WEI SHEN
LIN-MING DOU
HU HE
GUANG-AN ZHU
and
MIN ZHANG

Effect of a hole drilled under different stress conditions on the behaviour of a coal specimen

The drilling hole is an effective measure used to forecast and prevent rock bursts and is widely used during mining operations. To study the effect of a hole drilled under different stress conditions on the behaviour of a coal specimen, a drilling and reloading experiment is carried out. With increasing vertical load, the failure mode of the specimens is transformed from slow deformation to one entailing an undesirable brittle failure when a hole is drilled. The vertical load at the cut-off point between slow deformation and undesirable brittle failure is equal to, or slightly less than, 65MPa. The vertical stress-strain curve of a coal specimen with a hole could be divided into three stages, and its turning point between the first stage and the second stage is related to the stress on the coal specimen after drilling; acoustic emission events seldom occurred in the first stage, rapidly increased in the second stage, and remained at a higher level throughout the third stage. However, the vertical stress-strain curve of that coal specimen without a hole tended to be linear, and AE event counts gradually increased to a maximum. Due to the differences in the various coal specimens, there are two main failure modes seen in samples with a hole upon reloading. The failure mode is determined by the relationship between the reloading initial crack load and the stress after drilling. When the reloading initial micro-crack load is less than the stress after drilling, the coal specimen cracked slowly, otherwise, the specimens ruptured suddenly. We also found that a hole drilled can reduce the difference between the vertical stress and the confining pressure, and increase AE event counts when the coal specimen is reloaded.

Keywords: *Coal specimen; failure characteristics; drilling hole; tri-axial compression; AE events.*

1. Introduction

A large-diameter drilling hole, releasing part of the stored energy and altering the stress in the surrounding rock, is considered to be one of the most effective ways of preventing rock bursts. Extensive research has been implemented on specimens containing a drilled hole, including theoretical analysis, numerical simulation, and some experimental studies. From the theoretical perspective, the expression for the hoop stresses around a circular opening, the plastic area of the drilling hole, the stress variations around holes during tunnel excavation, and the critical pressure for hole bursting, have been predicted by many scholars [1-7]. From previous comments, we can see that the coal body is usually treated as a continuum; however, the coal body is actually crushed and is discontinuous. Numerical simulation takes the crack, fracture, and plastic softening of the coal body into consideration, and can effectively compensate for the problems in theoretical analyses.

Various simulation methods have been used to analyse the failure behaviour around a circular opening in rock and assess those factors associated with the failure behaviour. Finite element software FLAC was used to investigate the surrounding rock burst evolution process, failure modes, the swelling behaviour, and excavation unloading processes around a circular opening [8-10]. To determine the failure mechanism affecting a circular opening in rock, Li et al. [11], Wang et al. [12], and Jiaet al. [13] used discrete element software (RFPA3D and RFPA2D) to simulate crack initiation, propagation, coalescence, and interaction in specimens under uniaxial, biaxial, and tri-axial states of stress, and zonal disintegration under triaxial stress conditions. With a view to simulating a loading-type failure around a hole, some authors used particle flow software to study the influence of these conditions such as a biaxial compression test, intermediate principal stress, or a non-persistently jointed rock mass, for a sandstone specimen with a hole, and proved that the PFC model is able to reproduce the damage zone observed in laboratory testing [14-16]. Numerical simulation is commonly used; however, numerical methods cannot simulate the failure modes of a specimen drilled (ductility or brittleness) under triaxial compression, or model those characteristics of a coal specimen subjected to reloading after the drilling process.

In experimental research, a substantial effort by scholars to study the effect of hole parameters on the material strength and failure modes, and the form of crack propagation under uniaxial or biaxial loading has been made [17,18], however, little attention has been paid to what happend in the case of

Messrs. Wei Shen, Lin-ming Dou, Hu He, Guang-an Zhu and Min Zhang, State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China. E-mail: dlm_burst@126.com (L.M. Dou), 826618111@qq.com (W. Shen).

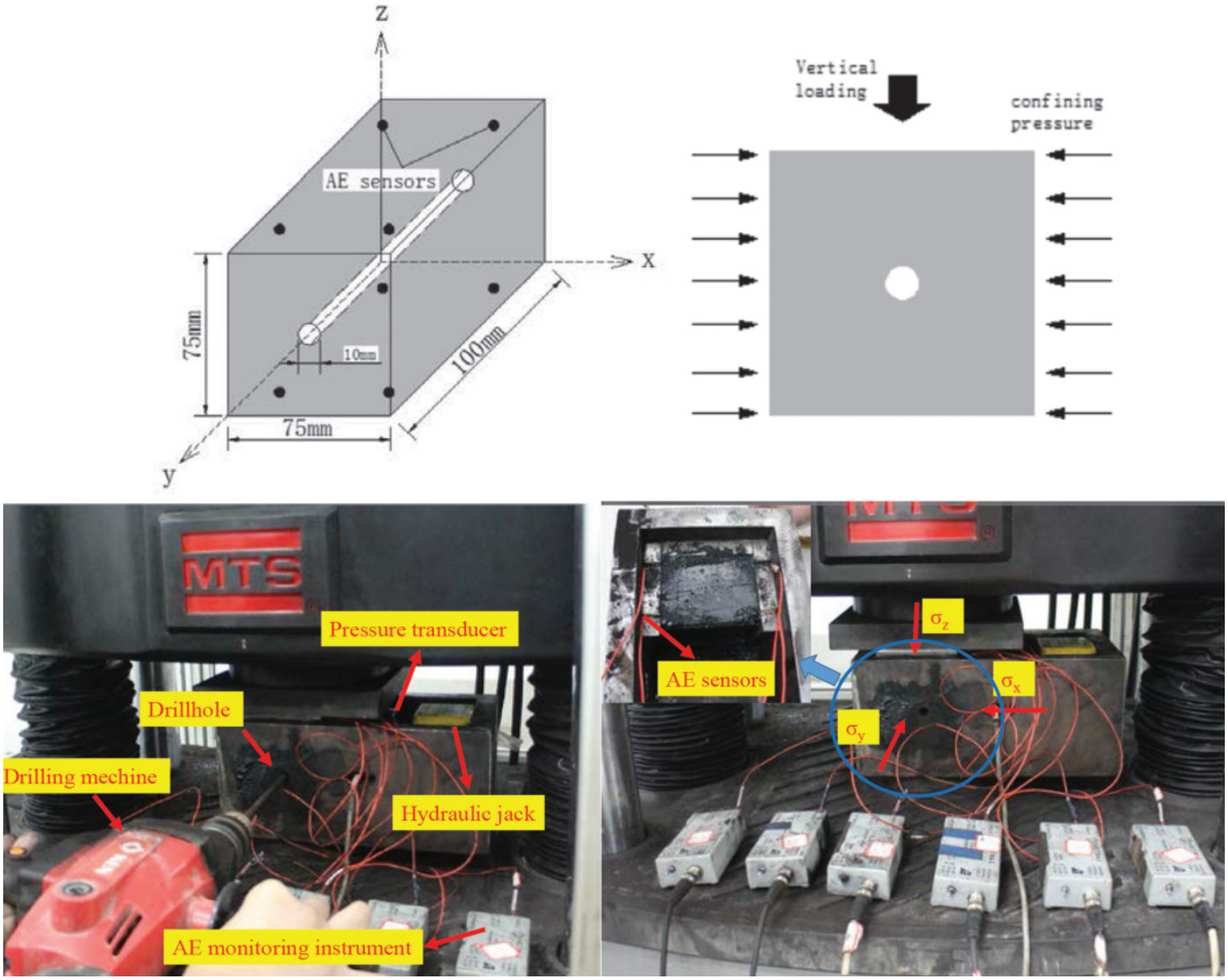

Fig.1 Sketch of the experimental apparatus

triaxial loading. From the documents, we only found few scholars from China, Germany, and Poland who had carried out drilling hole experiments under triaxial compression [19,20]. Only the critical pressure for a hole-burst and the relationship between drilling bits and stresses in coal specimens are found through their experiments.

According to earlier researchers, no study has been made of the effect of a hole drilled under differenttriaxial compressionstates on the behaviour of coal specimens. For example, differences in the failure mode of coal specimens drilled under differenttriaxial compression regimes, the difference in vertical stress-strain curves between the coal specimens with and without a hole, and the difference of AE count-time curves, or the effects of a hole drilled on the difference between the vertical stress and confining pressure have not been explained. To study this problem, drilling and reloading experiments on coal specimens under triaxial compression were carried out. Finally, conclusions are drawn to offer a reference for exploring the failure mechanism of deeply buried tunnels, and in forecasting and preventing rock bursts therein.

2 Materials and methods

2.1 Experimental system

We developed a 75mm × 75mm × 100 mm experimental system to represent the failure modes of coal specimens during, and after, drilling under triaxial compression (Fig.1). The experimental system consisted of the loading system, the monitoring system, and the drilling system. The main technical indicators are as follows: (1) the vertical stress is ó$_{z}$with a range of 0-130MPa as applied by the MTS testing machine; the confining pressure isó$_{x}$ with a range of 0-65MPa as applied by the hydraulic jack or the strain on the specimen, and the y-directional displacement was fixed. (2) An AE monitoring system, whose sensors are set, in iron, and in close contact with the specimen, was used to monitor the failure processes. Parameters involved in AE monitoring are as follows: an operating frequency range of 35-100 kHz, a resonant frequency of 55 kHz, a threshold value of 45 dB, a gain of 40 dB, and analogue filter lower and upper limits of 1 and 400 kHz, respectively.

The coal specimens are taken from working face 9119, Zhangshuanglou Coal Mine, and the average thickness of the N.9 coal seam is 3.5m. According to its coal-burst tendency and classification index from national standards (GB/T 25217.2-2010), this coal seam is identified as being a strongly burst-prone coal seam.

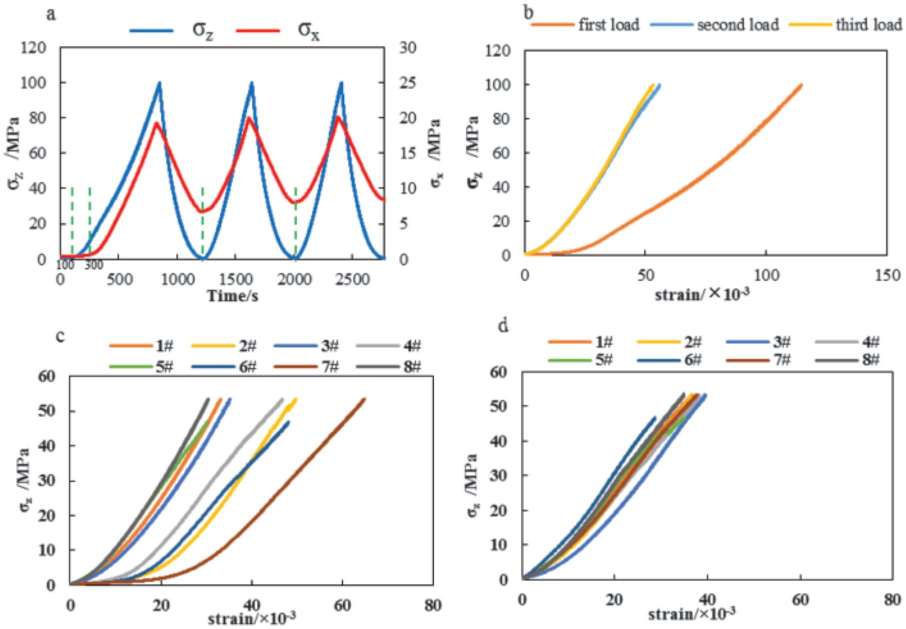

Fig.2 Stress-strain curves and stress-time curves. (a) stress-time curves for cyclic loading and unloading. (b) σ_z-strain curves of the same coal sample under cyclic loading, (c) first loading and (d) second loading σ_z-strain curves for different coal samples, respectively

2.2 Experimental methods

Stress σ_z is applied by an electro-hydraulic servo-controlled rock mechanics test system (MTS C46.106) with the loading rate of 0.01mm/s throughout the experiment. Based on a pressure plate displacement monitored by the test system, the axial strain in the specimen can be determined. Stress σ_x is applied by hydraulic jack or the strain in the specimen, and it was monitored by a pressure transducer. The y-directional strain is zero (Fig.1). The data acquisition interval for σ_z is set to 200 ms, and that of σ_x is set to 200 ms [21]. The dynamic failure time for coal samples are higher than 200 ms(in general), so, the failure process could be recorded. As a result, the σ_z-time curve, and the σ_x-time curve, can reflect the actual failure process of each coal sample in the drilling process.

The drilling experiments are mainly divided into three phases: firstly, to eliminate the physicalproperty differentiation caused by pores and fractures, we carried out cyclic loading and unloadingof all coal specimens. After the first loading phase, the formal experiment is carried out. Secondly, coal specimens are reloaded to the specified pressure and held at that stress for six minutes, and at the third minute of the holding stage a 10mm diameter circle hole is cut through the y-directional width of the specimen. Finally, coal specimens are loaded and unloaded for the third time. The parameters including the vertical stress, the z-directional displacement, the confining pressure, and acoustic emission events are monitored in this experiment.

3 Results and discussion

3.1 Effect of fissures and pore spaces

The cyclic loading and unloading stress-strain curves and σ_z-strain curves of coal specimens are shown in Fig.2. Stress σ_z is applied by the MTS testing machine at a loading rate of 0.01mm/s. The *x*-and *y*-directional displacements are fixed.

As seen from Fig.2a, over time, σ_x and σ_z did not increase in the first 200s of the first loading cycle: however, they increased synchronously in the next two loading cycles. There are obvious compaction stages in the *x*- and *z*-directions specimen in the first loading cycle, and the duration of the *x*-directional compaction is greater than that in the z-direction.

As there were fissures and pores in the samples, the slope of the σ_z -ε_z curve in the first loading phase is apparently smaller than the others (Fig.2b). As the fissures and pore spaces were compressed in the first loading stage, and no new cracks were generated in the second and third loading stages, the σ_z -ε_z curve slopes in the next two loading process similar.

The elastic modulus of eight specimens in the first loading stage ranged from 1.47 to 2.51 (Fig.2c), and the elastic modulus of specimens in the second loading stage are from 1.70 to 1.75 (Fig.2d). The range of elastic moduli in the first loading stage is greater than that in the second loading stage, which demonstrated that the second loading stage could reduce disparities inthe elastic modulus.

Results allow us to recognise that fissures and pore spaces affected the physico-mechanical properties of the coal specimens, such as the elastic modulus, the duration of the compaction phase, and the range in the elastic modulus. The method of cyclic loading and the unloading process could reduce the differences in the mechanical properties of these coal specimens, hence the method chosen here.

3.2 Failure characteristics during drilling

3.2.1 Confining pressure caused by specimen deformation

The stress-time curves during drilling are shown in Fig.3. According to the researches [19,20], only the stress reached

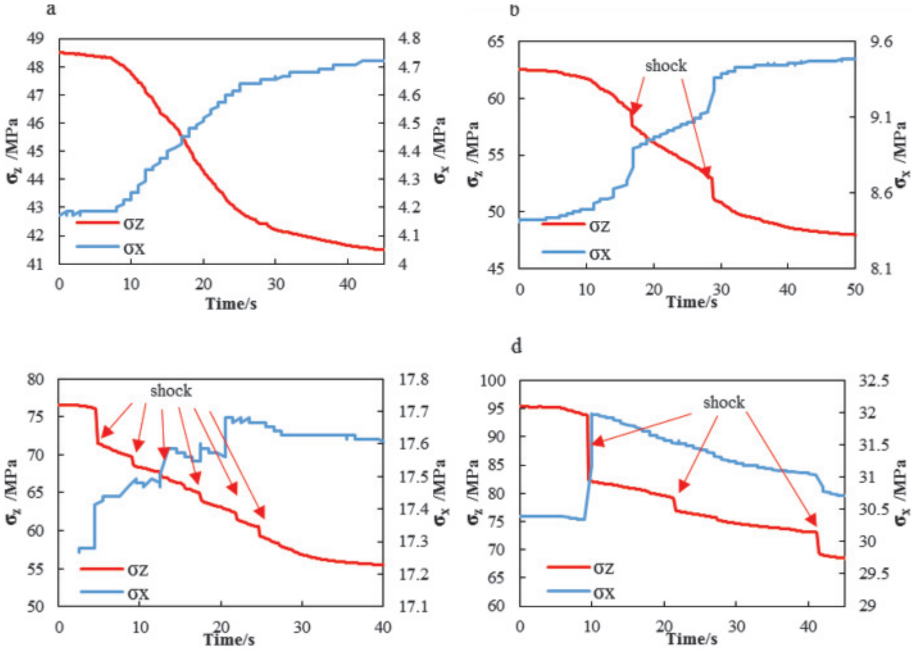

Fig.3 Stress-time curves at an initial σ_z of (a) 50MPa, (b) 65MPa, (c) 80MPa, and (d) 100MPa in the drilling experiment

60-80MPa, whereupon hole-bursting could be observed. So we carried out drilling experiments at initial vertical stresses of 50 MPa, 65MPa, 80MPa, and 100MPa. Stress σ_z is applied by the MTS testing machine at a loading rate of 0.01mm/s, and the *x*-and *y*-directional displacements are fixed. It is held for 6 minutes when the coal specimen is loaded to the specified pressure. At the third minute of the holding stage, a 10mm diameter circular hole is drilled. As the coal sample deformed gradually in the first three minutes of the holding stage, σ_z at the beginning of the drilling experiment is usually slightly less than the specified pressure, as shown in Fig.3. In the next section, the initial stress in this drilling experiment is less than 65MPa, for the same reason.

There is no sudden stress reduction in the drilling process at σ_z= 50MPa (Fig.3a), but the pressure dropps suddenly (with a bang)at σ_z > 65MPa, which is deemed to represent a drilling hole burst. However, the critical value is equal, to or slightly less than, 65MPa, which differs from Chen's conclusion (2004). Perhaps, the differencesin physico-mechanical properties of the coal specimens are the main factor causing this contradiction.

The pressure on the coal specimen decreased suddenly with the increase of initial vertical load in the drilling experiment. The greater is the initial vertical load, the greater is the drop (Fig.3). This result could be used to explain the mechanism by which the strength, and quantity, of rock bursts increases with the stress in the coal seam.

Stress σ_x increased and σ_z decreased with increased drilling time under an initial σ_z of 50MPa or 65MPa; when the initial σ_z exceeded 65MPa, the relationship was no longer evident, or σ_x and σ_z both decreased with time during the drilling experiment (Fig.3d). Regardless of the nature of the relationship between the σ_z-time and σ_x-time curves, σ_x before drilling is less than that after drilling.

3.2.2 Confining pressure applied by hydraulic jack

The stress-time curves during drilling are shown in Fig.4. Stress σ_z is applied by the MTS testing machine; σ_x is applied by hydraulic jack, and the *y*-directional displacement is fixed.

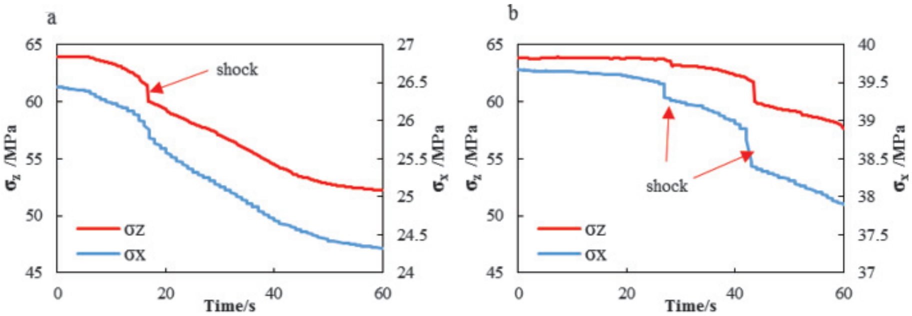

Fig.4 Stress-time curves:(a) σ_z= 65MPa, σ_x = 26.5MPa, and (b) σ_z = 65MPa, σ_x = 39.5MPa

From Fig.4, σ_x and σ_z all decreased with increasing drilling time, and σ_x before the drilling is greater than that after drilling. Pertinent to the conclusion to Section 3.2.1, we could draw the conclusion that the relationship between σ_x before, and after, drilling is affected by the method of application of σ_x before drilling. If σ_x arises from an external stress, σ_x would decrease during drilling; if not it would increase.

3.3 Characteristics seen during reloading

3.3.1 Effect of a hole on the deformation characteristics of the coal specimens

3.3.1.2. The three failure stages

As shown in Fig.5, the blue curves and black curves are the vertical stress-strain curves of coal specimens in the loading-drilling-unloading process and in reloading-unloading process, respectively; the red blocks are the AE events in the reloading process. A, B, and C are the stress point before drilling, the stress point after drilling, and the initial crack point during reloading, respectively.

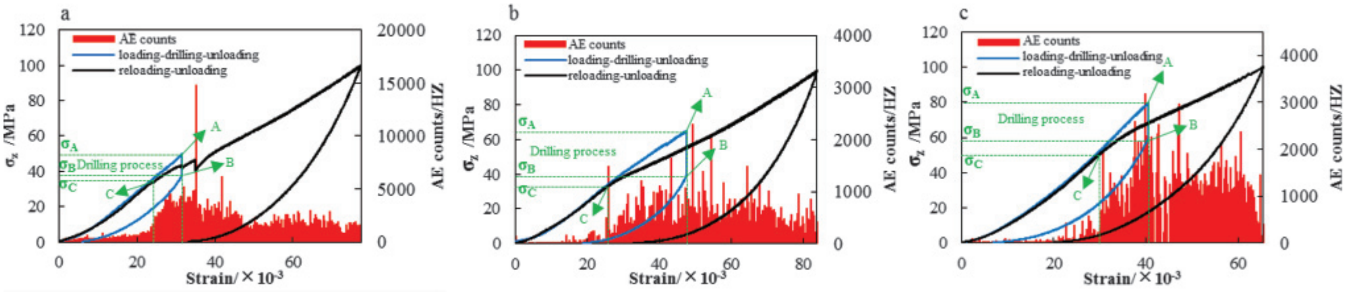

Fig.5 σ_z-strain curves and AE events during reloading. The drilling experiments were carried out at σ_z of (a) 50MPa, (b) 65MPa, and (c) 85MPa

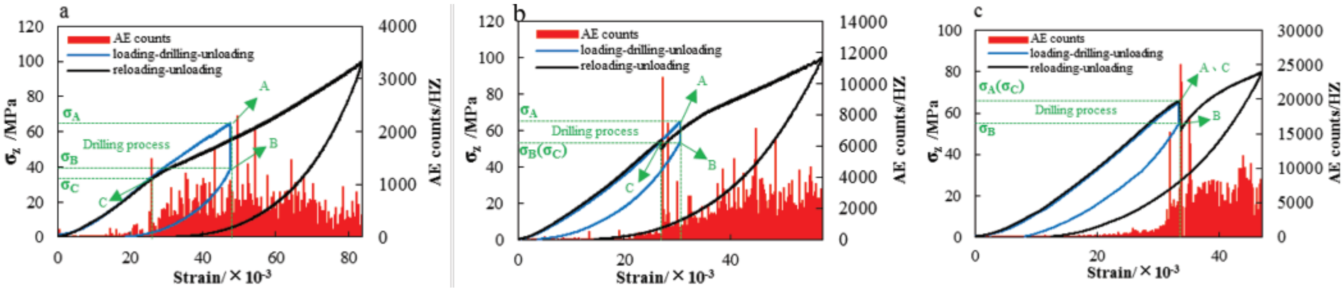

Fig.6 σ_z-strain curves and AE events during reloading. The initial vertical stress on the drilled specimen was 65MPa

Before the vertical stress reached point C in the reloading process, the reloading curve coincided with the loading curve, and AE events are rare: this is defined as the first stage under reloading conditions. In the first stage, the pressure did not reach the failure load for a circular opening, and so there is little cracking in the specimen.

When the vertical stress exceeded the stress at point C in the reloading process, AE event counts increased, and the reloading stress-strain curve dipped, which defined the second stage under reloading conditions. In this stage, the pressure reached the failure load for a circular opening, and micro-cracks formed and began to propagate through the coal specimen.

With the continuous increase in σ_z, the reloading stress-strain curve tended to be linear once again, and AE activities remained high. The deformation and crack propagation velocity tended to be stable in this stage, which is defined as the third stage under reloading conditions. Compared to those specimens in the first stage, those in the third stage are influenced by new cracks around the opening, and so, the elastic modulus in the third stage is less than that in the first two stages, as shown in Table 1.

The stress at point C is determined from the stress at point B. In Figs 5a and 5b, as the stresses at point B are the same, the stresses at point C are also similar. The stress at point B in Fig.5c is greater than that in Figs 5a and 5b, so the stress at point C increases accordingly.

Table 1

Initial σ_z before drilling/MPa	Elastic modulus (first stage)/GPa	Elastic modulus (third stage)/GPa
50	1.82	1.41
65	1.57	1.30
80	2.15	1.34

The failure modes of coal specimens with a hole

As shown in Fig.6, the blue curves and black curves are the vertical stress-strain curves of those coal specimens in the loading-drilling-unloading process and in the reloading-unloading process, respectively; the red blocks are the AE events recorded during reloading. A, B, and C are the stresses before drilling, after drilling, and atinitial cracking during reloading, respectively.

The failure modes of coal specimens with a hole are determined by the relationship between point B and point C. If the stress at point C is less than that at point B, the coal specimen with a hole slowly cracked in the reloading process, which is called the first failure mode (Fig.6a).

If the stress at point C is greater than that at point B, the coal specimen with a hole cracked suddenly, and this is called the second failure mode (Fig.6b). Before cracking, AE events are rare, while AE events remained numerous and frequent after cracking. With the increase of the initial crack stress, the stress reduction and the strength are more obvious (Fig.6c).

3.3.1.3. The characteristic difference between the coal specimens with, and without, a hole

As shown in Fig.7, the blue curves and black curves are the vertical stress-strain curves of coal specimens without a hole in the first loading, and reloading, processes, respectively. The red blocks are the AE events recorded in the third loading process.

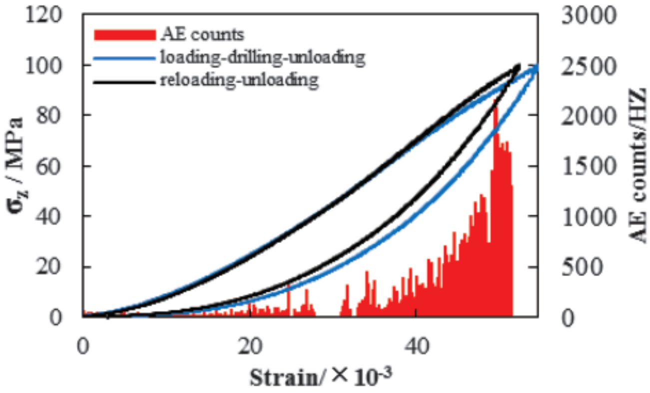

Fig.7 σ_z-strain curves during cyclic loading and unloading and AE events during reloading

The reloading vertical stress-strain curve of the coal specimen without a hole tended to be linear, which mainly coincided with the first loading curve. From Fig.8a, there are no signs of the three failure stages seen in the reloading process, which differs from the behaviour of coal specimens with a hole. From Fig.8b with increasing vertical stress, AE events gradually increases to their highest value in the reloading process, however, AE activities of coal specimens with a hole remained at the higher level throughout the third stage.

3.3.2 The effect of a hole on the confining pressure

The overall stress-time curves of specimen in cyclic loading, drilling, and final loading stages are shown in Fig.9: σ_z is applied by the MTS testing machine; the *x*- and *y*-directional displacements are fixed. In the first 2800s, the cyclic loading and unloading are carried out three times. Exceptin the case where the initial confining pressure is zero, the average maximum σ_z is 20MPa, and the average minimum σ_z is 7.5 MPa during the three cyclic loading and unloading stages. Then, the coal specimen is loaded to 65 MPa, and a hole is drilled between times of 2800s to 3700s from the start of the test. In the last stage, σ_z reaches 100 MPa and is then reduced to zero. The maximum σ_z of 26.93 MPa in the last stage exceedes that of 20 MPa in the three cyclic loading and unloading stages. Similarly, the minimum σ_z of 11 MPa is greater than that of 7.5 MPa seen elsewhere. The relationships between confining pressure in the cyclic loading stage and last loading stage under the other vertical stress are shown in Table 2. The maximum σ_z in the cyclic loading stages are greater than those in the last loading stage.

Under the same vertical stress, the confining pressure of coal specimens containing a hole is larger than in samples without a hole, which shows that a hole can reduce the difference between the vertical stress and the confining pressure.

Table 2

Vertical stress/MPa	The maximum value of σ_I in three cyclic loading stages/MPa	The maximum value of σ_x in the last loading stage/MPa
50	3.84	9.48
65	8.3	14.37
80	13.1	19.22
100	16.5	25.64

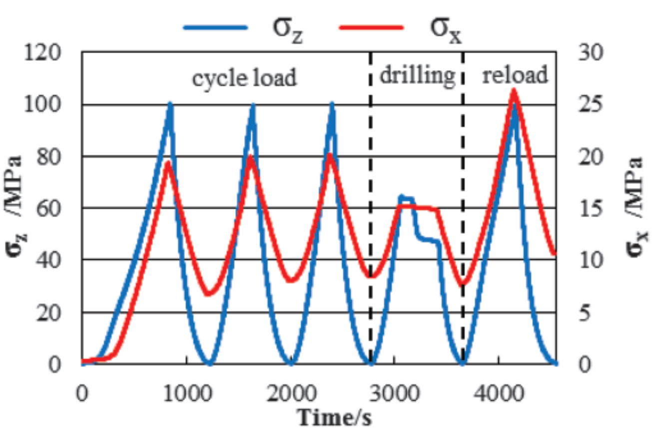

Fig.9 Overall σ_z-time curve and σ_x-time curve

3.3.3 *Effect of a hole on the AE event counts*

Amplifications of strain-time curve of the first, the second, the third, and last loading stages in Fig.10 are shown in Figs.10a to 10d, respectively. In the first loading stage, AE event counts increased then subsequently decreases with increasing σ_z (Fig.10a), and its turning point is at σ_z= 35MPa. The average maximum AE event count is 20,000 at this stage.

In the three cyclic loading stages, AE event counts continuously

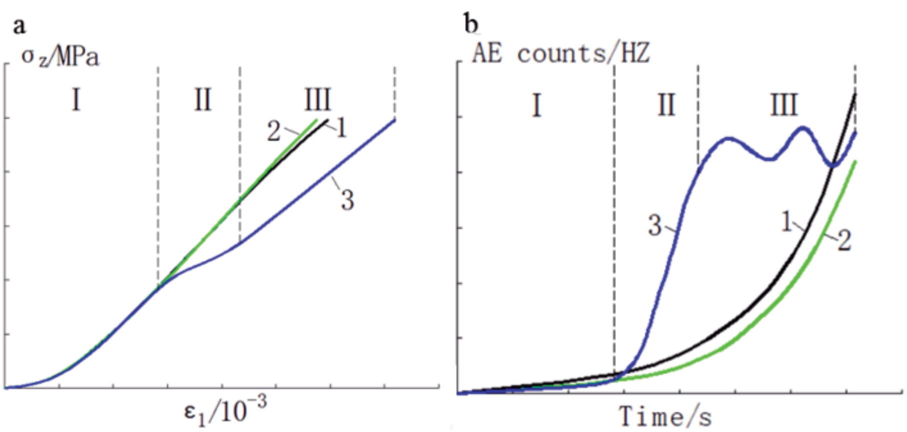

Fig.8 (a) σ_z-strain curves and (b) AE event count-time curves during loading
1, 2, 3-loading curves, reloading of a coal specimen without a hole, reloading curve of a coal specimen with a hole
I, II, III -three stages in the reloading curve of a coal specimen with a hole

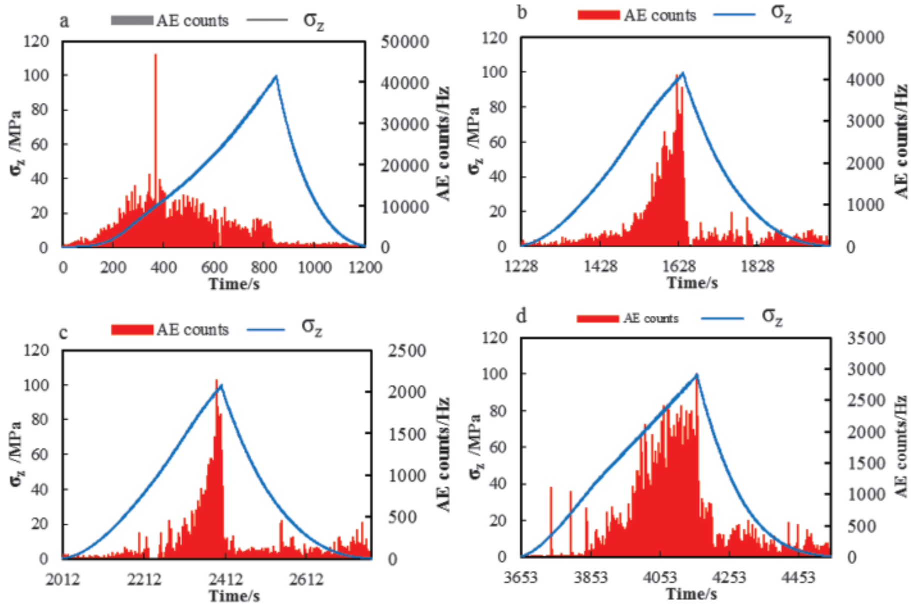

Fig.10 σ_z-time curve and AE events in (a) the first, (b) the second, (c) the third, and (d) the last loading and unloading stages, respectively

decreased with increasingnumbers of loading cycles. The average maximum AE event count is only 2,000 in the third loading stage (Fig.10c). From Fig.10, we know that the specimen is drilled after the three load cycles had been applied. Circle opening provided the necessary deformation and rupture space for the coal specimen: the average maximum AE event count is 2,500 in the last loading stage (greater than the count of 2,000 events in the third loading stage); however, the value is still far less than that of 20,000 in the first loading stage. The reason is attributed to the deformation and rupture space provided by the hole being less than that of the original coal specimen.

From the above experiment, the vertical stress in the coal specimens are all 100MPa in every loading stage, but the AE event counts varied. The deformation and rupture space of specimens in the first and last stage are larger than in the others, the AE event counts are larger. We can draw the conclusion that the AE event counts are not appreciably affected by the stress on the coal specimen but more so by the fractures and pores present therein.

4. Conclusions

This drilling and reloading experiment could effectively be used to study the effect of a hole drilled under different stresses on the behaviour of coal specimens. Based on our test data, the following conclusions can be drawn:

1. Cyclic loading and unloading could reduce the differencesin the mechanical properties of the coal specimens tested here.
2. With increasing vertical load, the failure mode changed from slow deformation to undesirable brittle failure when a hole was drilled. The vertical loadat the cut-off point between slow deformation and undesirable brittle failure is equal to, or slightly less than, 65MPa.
3. The reloading vertical stress-strain curve of the coal specimens without a hole is tended to be linear, and AE event counts gradually increased to their highest value; however, the vertical stress-strain curve of coal specimens with a hole could be divided into three stages. In the early reloading stage, the reloading stress-strain curve is consistent with the stress-strain curve measured during the drilling process, and AE events seldom occurred, at which stage no micro-crack had formed in the specimen; at the middle reloading stage, the reloading stress-strain curve dipped, and the AE event counts increased, at which stage micro-cracks began to form and propagate; in the late reloading stage, the reloading stress-strain curve of the coal specimen tended to be linear once again, but its slope at this stage is smaller than that of the early reloading stage, and AE activities remained high, at which stage micro-cracks maintained their propagation velocity. The presence of a drilled hole affected both the vertical stress-strain curve, and the AE event count-time curves of these coal specimens.
4. Due to the differencesin the coal specimens, there are two main failure modes seen uponreloading after drilling process. The failure modes are determined by the relationship between the reloading initial micro-crack load and the stress on the coal specimen after drilling. When the reloading initial micro-crack load is less than the stress after drilling, the coal specimen cracked slowly: otherwise, the coal specimen ruptured suddenly.
4. Through three cyclic loading stages, drilling, and a final loading experiment, we found that a drilled hole can reduce the difference between the vertical stress and confining pressure. AE event counts are not appreciably affected by the stress on the coal specimen but more so by the fractures and pores therein.

Acknowledgments

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