage supports and electromechanical equipment. Therefore, to improve the effect of energy dissipation for coal seams greatly, the spacing of pressure relief holes should be set at less than or equal to 0.5 m for areas with high rockburst risk.

5. Conclusions

(1) The upper and lower ends of the pressure relief holes have the highest energy dissipation degree and the largest dissipation range. However, the energy dissipation effect of the left and right sides of the pressure relief hole is poor, and the energy accumulation occurs in a certain range from the two sides of the hole wall.
(2) The dissipated energy of the coal seam increases continuously with the increase in mining depth and the decrease in the spacing of pressure relief holes. Specifically, the dissipated energy can rise suddenly when the hole spacing changes from 1.0 m to 0.5 m.
(3) The spacing of pressure relief holes can be arranged to be less than or equal to 0.5 m in the areas with high risk of rockburst, which can greatly improve the effect of energy dissipation of the coal seam.

Author Contributions: Conceptualization, H.Z.; methodology, H.Z.; software, Y.P. (Yisheng Peng); validation, Y.P. (Yisheng Peng); formal analysis, H.Z.; data curation, Y.P. (Yisheng Peng); writing—original draft preparation, H.Z.; writing—review & editing, J.L. and S.L.; visualization, Y.P. (Yisheng Peng); supervision, Y.P. (Yishan Pan). All authors have read and agreed to the published version of the manuscript.

Funding: The research is supported by the National Science Foundation of Liaoning Province (No. 2021-MS-337), the National Natural Science Foundation of China (No. 51504128).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: All authors would like to thank the anonymous reviewers for their valuable and constructive comments.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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