Research Article

The Principle of Invariant Stress of the Surrounding Rock of the Hole under the Condition of Equal Pressure in the Deep Rock Mass

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Based on the hydrostatic pressure theory of initial stress state of rock mass, combined with Saint-Venant's principle central idea, the principle of invariant stress of surrounding rock mass of the hole under the condition of equal pressure in deep rock mass is put forward. Numerical simulation is used to study the properties of surrounding rock and section shape of different holes, the depth of the plastic zone, the range of stress influence, and the relationship between them. The study results showed the following. (1) In the current mining depth range, it is difficult to reach the limit of 5 times the hole radius under the condition of invariant pressure of deep rock mass, and it has a significant impact on the near field and relatively small impact on the far field, reflecting the localization effect of the stress influence range. (2) The increase of stress influence range mainly moves outward with the increase of plastic zone range, and its growth slope is low and tends to be horizontal, and the increase amount is negligible. (3) When the failure range of the plastic zone of the hole is small, the influence range of the stress does not change itself, which reflects the stress invariability of the small-scale failure of the surrounding rock of the hole. The research results verify the principle of stress invariability of the surrounding rock of the hole under the condition of equal pressure of the deep rock mass, which is consistent with Saint-Venant's central idea.

1. Introduction

With the gradual depletion of shallow mineral resources and the continuous trend of resource development towards the depth of the earth, the exploitation of deep resources in kilometer deep wells has gradually become a new normal of resource development. Deep mining is usually accompanied by geological conditions, crustal stress, temperature, and other factors, resulting in a series of problems, such as increasing mining difficulty, deterioration of operating environment, and sharp increase in production costs. Academician Xie [1, 2] proposed in situ mechanical behavior and crustal stress environment of deep rock mass, which is particularly important as one of the key scientific issues of deep rock mass mechanics and mining theory.

After the excavation of the underground hole, the original rock stress state of the rock mass is destroyed,

resulting in the redistribution of stress. In the infinite space of the underground, the failure and stability of the surrounding rock can be unified into the study of the rock mechanics around the hole [3, 4]. Scholars at home and abroad have carried out a systematic study on the failure of surrounding rock of holes and obtained fruitful research results [5–10]. When Zhao et al. [11, 12] studied the plastic zone of the surrounding rock of the circular roadway, they found that the surrounding rock of the roadway would produce “butterfly shaped plastic zone” in the nonuniform stress field. Guo et al. [13] further studied the shape of the plastic zone in the nonuniform stress field and obtained the circular, elliptical, and butterfly judgment criteria and stress conditions. Liu et al. [14–17] found that when the shape of the plastic zone of the surrounding rock of the roadway is circular or elliptical, the maximum radius of the plastic zone increases linearly and slowly with the increase of the

principal stress, and the plastic zone and the range of stress influence increase linearly and slowly; when the shape of the plastic zone is butterfly, the plastic zone expands rapidly and the range of stress influence is nonuniform and rapid. Based on many years of theoretical research and field practice of surrounding rock failure of underground holes, combined with Saint-Venant's principle [18]: if the surface force on a part of the boundary of an object is changed into a static equivalent surface force with different distribution, this surface force will only produce significant stress in the near place, and the stress effect at the far end can be ignored.

Under the condition of equal pressure in deep rock mass, the principle of stress invariability of surrounding rock mass is that when the initial stress state of rock mass is in hydrostatic state, the change of surrounding stress caused by the arrangement of holes in rock mass has a great influence on the near field, while the far-field influence is ignored, and its influence range reflects the localized effect. The state of deep hydrostatic pressure is taken as the stress condition, and the relationship between the failure state of the surrounding rock and the influence range of the stress is analyzed under the conditions of different surrounding rock properties and section shapes. The analysis of the relationship between the failure state of surrounding rock and the influence range of stress is the basis of studying the mechanical properties of deep rock and analyzing the stability of surrounding rock. It has important scientific knowledge for further understanding the failure and mechanical mechanism of surrounding rock in deep rock. Especially in the process of deep mining, the selection of roadway and borehole spacing is of great engineering significance.

2. Establishment of Numerical Model

In the aspect of the influence range of the stress in the surrounding rock of the hole [19], in the elastic state, the stress range of the axisymmetric plane strain round hole problem is generally taken as the influence radius when the maximum principal stress exceeds 5% of the original rock stress, and it is concluded that the influence radius is $Ri = \sqrt{20}r_1 \approx 5r_1$, where Ri is the radius of the round hole. The numerical simulation software is used to analyze the stress change around the circular hole in the rock mass [20], and three states of circular, elliptical, and butterfly are obtained by the method of stress contour in the circular, elliptical, and butterfly plastic areas.

In this paper, FLAC3D numerical simulation software is used to establish a plane strain model of $50\text{ m} \times 0.1\text{ m} \times 50\text{ m}$ in X , Y , and Z directions by applying the Mohr–Coulomb strength criterion. The radius of the hole section is 2.5 m, the area is relatively small, and the cell width is 0.1 m. The horizontal displacement of the left and right sides of the model is limited, and the vertical displacement of the roof and bottom is limited. The initial force is used for loading. The original rock stress is all equal pressure (hydrostatic pressure) conditions. The lateral pressure coefficient λ value is 1, that is, $\sigma_x = \sigma_y = \sigma_z = \gamma H$ (σ_x is the X -axis stress, σ_y is Y -axis stress, σ_z is Z -axis stress, γ is bulk density of overlying strata, and H is the depth), and the buried depth is greater than or equal to 20 times the

roadway radius. The self-weight of the rock within the roadway influence range (5 times the roadway radius) is ignored. Figure 1 shows the numerical model schematic diagram of different hole shapes.

According to the influence range of single hole surrounding rock stress, this paper determines the influence range in which the maximum principal stress exceeds 5% of the original rock stress to reach $5r_1 = 12.5\text{ m}$ to define the stress influence range.

In order to make the verification results of universal significance, three representative rock materials in underground mining are selected as the surrounding rock conditions of holes, and the physical and mechanical parameters are determined according to the mechanical parameters of coal, mudstone, and sandy mudstone in the actual geological conditions [13, 21, 22]. The specific physical and mechanical parameters of rock are shown in Table 1.

3. Influence Range of Stress of Surrounding Rock with Different Lithology Holes

In underground coal mining, some preparation roadways are arranged in the coal body. Therefore, when the mechanical property of coal body is used as the lithology of surrounding rock of the hole, the change of the depth of the hole on the plastic zone $R_{\max}$ and the stress influence range Ri is studied. Through theoretical calculation, the original rock stress of different mining depths is loaded into the model, and through limiting the minimum value of the original rock stress, the numerical simulation results achieve the purpose that the stress influence range only reflects the part exceeding 5% of the original rock stress, as shown in Figure 2. Then, the specific value of stress influence range Ri is measured.

Under the condition that the surrounding rock of the hole is coal, the shape of the plastic zone of the surrounding rock of the hole is round with the increase of the depth from 100 m to 1600 m, and the damage range is gradually increased from 0.1 m to 4.4 m. It can be seen from the stress distribution state of the surrounding rock of the hole that the stress distribution form is also circular, and the stress concentration occurs outside the boundary of the plastic zone of the surrounding rock of the hole, and the closer it is to the boundary, the more obvious the stress concentration is, and the farther it is, the lower it is; the stress influence range gradually increases from 7.1 m to 12.7 m, and when the depth reaches 1600 m, it is more than 5 times the hole radius, which has exceeded the maximum mining depth in the coal safety regulations of 1200 m [23].

When the holes are arranged in the rock mass and the common mechanical properties of mudstone and sandy mudstone in the underground mining are used as the lithology of the surrounding rock of the holes, the change of plastic area and stress influence range under different burial depth is studied, and the results are shown in Figures 3 and 4.

It can be seen from Figures 3 and 4 that the shape of the plastic zone and stress influence range is circular under the two surrounding rock conditions. Under the condition of mudstone, with the increase of depth from 100 m to 4500 m,

FIGURE 1: The numerical model schematic diagram of different hole shapes.

TABLE 1: Rock mechanics parameters and model stress conditions of three forms.

Lithology	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)	Poisson ratio	Cohesion (MPa)	The angle of internal friction (°)
Coal	9.42	0.35	22.96	0.23	3	25
Mudstone	20.78	1.91	10.35	0.24	6	30
Sandy mudstone	34.57	4.39	2.69	0.22	9	35

the range of the plastic zone increases from 0 m to 4.1 m; the range of stress influence increases from 7.0 m to 12.5 m with the increase of depth, reaching 5 times the hole radius. Under the condition of sandy mudstone, from 100 m to 9000 m, the range of the plastic zone gradually increases from 0 m to 3.6 m, and the range of stress influence gradually increases from 7.0 m to 12.5 m. The influence range of the two kinds of lithology hole stress is more than 5 times the hole radius, which has exceeded the current limit depth of human underground mining (3800 m) [24].

It can be seen from the above that under the current mining technology conditions, it is difficult to reach the limit of 5 times the hole radius within the range of mining depth that can be achieved. Under this condition, the range of hole stress is relatively local, which has a significant impact on the near field and a relatively small impact on the far field.

4. Influence Range of Stress of Surrounding Rock with Different Section Shapes and Holes

It is established that the section shape of the model hole is rectangular and straight wall semicircle arch section, which was externally connected to a circle with the radius of 2.5 m [25]. Under the condition that the surrounding rock properties are all coal body, the change of the surrounding rock plastic area and its stress influence range when the

shape of the hole changes with the burial depth is studied, as shown in Figures 5 and 6.

As shown in Figures 5 and 6, under the two hole section shapes, the shape of stress influence range is circular.

With the increase of buried depth from 100 m to 1700 m, the plastic zone of the surrounding rock of rectangular hole increases continuously, and its failure range increases from 0.1 m to 3.5 m; the shape expands from four corners to the center of the depth → approximately diamond → approximately circular evolution distribution characteristics; the influence range of stress increases from 7.1 m to 12.5 m. At the initial stage of the change of the surrounding rock plastic area with the depth of the straight wall semicircular arch roadway, the expansion rule of the lower part and the rectangular roadway plastic area is the same, and the change of the upper part and the circular hole plastic area is the same, as shown in Figure 5(b); with the continuous increase of the depth, the shape of the plastic area gradually evolves into a nearly circular distribution feature, but the failure depth of the upper part is obviously smaller than that of the lower part. The buried depth increases from 100 m to 1700 m, and the plastic zone increases from 0.1 m to 4.3 m; the stress influence range increases from 7.2 m to 12.5 m with the increase of depth, reaching 5 times the hole radius. It can be seen that it is difficult to reach the limit of 5 times the hole radius by

FIGURE 2: Plastic area of the surrounding rock of hole in coal body and its influence range: (a) $H = 100$ m; (b) $H = 500$ m; (c) $H = 1000$ m; (d) $H = 1500$ m; (e) $H = 1600$ m.

FIGURE 3: Plastic area of the surrounding rock of the hole in the mudstone and its influence range: (a) $H = 100$ m; (b) $H = 1000$ m; (c) $H = 2000$ m; (d) $H = 3000$ m; (e) $H = 4000$ m; (f) $H = 4500$ m.

changing the shape and stress of the roadway cross section. For the shallow surrounding rock, the shape of the plastic zone changes greatly, and almost all of the deep parts form a circular distribution. Therefore, changing the shape of the hole section has a significant effect on the near field and a relatively small effect on the far field.

5. The Relationship between the Failure Range of Surrounding Rock and the Influence Range of Stress

It is found that with the increase of depth, the plastic zone and the influence range of stress are in the same process, and

FIGURE 4: Plastic area of the surrounding rock of the hole in the sandy mudstone and its influence range: (a) $H = 100$ m; (b) $H = 1000$ m; (c) $H = 2000$ m; (d) $H = 3000$ m; (e) $H = 6000$ m; (f) $H = 9000$ m.

FIGURE 5: Plastic area of surrounding rock of rectangular fracture face and influence range of stress: (a) $H = 100$ m; (b) $H = 500$ m; (c) $H = 1000$ m; (d) $H = 1500$ m; (e) $H = 1700$ m.

the increase part of stress is outside the boundary of plastic zone. In order to find out the relationship between the stress range and the plastic zone range, the difference between the stress influence range and the plastic zone range is defined as the stress ring range, and the data generation curve of the three is applied to the linear fitting of the data by the least squares method. The results under different surrounding rock conditions are shown in Figures 7–9.

From Figure 7, it can be seen that with the increase of depth, the plastic zone and the stress influence range show a linear growth trend. From the slope of the two, it can be seen that the increase degree of the stress influence range is slightly higher than the increase degree of the plastic zone range; from the correlation coefficient R^2 is

greater than 0.95, indicating that the degree of fitting is higher with the increase of depth range. The slope of the stress ring is 0.001, which means that its increasing range with depth is very small, its correlation coefficient R^2 is only 0.92, and the linear fitting degree is relatively low. The analysis data show that, due to the increase of buried depth from 100 m to 500 m, the range of plastic zone increases from 0.1 m to 1 m, and the range of stress influence increases from 7.1 m to 8 m, but the stress ring range does not change, and the stress influence range only increases with the depth of the plastic zone. When the buried depth is more than 500 m, the range of stress ring begins to increase as the depth of the plastic zone continues to increase.

FIGURE 6: Plastic area and stress influencing area of surrounding rock of straight wall semicircular arched section: (a) $H = 100$ m; (b) $H = 500$ m; (c) $H = 1000$ m; (d) $H = 1500$ m; (e) $H = 1700$ m.

FIGURE 7: Relationship between the plastic zone of holes in the surrounding rock and the influence range of stress.

In the case of mudstone, when the surrounding rock of the hole is not damaged, the stress influence range is 7 m; the buried depth is 100 m–1000 m, the plastic area is increased from 0 m to 0.8 m, the stress influence range is increased from 7 m to 7.8 m, and the stress ring range is unchanged; the buried depth is 1000 m–4500 m, the stress ring range is increased from 7 m to 8.5 m, and the growth slope is only 0.0004. In the case of sandy mudstone, when the surrounding rock of the hole is not damaged, the range of stress influence is 7 m, the buried depth is from 100–1500 m, the range of plastic area is from 0 m to 0.6 m, and the range of stress influence is from 7 m to 7.6 m, but the range of stress ring in this range is also unchanged; the buried depth is from

1000 m–4500 m, the range of stress ring is from 7 m to 8.9 m, and the increase slope is 0.0002, approaching the horizontal direction.

Figures 7–9 show that with the increase of depth, the plastic area and stress influence range show a linear growth trend, and the comparison slope shows that the higher the hole lithology strength is, the lower the increase range of plastic area, stress influence range, and stress ring range are; from the stress ring fitting correlation coefficient R^2 , it is found that the higher the stress ring fitting degree is with the increase of lithologic strength. The higher the analysis is due to the fact that the fitting line tends to be horizontal gradually.

FIGURE 8: Relationship between the plastic area range of holes and the influence range of stress under mudstone conditions.

FIGURE 9: Relationship between the plastic area range of holes and the influence range of stress under the condition of sandy mudstone.

In conclusion, the relationship between the failure range of the plastic zone and the influence range of stress can be summarized as follows: ① the increase of stress influence range mainly increases with the increase of plastic zone, and both increase linearly with the depth; ② the change range of stress loop is small with the depth and tends to be horizontal with the increase of lithologic strength; and ③ when the range of the plastic zone is small, the range of stress loop is not changed, and the range of stress influence only moves outward with the increase of the plastic region.

When the surrounding rock condition is fixed as coal body, the influence of section shape on the plastic zone and stress range of surrounding rock is analyzed. The results are shown in Figures 10 and 11.

It can be seen from Figure 10 that the buried depth of rectangular hole is within 100 m–700 m, the damage range of plastic area is increased from 0.1 m to 2 m, the stress influence range is increased from 7.1 m to 9 m, the damage range of stress ring in 100 m and 700 m is 7 m (in this range, the range of stress ring presents the trend of first decreasing and then rising), the buried depth is within 100 m–500 m, and the stress ring presents the trend of negative growth. The analysis is as follows: because the plastic zone of the surrounding rock of the rectangular hole presents nonuniform expansion in this range, its influence on the stress range is small, and the plastic zone has a large range, while the range of the stress ring decreases; after 500 m, the plastic zone gradually develops to the approximate circle, and the range of the stress ring begins to increase. After 700 m of buried

FIGURE 10: Relationship between plastic zone range and stress influence range of rectangular hole section.

FIGURE 11: Relation between plastic zone range and stress influence range of straight wall semicircular arch hole.

depth, the range of stress ring began to increase, and its overall increase slope was 0.0016, with a small increase. The change rule of the semicircular arch section of the straight wall is basically the same as that of the rectangle.

Through the comparative analysis of Figures 7, 10, and 11, it is found that the slope of plastic area and stress influence area of rectangular hole with depth is slightly lower than that of circular roadway. The reason for the analysis is that the plastic area of rectangular section hole expands from nonuniform to uniform, and this process reduces the development rate of both. When the failure range of the plastic zone is small, the failure range of the plastic zone of circular hole is uniform, and the influence range of stress moves outward with the increase of the failure range of plastic zone, but the stress ring remains unchanged. For rectangular and straight wall semicircle arch sections, because the failure

range of the plastic zone is not uniform, the stress ring shows wave adjustment, and the range of stress ring does not increase during the adjustment process.

The above results show that when the shape of the hole section changes, the range of stress influence is smaller with the increase of the depth, and the slope of the stress loop tends to be horizontal, and in the small-scale failure range, the stress influence range is invariable.

6. Conclusion

- (1) In the current mining depth range, under the condition of constant pressure of deep rock mass with different lithologies and cross-sectional shapes, the influence range of hole stress is difficult to reach the limit of 5 times the hole radius, and it has significant

influence on near field and relatively small influence on far field, reflecting the localization effect of stress influence range.

- (2) Through the study of the influence range of the stress in the surrounding rock of circular holes with different lithologies, it is shown that the increase of the influence range of the stress in the deep rock mass under the condition of equal pressure mainly moves outward with the increase of the plastic area, and its growth slope is low and tends to be horizontal. With the increase of the strength of the lithology, the slope is closer to the horizontal direction, and its increase can be ignored.
- (3) When the failure range of the plastic zone of circular hole is small, the influence range of stress only increases with the change of the plastic zone, while the influence range of stress itself does not change. In a certain range, the influence range of stress is not increased, which shows the invariable characteristics of small-scale failure stress.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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