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Research Article

Parametric Study of the Borehole Drilling in Jointed Rock Mass

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Gas is associated with coal mining; it commonly exists in the coal seam. It is one of the major dangers during the production because its reaction between the coal masses may induce the gas-coal outburst as well as it being an expositive matter. The gas accident has caused a huge amount of property damage and casualties. Therefore, the primary precaution for coal mining is gas control. At present, drilling and extraction are the main approaches for gas accident prevention. After drilling, the ground pressure will be released; the gas which is in a free state or absorbed in the coal seam will be easy to extract as the migration channel is enhanced. Hence, one of the most concerned problems is the stress redistribution of the coal and rock mass around the borehole. In practical engineering, there are many joints distributed in the coal and rock strata, so it is necessary to investigate the effect of the drilling in the jointed coal and rock mass. In this paper, the boundary element model of the borehole in the jointed coal and rock mass is established to study the influence of joints on the stress and displacement field. The following results can be obtained. The number of joints has a significant effect on the maximum displacement of the coal and rock mass. The maximum displacement increases with the number of the joint. The position of the maximum displacement shifts from the boundary of the borehole to the far field. Meanwhile, it can be found that the displacement may reach a peak value when the joint angle is 30° and if the joint number is less than 4, and the maximum displacement may occur under the joint angle of 45° and if the joints number continuous increases. The von Mises stress has a trend of increasing with the number of joints when the joint angle is less than 30°, while it has a decreasing trend when the joint angle is larger than 30°. The max stress may occur at the joint angle of 15°. The maximum shear stress occurs mostly in the No. 4 joint and the No.7 joint. When the joint angle is 30°, the maximum shear stress occurs in the No. 3 joint and the No. 4 joint. The overlap of the position of the maximum von Mises stress or the maximum displacement with different joint angles or different numbers of joint leads to a reexploration of such positions. The position of the maximum von Mises stress and the maximum displacement *o* is relatively steady, which locates symmetrically around the borehole. The line between the points that behaves as the maximum von stress is approximately perpendicular to the joint direction.

1. Introduction

Gas is associated with coal mining; it commonly exists in the coal seam. It is one of the major dangers during the production, because its reaction between the coal masses may induce dynamic disasters such as gas-coal outburst, as well as it being an expositive matter. The gas accident has caused a huge amount of property damage and casualties [1–5].

Therefore, the primary precaution for coal mining is gas control. At present, mining of the protective layer and drilling-extraction are the main approaches for gas accident prevention. However, a suitable protective layer cannot be always found, especially in the deep underground. Thus, drilling-extraction may be the preferred method for the regional gas control under this circumstance [6–10]. After the drilling, the ground pressure will be released, the gas which is in a free state or absorbed in the coal seam will be easy to extract as the migration channel is enhanced. Hence, one of the most concer1ned problems is the stress redistribution of the coal and rock mass around the borehole.

At present, many studies have been carried out to investigate the process, effect, and the mechanism of pressure relief by drilling. Wang optimized the surface drilling position and drainage pressure of Yuwu coal mine. The results show that the position in horizontal of surface drilling should arrange inside of "O" ring, and in vertical, it should be arranged between the collapse zone to the middle part of the fracture zone [11]. Tong et al. studied the behavior of gas extraction from the protected layer by surface drilling. It is found that, after the protected layer working face was advanced through the surface drilling, the gas extracted by surface drilling behaves as 3 periods, i.e., the rising period, stable period, and decay period [12]. Lian studied the key factors of well completion such as well layout, well structure, drilling technology, and drilling management and provided reference for the application of gas extraction in surface wells [13]. Liu et al. proposed an efficient strategy to minimize air leakage for underground gas extraction based on the controlling of the fracture permeability of the coal rock mass. A good strategy to minimize air leakage for underground gas extraction is to seal the developed fractures around the borehole [14]. Based on the results of the drainage from pressure release area, Wu indicated that the coalbed methane drainage from coal seams with low permeability in the release area of pressure is not only advantageous to the coal mine safety production but also can enhance recovery ratio of the coalbed methane enormously and enhances the economic efficiency of the coalbed methane development [15]. Chen et al. carried out a hydraulic flushing technology with cross-seam boreholes to solve this problem. Furthermore, the optimal spacing of hydraulic flushing boreholes (HFB) is determined to provide the basis for field testing [16]. Hu et al. conducted an experimental study on the permeability enhancement of boreholes by using liquid CO_2 phase-transition blasting (LCPTB). The results indicated a significant increase in the permeability of the coal seam, and the efficiency of gas drainage can be obtained by using LCPTB. The amount of gas extracted from the LCPTB-enhanced holes was 1.8–8 times greater than that extracted from common borehole [17]. Gao et al. studied the effect of the borehole and the borehole-slotting on the pressure relieve. The parametric study of the geometry of the slotting, and the in situ stress is carried out [18]. Wei et al. optimized the process parameters of gas extraction and carried out the application study in the field. The results show that the reduction of gas pressure around the borehole group is larger than that from a single borehole. The borehole spacing is suggested to be 2 times of or over the effective drainage radius [19]. Zhao et al. studied the influence of coal gas seepage law between boreholes for gas extraction and proposed the law of gas pressure distributions, gas seepage velocity distributions, and permeability change in the coal rock mass between two drilled boreholes and around the two boreholes [20].

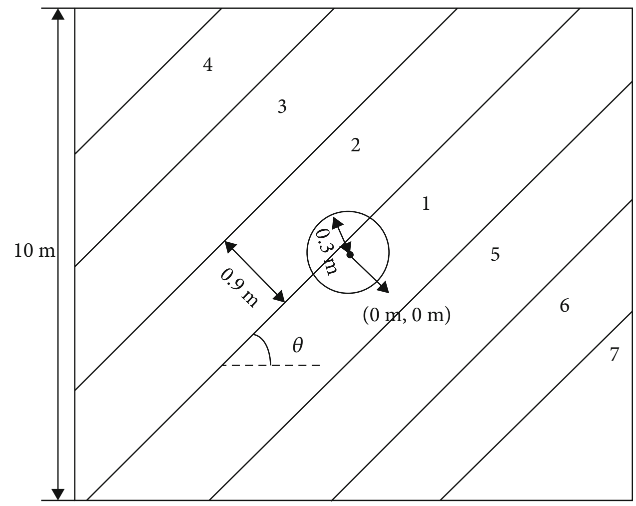


Figure 1: Geometry model.

Table 1: The mechanical parameters of the coal rock mass.

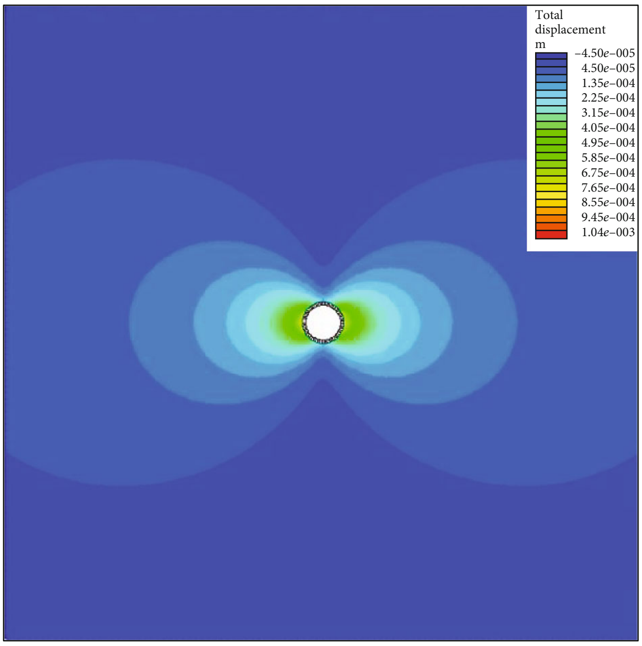
Parameter	Poisson's ratio	Frictional angle	Cohesion	Elasticity modulus	Tensile strength
Value	0.25	50°	2 MPa	10 GPa	0.3 MPa

As we know, the underlying mechanism of drilling-extraction is pressure relief. When a borehole is drilled in the coal rock mass, the stress will be released and the permeability of the coal mass is also changed as the deformation. Therefore, the stress and displacement may be the important indexes for describing the drilling effect. Meanwhile, there are many joints in the coal rock mass which may also impact the drilling effect. In this paper, a boundary element model of a borehole in jointed coal rock mass is established and simulated. The stress and displacement of the coal rock mass around the borehole is analyzed. The influence of the angles and number of joints on the stress and displacement field is discussed. The results can be a reference for borehole drilling evaluation of coal bed methane gas engineering.

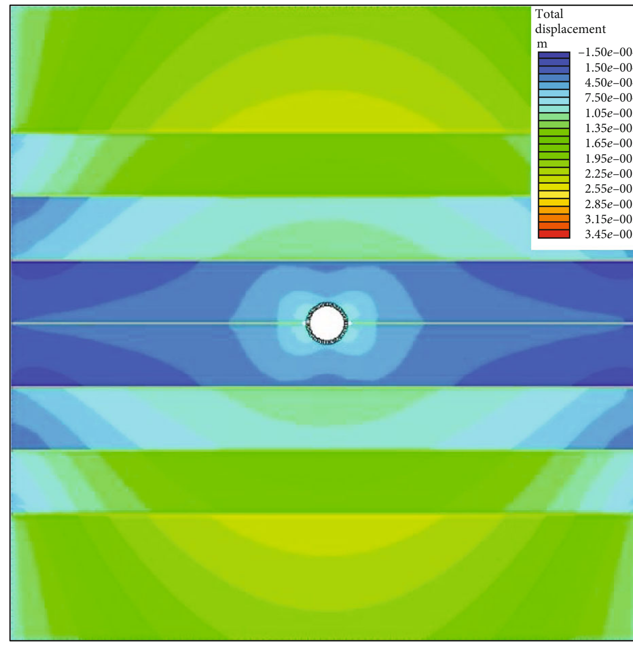
2. Model Establishment

The analysis domain is a $10\,\mathrm{m} \times 10\,\mathrm{m}$ square. The borehole is a circle with a radius of 0.3 m, and the center of the borehole is located at the point of $(0, 0)$. The in situ stress in the horizontal direction is 10 MPa, and the in situ stress in the vertical direction is 17 MPa. As shown in Figure 1, there are 7 paralleled joints in a group. And the joint direction θ varies from 0° to 75° with the interval of 15°. The spacing of the joints in each group is about 0.9 m.

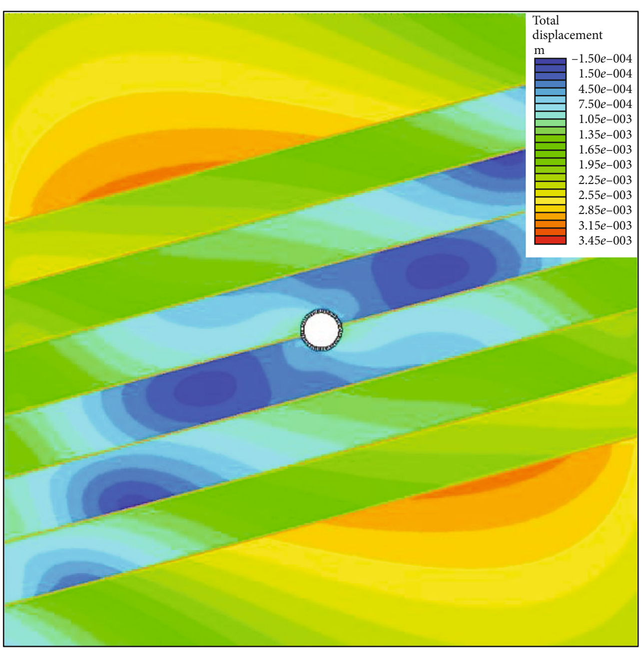
The mechanical parameters of the coal rock mass are listed in Table 1. The normal stiffness and the shear stiffness of the joint are assumed as 10000 MPa/m and 1000 MPa/m,



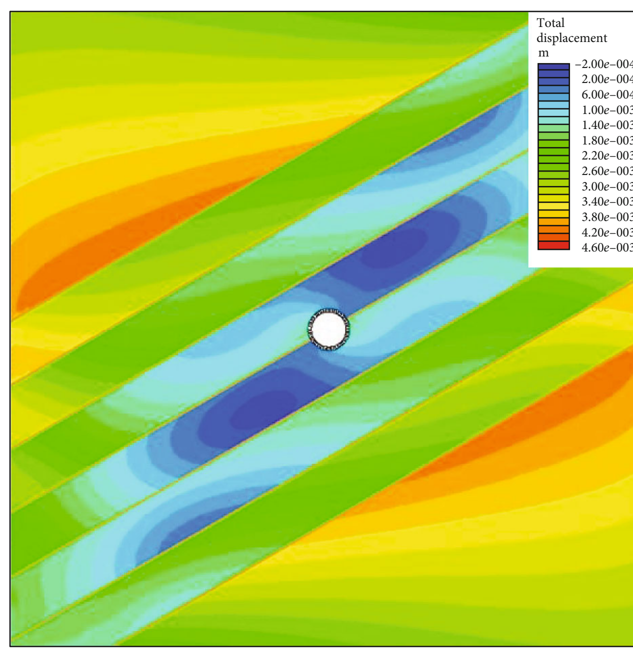
(a) Without joint



(b) Joint angle: 0°

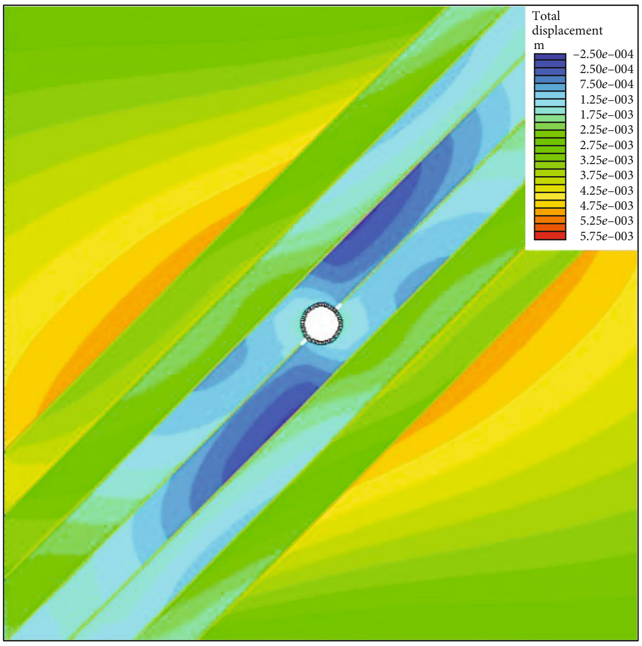


(c) Joint angle: 15°

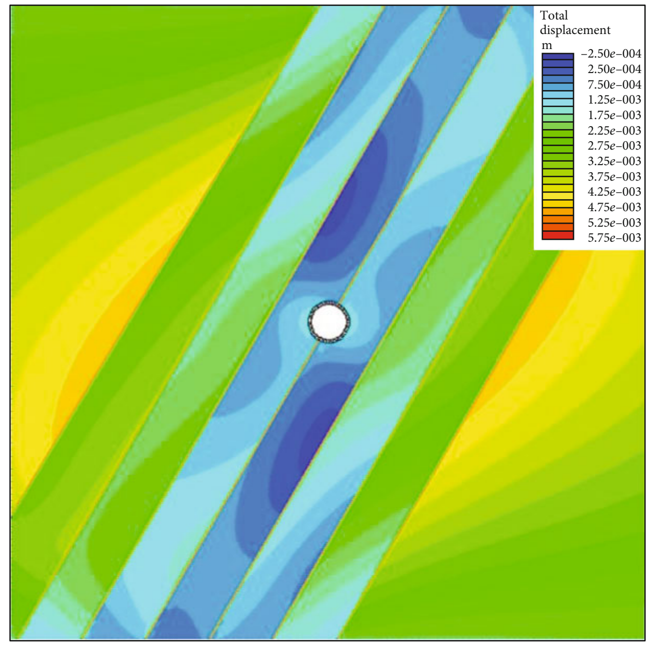


(d) Joint angle: 30°

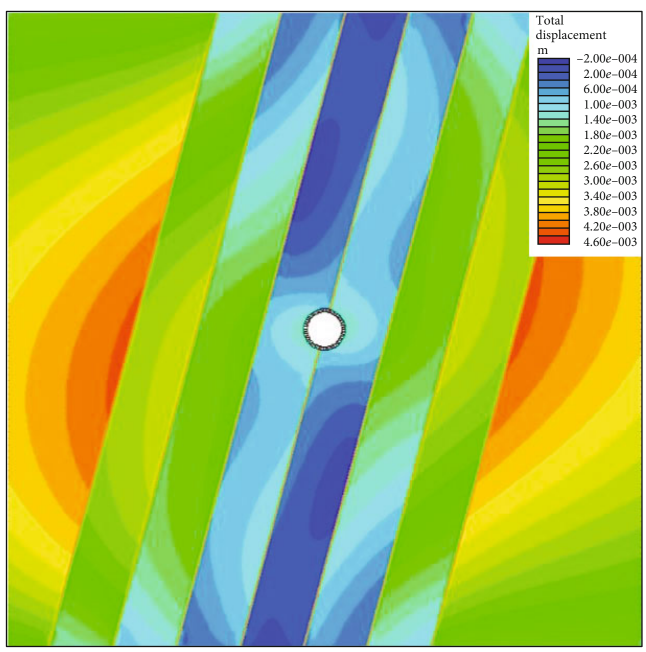
Figure 2: Continued.



(e) Joint angle: 45°



(f) Joint angle: 60°



(g) Joint angle: 75°

Figure 2: Displacement nephogram.

respectively. In this paper, the maximum stress and the maximum displacement are most concerned as such physical values may results in key issues that represent the drilling effect in practical engineering.

3. Analysis of the Numerical Results

3.1. Displacement Field. As shown in Figure 2(a), the total displacement of the model is symmetric in vertical and horizontal directions as there is no joint distributed in the model. The maximum displacement occurs at the boundary of the borehole. As shown in Figures 2(b)–2(g), compared with the model of Figure 2(a), the displacement field changes greatly under the effect of the joints. The position of the maximum displacement shifts from boundary of the borehole to the far field. The maximum displacement of the coal rock mass can be found around the No. 4 joint and No. 7 joint (Figure 1).

The max displacement is the maximum total displacement of the model under different conditions, including the horizontal displacement and the vertical displacement. The total displacement is the vector sum of the vertical

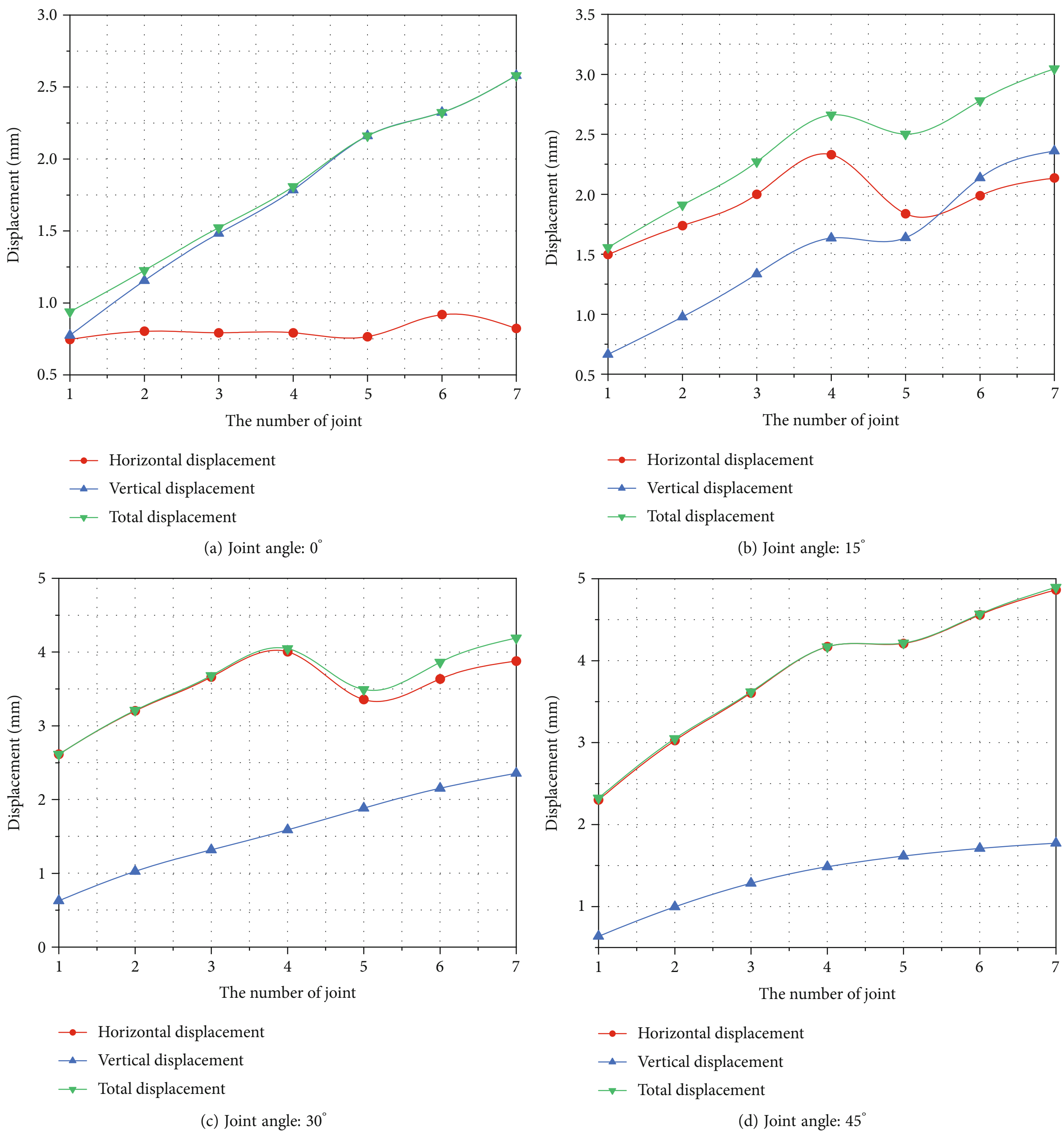
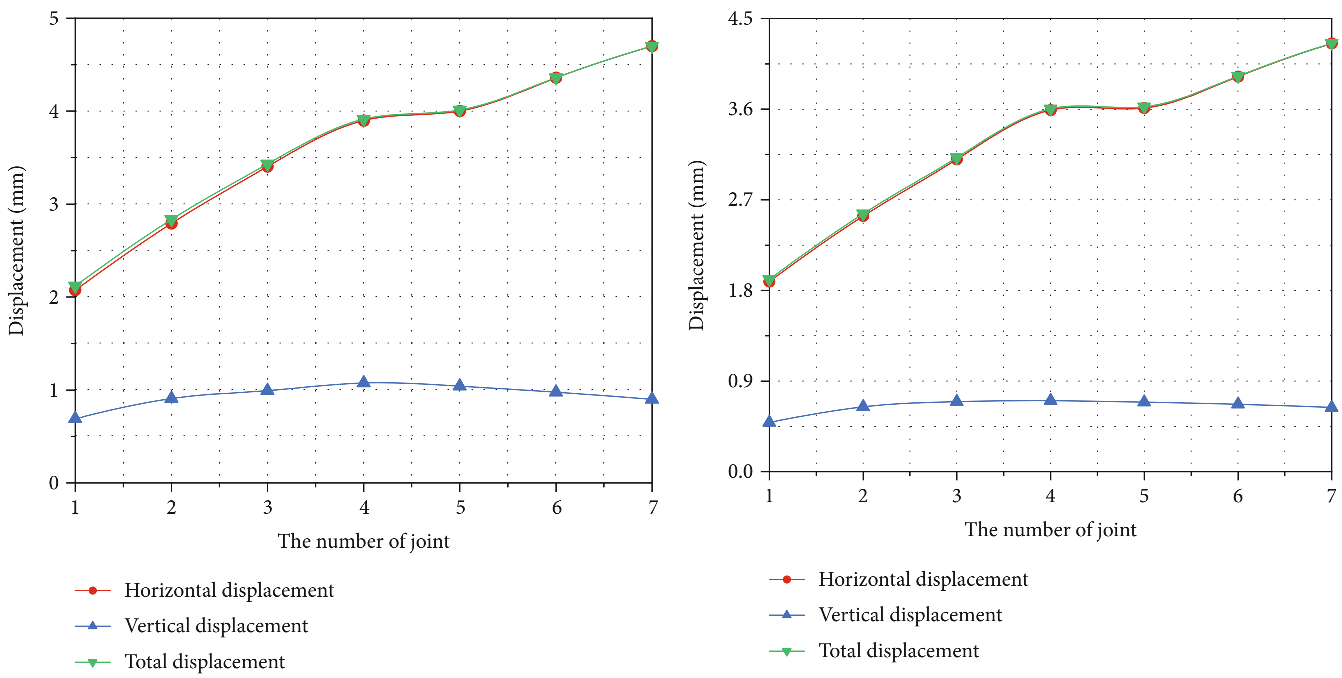


Figure 3: Continued.



(e) Joint angle: 60°

(f) Joint angle: 75°

Figure 3: Variation of the displacement.

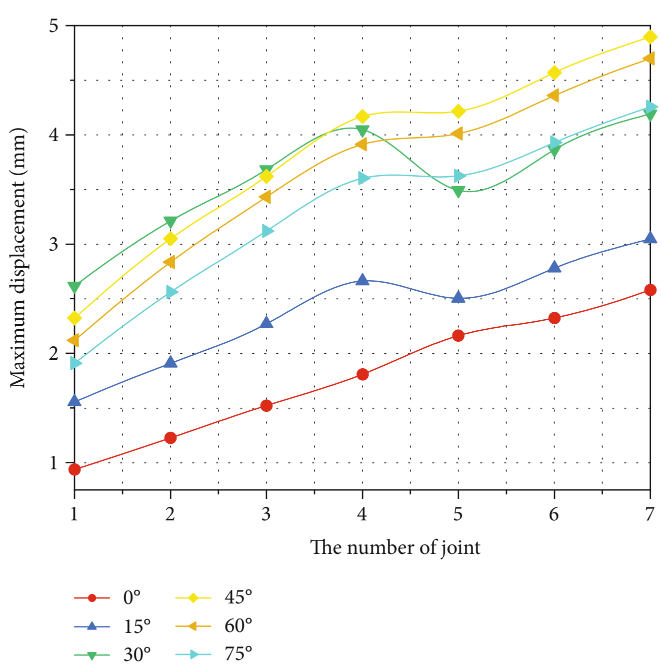
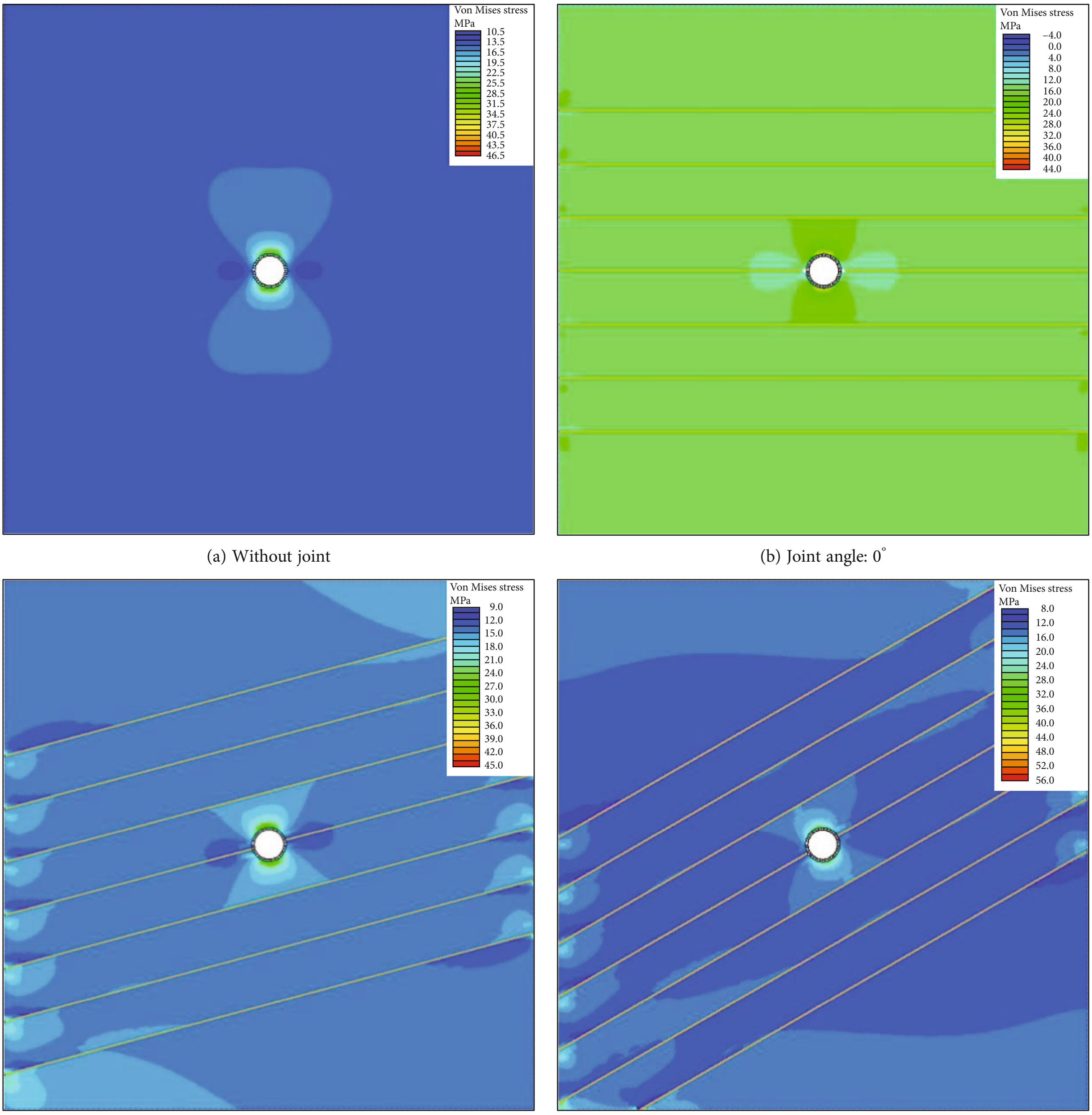


Figure 4: Maximum displacement with the number of joints.

displacement and the horizontal displacement. As shown in Figure 3, the maximum displacement of the coal rock mass is impacted significantly by the number of joints as it has an entire trend of rapid increase rapidly with the number of joints. Meanwhile, it can be seen that there is a slight drop of the displacement when the joints distributed at 15° (Figure 3(b)) or 30° (Figure 3(c)). And the drop occurs when the joint number rises by 4 to 5. It also can be found that the domination component of the maximum displacement gradually transits from vertical displacement to horizontal displacement as the joint angle varies from 0° to 75°.

As shown in Figure 4, if the joint number is less than 4, the maximum displacement increases with the angle of the joint $(0^\circ \leq \text{joint angle} \leq 30^\circ)$. However, the maximum



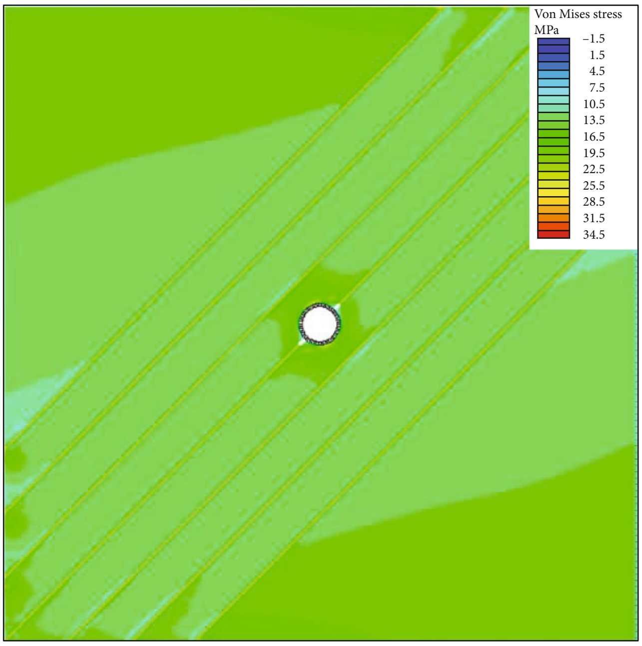
(a) Without joint

(b) Joint angle: 0°

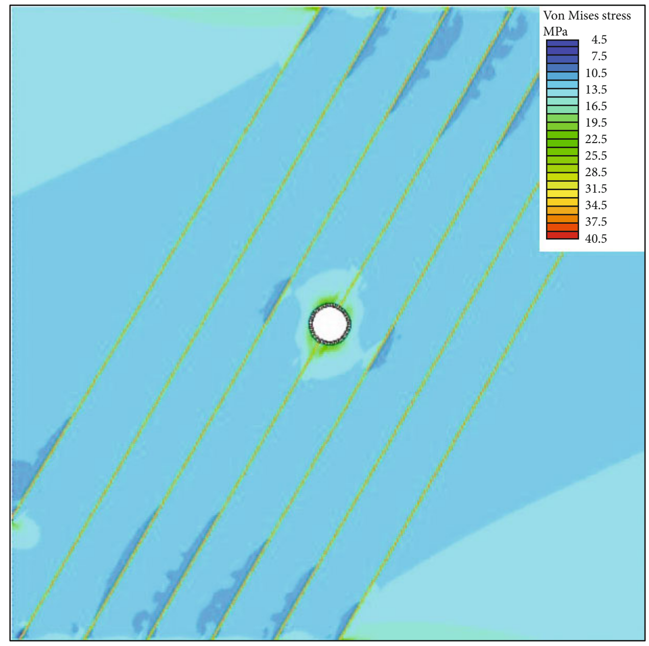
(c) Joint angle: 15°

(d) Joint angle: 30°

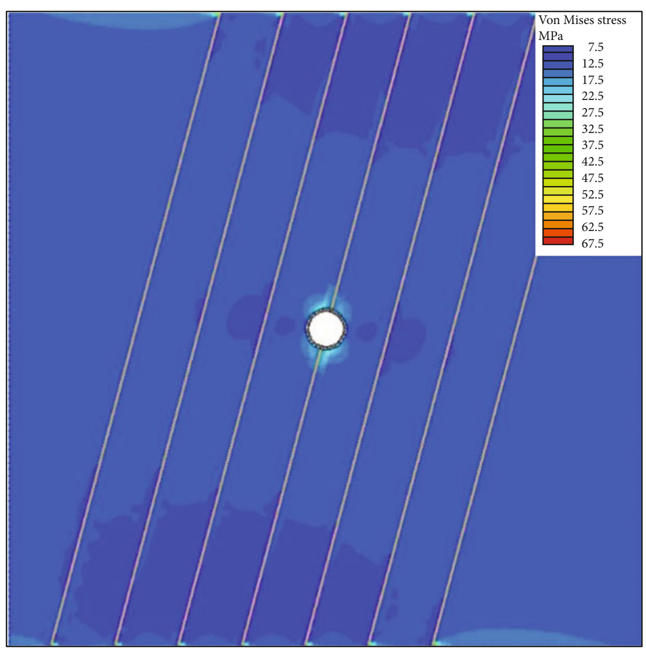
Figure 5: Continued.



(e) Joint angle: 45°



(f) Joint angle: 60°



(g) Joint angle: 75°

Figure 5: Von Mises stress nephogram.

displacement behaves in an opposite trend when the joint angle is larger than 30°, i.e., $30° \leq$ joint angle $\leq 75°$. And it can be concluded that the displacement may reach a peak value when the joint angle is 30° if the joint number is less than 4.

3.2. Stress Field. As shown in Figure 5, the maximum von Mises stress is around the boundary of the borehole with any joint angle. It means that the joints have little effect on the position of the maximum von Mises.

As shown in Figure 6, the von Mises stress has a trend of increase with the number of joints when the joint angle is less than 30°, while it has a decreasing trend when the joint angle is larger than 30°. It also can be found that the stress generally decreases with the incline joints (joint angle > 0°). In addition, the max stress may occur at the joint angle of 15°.

For each joint angle, the maximum shear stress of the joints is summarized in Table 2. The value in the table is calculated with the distribution of 7 joints for each joint angle. It can be seen that the maximum shear stress occurs mostly

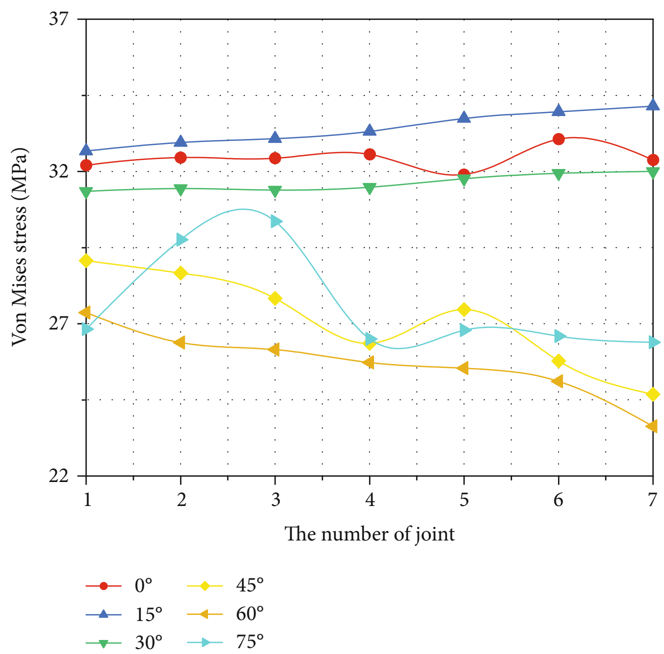


FIGURE 6: Maximum von Mises stress with the number of joints.

TABLE 2: Summary of the maximum shear stress of the joints (MPa).

Joint number	Joint angle					
	0°	15°	30°	45°	60°	75°
1						
2						
3			1.67			
4	0.32	1.22		1.61	1.50	1.01
5						
6			1.67			
7	0.32	1.22		1.61	1.50	1.01

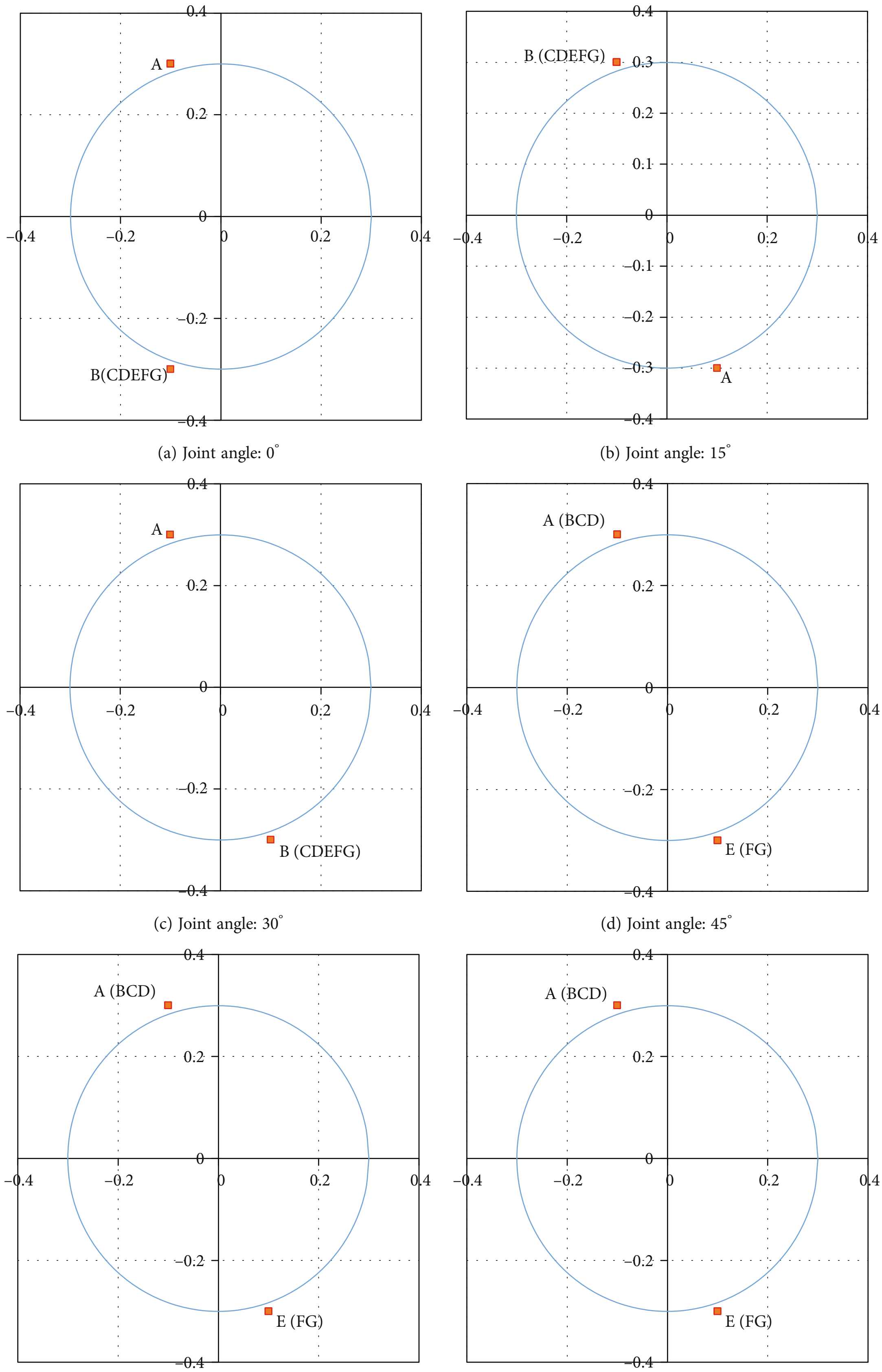
in the No. 4 joint and the No.7 joint. When the joint angle is 30°, the maximum shear stress occurs in the No. 3 joint and the No. 4 joint. And it should be noted that the relationship between the shear stress and shear displacement is a linear relationship with one parameter, i.e., the shear stress divided by the shear stiffness is the shear displacement. Thus, the shear displacement is not listed in this paper. And it can be concluded that the maximum shear displacement occurs in the same position of the maximum shear stress. This indicates that the farther the joint is from the borehole, the joint behaves the greater the shear displacement.

3.3. Discussion. In Sections 3.1 and 3.2, the displacement field and the stress field are analyzed in the view of the joint angle and the number of the joints, while to get a well understanding of the evolution of such physical fields should be not only focused on the quantity that was affected by the joints but also focused on the position evolution.

Figure 7 is the plot of the occurrence of the maximum von Mises stress. As described in Section 3.2, the maximum von Mises in each distribution model of the joints may occur around the borehole. *A*, *B*, *C*, *D*, *E*, *F*, and *G* are denoted as the position that the maximum stress occurs. Besides, the relevant data is summarized in Table 3. It should be pointed that each model has a characteristic of symmetry, and the position may be not unique. Here, only one position for each model is listed.

It is obvious that all the position of the maximum von Mises stress occurs in the same position which is close to the borehole boundary. It means that such position does not change with the number of joints or the joint angle. This finding is not very reasonable as the joint angle varies. However, it can be found that the similarity in position or the same positions may be due to the computation element/unit size after a double check of the results obtained by software. Therefore, further exploration of the results is needed. And the refined results of the position are then obtained. The positions of the maximum von Mises stress and the displacement for each joint angle are plotted in Figure 8. A1 and A2 are the position that the maximum von Mises stress behaves. Similarly, B1 and B2 are the position that the maximum stress behaves.

Based on Figure 8, the symmetry of A1 and A2 (B1 and B2) can be observed. And in accordance with the current results, those positions are located around the borehole. In addition, it can be inferred from Figure 8 that the line between A1 and A2 is approximately perpendicular to the joint direction. The reexplored values of the maximum von Mises stress and the maximum displacement are listed in Tables 4 and 5. The trend of the stress and the displacement generally agrees with the results of Section 3.1 and Section 3.2 in terms of the joint angle and joint number.



(a) Joint angle: 0°

(b) Joint angle: 15°

(c) Joint angle: 30°

(d) Joint angle: 45°

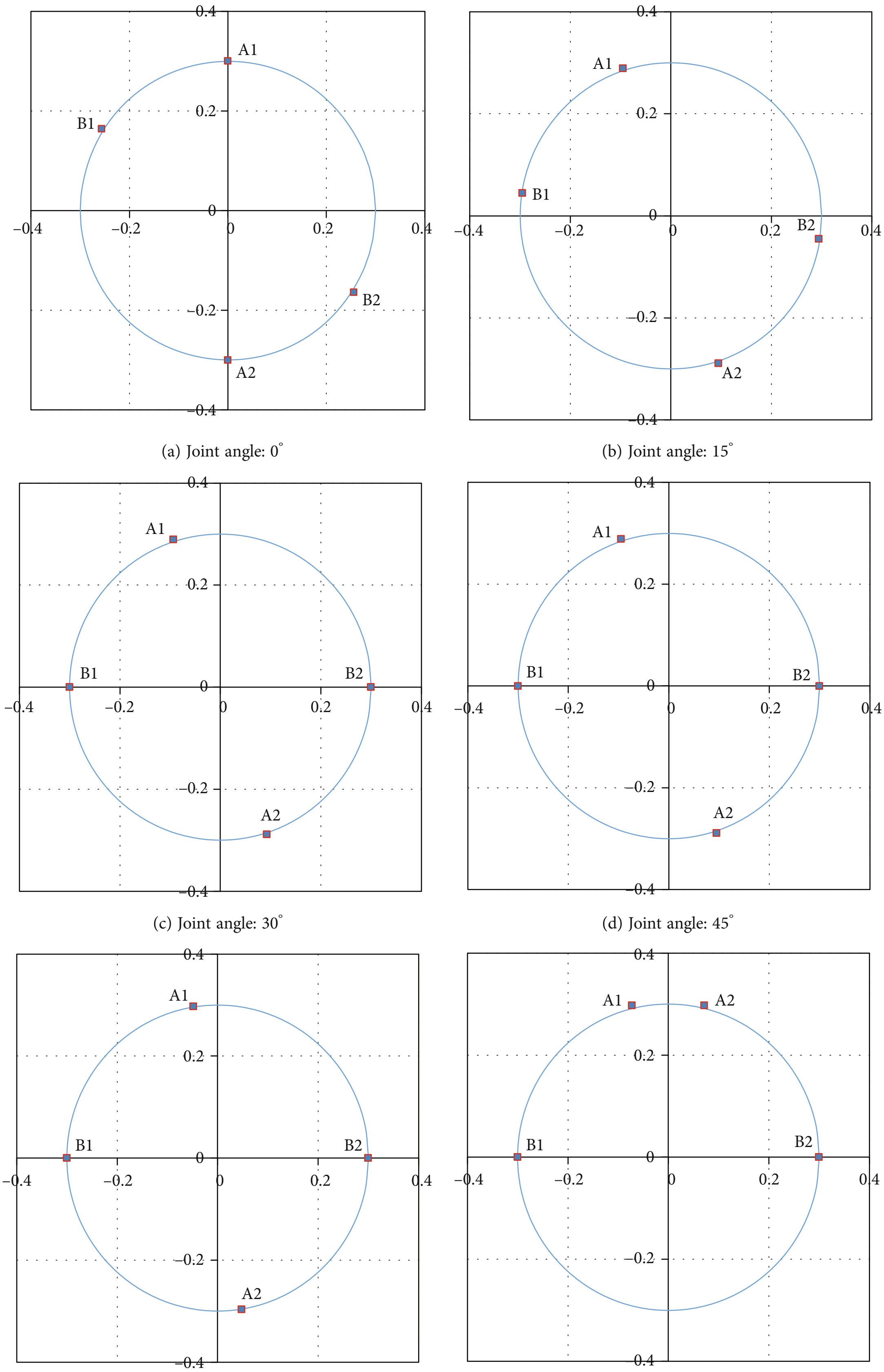
(e) Joint angle: 60°

(f) Joint angle: 75°

Figure 7: The position of the maximum von Mises stress.

Table 3: Summary of the maximum von Mises stress and the coordinates.

Joint angle	Parameter	A	B	C	D	E	F	G
0°	Stress (MPa)	32.2	32.5	32.40	32.6	31.9	33.1	32.4
	x, y (m)	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3
15°	Stress (MPa)	32.7	33.0	33.1	33.3	33.7	34.0	34.1
	x, y (m)	0.1, -0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3
30°	Stress (MPa)	31.4	31.4	31.4	31.5	31.8	31.9	32.0
	x, y (m)	0.1, -0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3
45°	Stress (MPa)	29.1	28.7	27.8	26.4	27.5	25.8	24.7
	x, y (m)	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	-0.1, 0.3	0.1, -0.3	0.1, -0.3	0.1, -0.3
60°	Stress (MPa)	27.4	26.4	26.1	25.7	25.5	25.1	23.6
	x, y (m)	-0.1, 0.3	-0.1, 0.3	0.1, 0.3	0.1, 0.3	0.1, 0.3	0.1, 0.3	-0.1, 0.3
75°	Stress (MPa)	26.8	29.8	30.4	26.5	26.8	26.6	26.4
	x, y (m)	0.1, -0.3	-0.1, -0.3	-0.1, -0.3	-0.1, 0.3	0.1, -0.3	-0.1, 0.3	0.1, -0.3



(a) Joint angle: 0°
(b) Joint angle: 15°
(c) Joint angle: 30°
(d) Joint angle: 45°
(e) Joint angle: 60°
(f) Joint angle: 75°

Figure 8: The reexplored position of the maximum von Mises stress and the maximum displacement.

Table 4: The maximum shear stress around the borehole (MPa).

Number of joints	Joint angle 0°	15°	30°	45°	60°	75°
1	33.6	33.0	31.6	29.3	27.5	27.0
2	33.6	33.0	31.4	28.3	26.4	28.6
3	33.2	33.1	32.0	27.8	25.8	27.1
4	33.3	33.0	31.8	26.5	25.3	26.6
5	32.7	33.9	32.2	27.7	24.8	27.0
6	32.8	34.2	32.1	26.0	24.0	26.8
7	32.5	34.6	32.4	24.9	23.8	26.5

Table 5: The maximum displacement around the borehole (mm).

Number of joints	Joint angle 0°	15°	30°	45°	60°	75°
1	0.95	1.5	2.4	2.4	2	1.9
2	1.1	1.9	3	3	2.8	2.7
3	1.5	2.6	3.8	3	3.4	3
4	1.8	2.6	3.8	3.8	3.8	3.4
5	1.9	1.9	1.9	2.9	2.8	2.6
6	1.4	1.7	2.4	2.8	2	1.8
7	1.2	1.2	1.8	1.5	1.3	1.4

4. Conclusions

Based on the boundary element, the numerical model of the coal rock mass with the distribution of the joints is established to study the influence of borehole drilling on the stress and displacement field. The parametric study is carried out in terms of the joint angle and the number of joints. The following conclusions can be obtained.

(1) The maximum displacement increases with the number of joints. The position of the maximum displacement shifts from the boundary of the borehole to the far field. The maximum displacement of coal rock mass can be found around the No. 4 joint and No. 7 joint. There is a slight drop of the displacement when the joints are distributed at 15°or 30°. The displacement may reach a peak value when the joint angle is 30° and if the joint number is less than 4. The drop occurs when the joint number rises by 4 to 5. The domination component of the maximum displacement gradually transits from vertical displacement to horizontal displacement as the joint angle varies from 0° to 75°

(2) The von Mises stress has a trend of increase with the number of joints when the joint angle is less than 30°. It has a decreasing trend when the joint angle is larger than 30°. Such stress generally decreases with the incline joints (joint angle > 0°). The maximum von Mises stress may occur at the joint angle of 15°. The maximum shear stress occurs mostly in the No. 4 joint and the No.7 joint. When the joint angle is 30°, the maximum shear stress occurs in the No. 3 joint and the No. 4 joint

(3) The overlap of the position of the maximum von Mises stress or the maximum displacement with different joint angles or different numbers of joints leads to a reexploration of such positions. The position of the maximum von Mises stress and the maximum displacement is relatively steady, which locates symmetrically around the borehole. The line between the points that behaves as the maximum von stress is approximately perpendicular to the joint direction

Data Availability

The data used to support the findings of this study are available from the first author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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