Study on the Effect of Borehole Size on Gas Extraction Borehole Strength and Failure Mode

Yabin Gao and Jie Ren*

ABSTRACT: In the coal mine industry, the instability failure of an extraction borehole is one of the main factors leading to the decrease in gas extraction rate. The study on borehole strength and failure mode with different sizes can provide a theoretical basis for the optimization and selection of a gas extraction borehole. In this paper, biaxial loading tests are carried out on similar coal specimens, and the prediction model of borehole strength is proposed and verified. At the same time, numerical simulation of similar specimens is carried out to analyze the failure process of boreholes of different sizes. The results show that hole size has a great influence on hole strength, and the hole strength decreases with an increase of hole size. Size change has a great influence on the strength of a small-size borehole, and the strength of the borehole gradually stabilizes with an increase of size. The process of borehole failure can be divided into three stages, borehole top failure, borehole deformation, and crack extension. Stress concentration and a large number of cracks occur on the two wings of the borehole, and these cracks reduce the strength of the borehole. The stress concentration area of the borehole is X-shaped distribution, and the through crack mainly extends along this area and leads to the failure of the specimen.

INTRODUCTION

In the coal mine industry, the instability failure of an extraction borehole is one of the main factors leading to the decrease in gas extraction rate. The size of a borehole is an important factor in determining the strength of the borehole. The study on borehole strength and failure mode with different sizes can provide a theoretical basis for the optimization and selection of a gas extraction borehole. Due to the exhaustion of shallow coal resources, the depth of the mine is increasing year by year, and the deep drilling operation is faced with difficulties such as high in situ stress, easy instability, and failure of drilling, which seriously threaten the mining of deep coal resources. Optimizing the size selection to improve the strength of a borehole is the key to improving the gas extraction rate.

The performance differences caused by different sizes of materials are collectively referred to as the size effect, which is widely found in rock materials. Existing studies show that the size effect is related to rock heterogeneity. Experiments and numerical simulations show that the size effect has a great influence on the properties of rock materials. Similarly, the strength of the borehole in a rock medium is also affected by its size, resulting in the size effect. Gou conducted a marble cylinder triaxial compression experiment and verified that the peak strength of the borehole is inversely proportional to the radius of the borehole within a certain pressure range. Lin analyzed the borehole stress distribution through numerical simulations and proved that the borehole size effect mainly affects the borehole wall. Qi conducted uniaxial compression experiments on coal pillars containing boreholes and analyzed the strength of boreholes of different sizes in rectangular coal pillars. As the main body of gas extraction, the stable existence of a borehole is the key to ensuring efficient gas extraction, and the size effect has a decisive influence on the stability of the borehole.

The classical elastic—plastic theory and fracture mechanics are the basic methods for studying borehole instability failure. Tehrani carried out a sandstone thin-wall cylinder compression experiment and verified that drilling size has a great influence on borehole stability. Joung used the classical elastic—plastic theory to predict the strength of a certain size borehole. However, classical elastoplastic mechanics lacks a description of the borehole size. Papanastasiou and Vardoulakis tried to add parameters such as strain gradient to predict the borehole strength of different sizes. Tronvoll proposed to use fracture mechanics to describe the crack around the borehole.

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and indirectly predict the borehole strength by calculating the crack strength.\textsuperscript{18} In the above theory, fracture mechanics can better describe the process of instability deformation and crack propagation around the borehole. However, the prediction of borehole strength of different sizes by fracture mechanics remains to be further studied.

As a typical plant sedimentary rock, coal has a complex primary joint and fissure structure. Anisotropy leads to the size effect having a greater impact on drill holes in coal.\textsuperscript{19,20} In addition, the primary cracks around the borehole will guide the crack propagation direction and influence the failure mode of the borehole.\textsuperscript{21,22} This paper attempts to establish the relationship between the size and strength of boreholes through biaxial compression experiments of simulated specimens and analyzes the failure modes of boreholes with different sizes.

Boreholes in rocks are subjected to stress, and many primary fissures are enlarged or connected. These structures are also called buckling layers. These layered structures will form a new stress balance and transfer stress. According to the buckling layer theory, the layered structure of borehole’s two wings will be further extended and finally detached from the original structure in the compression process, and the above process in turn will further prolong the failure surface of the borehole and finally lead to failure.\textsuperscript{22} This process can well describe the failure process of coal seam boreholes, so the buckling layer theoretical model is used to study the strength of coal seam boreholes.

1. METHODOLOGY

1.1. Experiment Preparation. The experimental specimens were formed by mixing coal powder, cement, gypsum, additives, and water in a mass ratio of 4:1:0.3:8 and then compressed for 30 min under 50 MPa pressure, with a size of 150 mm × 150 mm × 30 mm. Raw coal was from Henan Pingdingshan, and 60–80 mesh coal powder was broken and screened. Mechanical parameters of raw coal and specimens are shown in Tables 1 and 2. The molded specimens were cured in an incubator for 28 days. Finally, eight holes of 2–16 mm were drilled at 2 mm intervals on the eight molded specimens.

Table 1. Mechanical Parameters of the Coal Sample

| density (kg/m\(^3\)) | elasticity modulus (MPa) | UCS (MPa) | UTS (MPa) | internal friction angle (\(^\circ\)) | cohesive forces (MPa) |
|------------------------|--------------------------|-----------|-----------|-----------------------------------|------------------------|
| 1280                   | 1501                     | 1.631     | 0.485     | 25.2                              | 0.575                  |

As shown in Figure 1, the biaxial loading system includes an MTS Criterion hydraulic universal testing machine and a lateral hydraulic pressure stabilizing loading system. The vertical MTS servo testing machine uses an MTS servo control hydraulic actuation system and a high-speed, digital closed-loop controller to perform a high-precision stress control loading test. The lateral hydraulic pressure stabilizing loading system can steadily apply pressure from 0 to 20 MPa. The strain acquisition system consists of a strain acquisition instrument, a strain gauge, and an acquisition computer. Four gauging points were set on the surface of the specimen, among which gauging 2 and gauging 3 are equal to the distance from the borehole and gauging 1 and gauging 4 are equal to the distance from the borehole.

Before the test, the strain gauge was pasted in the horizontal and vertical directions of the drilling hole, and the collection frequency of the strain gauge was set to 0.25 Hz. After the initial balance, the press was started at the same time. All data were collected by the acquisition instrument and recorded on the computer.

During the test, the horizontal load was first loaded to 0.2 MPa and kept constant. After the lateral stress reached the requirements, the vertical load was loaded at a rate of 10 N/s until the specimen was destroyed. During the loading process, to ensure the specimen crack development, the loading was stopped after the specimen strength was reduced to 40% of the peak strength. Under the same conditions, eight specimens were subjected to compression tests to observe the failure process and fracture morphology of drilling holes.

1.2. Prediction Model of Borehole Strength. There is a strong correlation between borehole strength and borehole size. To calculate the peak stress of boreholes with different sizes, the following model is established. Suppose there is a circular hole with aperture R in the infinite elastic medium, as shown in Figure 2, and there are maximum principal stress and another small stress perpendicular to each other in the direction of the circular aperture (\(\sigma_{yy} > \sigma_{xx}\)). The borehole tends to change into an elliptical hole with the long axis parallel to the direction of maximum principal stress and the short axis parallel to the direction of minor stress,\textsuperscript{23} and the short axis length is almost equal to the radius of the circular hole R. According to the buckling layer theory, such instability in the two-wing failure zone is caused by the mutual expansion and connection of flat failure layers of the same thickness in the medium, which are called buckling layers. Figure 2 shows that the buckling layer expands inside the medium and gradually shortens along the direction of maximum principal stress.\textsuperscript{24}

For coal seam drilling, due to the widespread distribution of joints, cracks, and other original defects in coal rock, it is easier for the bedding drilling to form the above buckling layer failure structure along the natural weak surface of the structure under pressure.

According to Eshelby’s theory, under biaxial stress, when an elliptic hole with a long axis of 2a and a short axis of 2R is cut off in an infinite elastic medium, the internal stress changes to a specific \(\sigma_{yy}\). The energy change as the pressure inside the ellipse decreases from \(\sigma_{yy}\) to a specific \(\sigma_{\epsilon}\) can be expressed as

\[
\Delta Q = -\frac{\pi}{2E'}\left[(aR - R^2)\sigma_{yy}^2 + (2a^2 + Ra - 3R^2)\sigma_{yy}^2 + 2R(R - a)\sigma_{xx}\sigma_{yy} - 2a^2 \sigma_{xx}^2\right]
\]

\(E' = E/(1 - \nu^2)\) is defined as the plane elastic modulus, \(E\) is the young’s modulus of the medium, \(\nu\) is Poisson’s ratio, \(\sigma_{xx}\) and \(\sigma_{yy}\) are the radial pressures applied at an infinite distance, where \(\sigma_{yy} < \sigma_{xx}\).

The buckling layers formed by compression are parallel to each other and of equal thickness. Each buckling layer can be simplified as a fixed-end parallel column with the same length as

Table 2. Mechanical Parameters of Forming Test Block

| elasticity modulus (MPa) | shear modulus (MPa) | poisson ratio | UCS (MPa) | UTS (MPa) | \(\lambda\) (mm) | \(K_{IC}\) (MPa × mm\(^{1/2}\)) | internal friction angle (\(^\circ\)) |
|--------------------------|---------------------|--------------|-----------|-----------|----------------|-------------------------------|-------------------------------|
| 1712                     | 602                 | 0.287        | 1.252     | 0.631     | 0.3215         | 0.3215                        | 26.7                          |
the borehole. The vertical pressure \( \sigma_c \) is obtained by the critical Euler load on the end column. The crack opening displacement caused by compression splitting is very small, and each buckling layer has no displacement in the direction perpendicular to the maximum principal stress, so the shear force can be transferred on the contact rough surface and the critical stress \( \sigma_c \) can be changed\(^\text{26}\)

\[
\sigma_c = \frac{\pi^2 E h^2}{\kappa^2 R^2} - \frac{h}{\lambda G}
\]

(2)

where \( h \) is the thickness of the buckling layer, \( \lambda \) is the intrinsic length and represents the thickness of the parallel plate equal to the relative displacement of the elastic shear of the parallel plate under the action of unit shear stress, which can be determined by the parallel plate shear test. \( \kappa \) is an empirical constant less than 1, which is the coefficient of unifying the buckling layer in the elliptic region into an equal-length parallel column; previous experiments have proved that \( \kappa \) has better accuracy when it is 0.25.

The residual strain energy between the initial drilled circular region and the damaged elliptic region can be determined by adding the stored elastic energy of each buckling layer

\[
Q_c = \left( \pi a R - \pi R^2 \right) \frac{\sigma_c^2}{2E'}
\]

\[
= \frac{\pi a (a - R)}{2E'} \left( \frac{\pi^2 E h^2}{\kappa^2 R^2} + \frac{h}{\lambda G} \right)^2
\]

(3)

From another perspective, the energy loss in the whole process can be determined by summing the energy loss of each buckling layer\(^\text{27}\)

\[
U_i = -\Delta Q + Q_c = \left( \pi a R - \pi R^2 \right) \frac{G_i}{h}
\]

(4)

where \( G_i/h \) is the energy dissipation of each buckling layer, \( G_i = K_{IC}^2/E' \) is the fracture energy of the specimen, and \( K_{IC} \) is the fracture toughness of the specimen.

Assuming that the buckling layers are generated one by one during fracturing, the equation about energy change can be obtained by differentiating both sides of the above equation with respect to \( a \). Substituting \( a = R \) when no fracture occurs, we can get

\[
\left[ \sigma_{xx}^2 + 5\sigma_{yy}^2 - 2\sigma_{xx}\sigma_{yy} - 4\sigma_{xx} \right] = \left( \frac{\pi^2 E h^2}{12\kappa^2 R^2} + \frac{h}{\lambda G} \right)^2 + \frac{2E'G_i}{h}
\]

(5)

The pressure on the left side of the above formula can be uniformly expressed as

\[
\sigma_{xx}^2 = F(R, h) = \left( \frac{\pi^2 E h^2}{12\kappa^2 R^2} + \frac{h}{\lambda G} \right)^2 + \frac{2E'G_i}{h}
\]

(6)

The right-hand side of the equation can be considered as a function of \( R \) and \( h \), \( \sigma_{xx} \) is the peak stress of the material, and the expression of \( \sigma_{xx} \) is a power function, so there is a stagnation point. Parameter \( h \) is the critical thickness of the buckling layer, and the corresponding \( \sigma_{xx} \) is the critical failure stress of borehole failure. In other words, the medium splits under the maximum pressure it can bear, and a buckling layer with the corresponding width of \( h \) is obtained. Solving the extreme value of eq 6 is the value of finding the stagnation point \( h \), and the solution accuracy of the stagnation point \( h \) will directly affect the solution accuracy of pressure

\[
\frac{5\pi^4 E^2}{72\kappa^4 R^2} h^5 + \frac{15\pi^2 E'G_i h^4}{12\kappa^2 R^2\lambda} + \frac{5G_i^2 h^3}{\lambda^2} - E'G_i = 0
\]

(7)

Equation 7 takes \( h \) as the independent variable, and the solution process of a higher-order polynomial is complex and will change according to different types of solution methods. Accurate solutions and approximate solutions can be obtained according to different precisions. Using a gradually approximation method can find the exact solutions of the equation; mathematical tools such as Mathematica can accelerate the speed of solving; usually, the results will be a number of different stagnation points; only positive numbers within the scope of the stagnation point have physical meaning, and since \( h \) is the thickness of cracks on both sides of the borehole, the exact solution exceeding the diameter of the borehole should be discarded. The reserved exact solution can best describe the
predicted results of the model, and the exact peak stress solution can be obtained by substituting it into eq 6.

To simplify the difficulty of solving eq 7, the approximation solution can also be used. The approximation solution is to ignore the second and third terms of eq 7 when R is very small and ignore the first and second terms of eq 7 when R is very large. The monomials of two h’s are substituted into eq 6, respectively, and then summed and sorted out to obtain the approximate solution expression of peak stress

\[ \sigma_{tr} = \left( \frac{\pi^2}{1200k} \right)^{1/5} \left( \frac{E^3G_l}{\pi^2} \right)^{2/5} R^{-2/5} + \sqrt{ \frac{GE'G_l}{5\lambda} } \left( \frac{G_l}{\pi^2} \right)^{1/3} \]  

(8)

To intuitively compare the two solutions, the prediction of Tronvoll and Papamichos experimental results by the two solutions is plotted in Figure 3.

As shown in Figure 3, the approximation degree of the two solutions is high when the pore size is less than 30 mm. When the pore size is between 60 and 300 mm, the exact solution is more consistent with the compression test results of rock drilling, and the two solutions have the same trend in the whole range. Tronvoll et al. used hollow cylindrical specimens with an inner/outer diameter ratio of 1:5 to conduct compression experiments. The model calculation results showed that the average error of approximate solutions of Red Wildmoor rock could reach more than 40% of the experimental results. Therefore, exact solutions could better predict the borehole strength in the whole range. In this paper, the exact solution of the model is used to calculate the borehole strength. In addition, the physical significance of \( h \) refers to the thickness of the buckling layer of the two wings when the borehole is damaged. In engineering construction, the energy around the borehole is more likely to be released along the original fracture, resulting in the thickness of the buckling layer closer to the thickness of the original fracture. To better describe the actual situation, the thickness of the buckling layer can be calculated according to the actual thickness of the original fracture of the material.

2. RESULTS

2.1. Strain Characteristics of Specimens. The mechanical parameters of the loading test are shown in Table 3. The outward expansion at the gauging point is a positive displacement, and the inward contraction is a negative displacement. It can be seen that there is a linear relationship between peak stress and peak strain and hole size. During the experiment, the peak strain is consistent with the changing trend of borehole size, and the peak strain at gauging points around the large-size borehole increases obviously.

| specimen no. | hole diameter (mm) | peak stress (MPa) | peak strain (%) | density (kg/m³) |
|--------------|-------------------|------------------|----------------|----------------|
| S02          | 2                 | 2.52             | 2.61           | 944            |
| S04          | 4                 | 2.71             | 3.62           | 953            |
| S06          | 6                 | 2.24             | 2.68           | 938            |
| S08          | 8                 | 2.82             | 1.68           | 956            |
| S10          | 10                | 1.46             | 3.10           | 915            |
| S12          | 12                | 2.38             | 2.95           | 953            |
| S14          | 14                | 2.08             | 3.36           | 930            |
| S16          | 16                | 2.01             | 4.19           | 936            |

Figure 3. Difference between the exact solution and the approximation solution.

2.2. Stress Peak Characteristics of Specimens. Studies have shown that the ratio of loading rate to pressure \( (\sigma_{tr}/\sigma_{p}) \) will affect the peak strength of the specimen. Under the same conditions, the existing conclusions show that a fast increase in the ratio of pressure to reduce the pressure can effectively improve the peak stress. However, the loading rate is not easy to control in the actual situation. The loading rate and the magnitude of stress in different directions are limited by geological conditions, and generally speaking, the size of the specimen will increase with the borehole size in the borehole experiment, but it will also lead to the size effect of the rock specimen itself and affect the experimental results. Therefore, it is necessary to study the size as a single variable.

Many researchers have proved that the size of the hole is an important parameter affecting the drilling strength through the compression test of prefabricated drilled specimens and hollow cylinders. The stress change process of the experimental specimen is shown in Figure 5. The peak stress of the specimen...
varies in the range of 1.43–2.8 MPa. The strength of specimen S04 is the highest, and the strength of specimen S10 is the lowest. It may be due to the low density caused by defects in the manufacturing process of the specimen. The stress concentration of large hole drilling is obvious, and the strength of specimen S16 is 49% lower than that of specimen S08, which proves that the drilling strength decreases gradually with an increase of drilling size. The strength of specimens S02 and S04 fluctuates in a small range, which shows that the relationship between small-size drilling strength and hole diameter is not
strictly monotonic, indicating that the influence of hole diameter on drilling strength gradually increases with an increase of drilling size.

As shown in Figure 5, the peak stress of the specimen is roughly linearly distributed along the loading time. If the loading rate is considered to be the force applied per unit time, the instability peak stress points of holes of different sizes are distributed along the loading rate curve. It is useful to further simplify eq 6.

$$\sigma_{cr} = \left( \frac{2E^2}{3R^2} \left(\frac{h}{G} \right) + \frac{2E'}{h} \right)^{0.5}$$  \hspace{1cm} (9)

The calculation method of borehole peak stress $\sigma_{cr}$ is shown in eq 9, where are constants except $R$ and $h$, and drilling radius $R$ is a dependent variable. Parameter $h$ is the fragment thickness generated at both wings when the drilling medium is damaged. Therefore, to calculate the drilling peak stress, it needs to be further determined. The developed primary joints and fissures in sedimentary rocks such as coal and rock can promote the formation of fragments as a structural weak plane when the drilling is expanded and damaged. Therefore, the joint fissure thickness of materials such as coal and rock can be considered as the thickness of the buckling layer, and $h$ can be substituted into eq 9.

The simulated specimen used in the experiment can also be verified by a model. A large number of cracks between the simulated specimen particles are the best channel for energy release. Therefore, the average distance of particles is used to replace the original crack width $h$ in the calculation. The main material of the test piece is 60−80 mesh pulverized coal, and the particles are connected with each other by an adhesive. Accumulation can be considered as a dense accumulation of unequal large spheres with a particle size ratio of 0.72. According to the dense accumulation of unequal large spheres, the void ratio of the test piece is about 0.74. The accumulation model of particles in the spontaneous state is similar to the third model of nonabsent Bravais lattice accumulation proposed by Ye et al. Based on this, it can be calculated that the average gap between particles of the test piece is about 0.01058 mm. Replace eq 9 to calculate the peak drilling strength and draw Figure 6. Based on this, it can be calculated that the average gap between particles of the test piece is about 0.01058 mm. Bring it into eq 9 to calculate the peak drilling strength and draw Figure 6.

Figure 6 shows that the model can predict better the peak stress of the borehole. Due to the existence of primary joints and fissures in coal and rock, the peak stress of the borehole can be considered as only $R$. The relationship between the peak stress of the borehole and the borehole size is a logarithmic function. The peak stress decreases with an increase of borehole size, but the downward trend gradually slows down. Therefore, the peak strengths of specimens S16 and S18 are similar, and the peak strength of a large-size borehole decreases under the influence of borehole size. The reason is that the decrease of large-size borehole strength is the result of the joint action of the hollow-out area and the edge stress concentration. With an increase of borehole size, the increase rate of the borehole area is greater than the perimeter. The increase of drilling area of specimen S16 is 22% more than the increase of perimeter. At this time, the influence of excavation plays a leading role and leads to rapid instability and deformation of drilling. In addition, comparing Figure 6 with Figure 3, it can be found that the falling speed of drilling strength of high-strength rock is slower, which is manifested in the slow approaching speed of the back section of the curve of hard rock. The size of about 60 mm still has a great impact on the drilling strength of Berea rock. The reason may be that the high-strength rock has strong deformation resistance, and drilling will not collapse rapidly under pressure and can maintain a more complete shape.

2.3. Analysis of the Crack Propagation Process. The failure mode of borehole instability is shown in Figure 7, and the serial number in the figure indicates the failure sequence. The failure process is divided into three stages. First, fine cracks are caused by extrusion at the upper and lower ends of the borehole, and the cracks will only extend briefly, so this will not affect the borehole shape. Then, the borehole shape gradually becomes oval. Many experiments show that the two wings of the borehole are important nodes for crack extension. These cracks are mainly shear failure. With an increase of pressure, cracks appear on the two wings of the borehole and the diagonal of the specimen and extend along the diagonal direction. The cracks communicate with each other and eventually lead to the failure of the specimen.

The specimen is approximately broken into two triangles along the diagonal under the action of pressure, which is similar to the experimental results of Zhang et al. This is because the stress concentration on the two wings of the borehole is obvious during the splitting process of the specimen, and the cracks gradually communicate with the two diagonals, which improves the failure speed of the specimen. Taking the diagonal line as the
dividing line, the triangular area at the upper and lower ends of the borehole is the stress transfer region, and there are only a few cracks or even no cracks in the range. The triangle area of the two wings of the drill hole is the shear crack region, which will be severely squeezed in the vertical direction during the compression process, and obvious shear cracks will appear. The through crack of the specimen often passes through the two wings of the elliptical drilling, which indicates that the two wings of the drilling form an obvious weak area. Therefore, the two wings of the drilling and the diagonal of the specimen produce cracks at the same time, extending from two directions and finally intersecting, which also explains the reason why the drilling will reduce the strength of the specimen.

The failure mode of the specimen is shown in Figure 8, in which the main cracks of the specimen extend in the diagonal direction and pass through the two wings of the borehole. Among them, the direction of the arrow is the direction of crack extension. The main failure modes of specimens S06 and S08 are the mixed failure mode of tensile cracks and shear cracks. The crack passes through the borehole and forms a wide range of tensile cracks on the path. The tensile crack of specimen S08 passes through the specimen and directly causes instability failure. In this process, the shear cracks around the borehole are randomly distributed, indicating that there is a certain stress concentration around the borehole, but it is not the best path for energy release. The failure modes of specimens S10 and S14 are mainly shear cracks. Several main shear cracks directly pass through the main diagonal of the specimen, and shear crack regions on both sides also form shear cracks, resulting in the Z-shaped division of the specimen.

It can be seen that the hole size determines crack distribution. With an increase of hole diameter, the failure mode of the test block changes from tensile shear mixed failure to diagonal shear crack dominated through failure. In this experiment, taking specimen S10 as the boundary, the stress concentration of a large-size borehole is obvious, forming a typical X-shaped failure mode. The failure mode of small-size drilling is closer to the inside of the specimen under the servo loading mode. During the loading process, the wall speed is adjusted by the servo mechanism to ensure that the applied pressure remains unchanged until the specimen is damaged.

3. DISCUSSION

3.1. Numerical Simulation Conditions. Although the above experiments have studied the macrofailure mode of a borehole, the distribution of the stress field in the specimen still needs to be further studied. If we want to study the internal stress of the specimen, we need to embed sensors in the specimen in advance, but this will affect the strength of the specimen itself. Limited by the experimental conditions, it is impossible to count the stress distribution in all parts of the specimen. To overcome the shortcomings of the experiment and study the shape of the internal stress field of the specimen, three-dimensional particle flow software (PFC3D) is used in this study. In this software, a large number of particles are connected with each other to form the test piece. Because the internal bonding mode is similar to real rock, researchers can use this feature to study better the rock instability and failure mechanism. The particles are connected through rigid blocks at the contact point. If the relevant shear or tensile stress exceeds the strength limit, a fracture occurs at the connecting block at the contact point. The rule to control the fracture is the Mohr–Coulomb criterion. When the contact points between particles are connected by rectangular constraints, it is called the PB model, in which the contact force and sliding force can be transmitted between particles. In this paper, the PB model is used to construct the simulation specimens S02–S16, and the parameters of the simulation specimens are shown in Figure 9.

The simulation adopts the same loading method as the experiment in this paper. Lin conducted a similar simulation experiment and proved that the profit can be evenly transmitted to the inside of the specimen under the servo loading mode. During the loading process, the wall speed is adjusted by the servo mechanism to ensure that the applied pressure remains unchanged until the specimen is damaged.

3.2. Stress Distribution Analysis of an Unstable Borehole. The experimental results of simulated specimen S02 are shown in Figure 10. The stress field in the figure includes the range of the whole specimen. In the initial stage of loading, the stress increases uniformly on the whole specimen (stage B), and there is no obvious stress concentration area. With an increase of load, an “X”-shaped stress concentration area is gradually formed along the main diagonal of the specimen. When the load reaches the peak stress of the specimen, the stress
concentration area is more obvious, and the area of the stress concentration area on the two wings of the borehole is the largest. With the further increase of load (stage D), the stress distribution range has basically shrunk in the above X-shaped stress concentration area, and obvious defects appear at the edges and corners of the simulated specimen, resulting in sparse stress distribution. There are two triangular stress sparse areas at the upper and lower ends of the borehole, which also explains the reason for the sparse distribution of cracks in this area in the experiment.

The experimental results of simulated specimen S16 are shown in Figure 11. There are many differences between the two in the experimental results. The increase of borehole size leads to a decrease of peak stress and peak strain of the specimen. In the stress distribution diagram, there has been an obvious stress concentration area on the two wings of the borehole in the early stage of loading (stage B). The stress distribution at the upper and lower ends of the borehole is sparse. With an increase of load, the drilling shape obviously changes to an ellipse, and the stress concentration on the two wings of the drilling hole of simulation specimen S16 is more obvious than that of simulation specimen S02. In addition, there is an elliptical stress sparse area (stage D) at the upper and lower ends of the borehole, which is dominated by shear stress. With the compression, the failure of the two wings of the S16 borehole of the simulated specimen further expanded, resulting in sparse stress distribution, and the sparse area of compressive stress at the upper and lower ends of the borehole further expanded.

Compared with the above results, it can be found that the stress concentration area of the specimen is mainly distributed along the diagonal of the specimen. However, around the drill hole, the small-size drill hole mainly transmits the stress in the inclined direction, and the difference between the stress field distribution around the drill hole and the complete test block is small. After the large-size drill hole is compressed, the failure area of the two wings and the upper and lower ends form an elliptical stress sparse area.

4. CONCLUSIONS

To study the influence of size on borehole instability and failure, a theoretical model for predicting the borehole strength through size is proposed, the biaxial loading compression experiment of prefabricated borehole specimens is performed, and the evolution process of stress and strain obtained from the experiment is analyzed. Combined with the measured images and the results of particle flow simulation software, the instability and failure process of the borehole are summarized. The results show the following:

(1) Borehole size is an important factor affecting its peak stress. The borehole strength decreases gradually with an increase of borehole size. Size change has a greater influence on the strength of small-size borehole, and the strength of borehole gradually stabilizes with an increase of size.

(2) Based on fracture mechanics, a theoretical model for calculating borehole strength is proposed, and the analytical solution of the theoretical model is proved to be able to better predict the borehole strength through experiments.

(3) The process of borehole failure can be divided into three stages: borehole top failure, borehole deformation, and crack extension. Stress concentration and a large number of cracks occur on the two wings of borehole, and these cracks reduce the strength of the borehole. The stress concentration area of borehole is X-shaped distribution, and the through crack mainly extends along this area and leads to the failure of the specimen. With an increase of borehole size, shear cracks replaced tensile cracks as the main failure mode.

AUTHOR INFORMATION

Corresponding Author
Jie Ren — College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024 Shanxi, China; Center of Shanxi Mine Safety for Graduate Education Innovation, Taiyuan University of Technology, Taiyuan 030024, P. R. China; Email: renjie1289@link.tyut.edu.cn

Author
Yabin Gao — College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024 Shanxi, China; Center of Shanxi Mine Safety for Graduate Education Innovation, Taiyuan University of Technology, Taiyuan 030024, P. R. China; orcid.org/0000-0003-2243-4945

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c02834

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