INTRODUCTION

Energy produced from coal constitutes approximately 70% of the energy consumed in China, with the total demand for coal increasing annually. Roadway construction is the first step in coal mining. Rock formations are typically mixed with coal seams; consequently, roadways can be made of rocks or coal. Roadheaders are one of the most widely used machines for fast roadway constructions in soft to medium-hard rocks owing to their advantages, such as high advance rates, good mobility, and versatility.\(^1,2\) However, when breaking hard and abrasive rocks, the cutters of a roadheader are subjected to serious shock, high forces, excessive wear, and high temperature, which reduces the cutter life and advance rates and increases the machine downtime and project cost.\(^3-5\)

Several methods have been proposed to address the issues above, which are generally categorized into the following three methods. The first method is to increase the cutter motor power of the roadheader, which will cause an increase in the roadheader size and weight; therefore, it may be limited by the roadway size. In one study, the cutter motor power of the Sandvic roadheaders MR120 and MR620 was increased from 100 to 300 kW, whereas the machine height and weight increased from 1.45 to 2.5 m and from 23 to 128 t, respectively.\(^6\) The second method is to improve the cutter structure and arrangement. By analyzing full-scale rock cutting test...
data, Goktan proposed a modification of Evans’ cutting theory for point attack picks, and the effect of cutter structure on cutting force was investigated. Liu et al. investigated the effect of installing angles on the wear of conical picks by simulations and experiments. Although the cutter wear reduced, it was primarily affected by the hardness of the rock. The third method aims to break rocks using water jets or microwaves. The results indicated that rocks could be damaged by the methods above. However, the results were based on theory and laboratory tests, and further studies are necessitated before they can be applied to actual working conditions. Therefore, a new method should be developed for the rock breaking of roadheaders; extensive studies indicate that rock-like materials can be weakened by pre-existing cracks and holes.

A number of specimens made of gypsum with three and 16 flaws were prepared and tested in compression by Sagong and Bobet, and the effect of flaw number on the crack growth mechanism was investigated. A comparison was presented between experimental observations of gypsum specimens loaded in uniaxial compression, with open and closed flaws. Jespersen et al. studied the effect of macro pore spacing on failure mode, strength, and stiffness using integrated modeling and laboratory testing. Lee and Jeon investigated the crack initiation, propagation, and coalescence at or near pre-existing open cracks in a specimen under uniaxial compression. The breakage process of disks containing single and double cracks with different inclination angles was investigated by Haeri et al.; they observed that wing cracks propagated toward the direction of compressive line loading. Long et al. investigated the effect of drilling radius and impact distance to a hole on the stress behavior of rocks. Experimental and numerical studies (using the numerical code RFPA) have been conducted to examine crack initiation and coalescence mechanisms and fracture behaviors in a granite material containing multiple holes under uniaxial compression. The dynamic Brazilian splitting test was used by Li et al. to study the effect of specimen hole diameter on the dynamic peak stress, deformation characteristics, and fracture mechanisms of rock specimens. Liu et al. studied the spatial-temporal evolution of microcracks of coarse-grained granite samples containing a circular opening, which was subjected to uniaxial compression; the results implied that tensile stress was concentrated near the roof and that shear stress was concentrated on the sidewall. The split Hopkinson pressure bar was used by Tao et al. to determine the fracture characteristics of a long bar rock specimen with an elliptical cavity under different axial ratios and dip angles; experimental results revealed that the fracture characteristics around the elliptical cavity were closely related to the axial ratio and dip angle. Chen conducted a series of uniaxial compression experiments on rock-like specimens containing nonpersistent fissures to study the crack propagation and coalescence in fissured rock masses; the results indicated that the strength and deformation modulus of the specimens were significantly affected by fissure inclination. A series of numerical simulations was implemented to study the effects of hole size and location on the tensile breakage pattern and tensile strength of rock specimens. It was believed that the existence of cracks and holes significantly affected rock breakage. However, the sizes of most specimens used were extremely small. Moreover, the effects of cracks and holes on the specimens were emphasized primarily, whereas the interactions between the pre-existing flaws and cutters were not fully investigated.

In this study, considering the structure and working conditions of the roadheader, holes were easier to achieve than cracks. Hence, a series of experimental investigations was performed to analyze the performance characteristics of a roadheader for breaking rocks containing different numbers and sizes of predrill holes. A detail discussion is presented regarding the cutting torque, thrust force, specific energy, and fracture behavior during the cutting process. Three-dimensional (3D) numerical simulations were conducted using LS-DYNA software, and the results were further validated with experimental data. Moreover, the optimal parameters of the holes for the cutterhead were investigated by considering the energy efficiency and cutting effect.

## 2 | LABORATORY TEST

### 2.1 | Test platform

Figure 1 illustrates the test platform for rock breaking by the cutterhead. It included a table on which a motor, gearbox, and cutterhead were mounted. Two hydraulic cylinders were used to move the table along the tracks. The force transducer, torque transducer, and displacement transducer were used to measure the thrust force, cutting torque, and cutterhead displacement, respectively. The transducers were connected to a data acquisition system; subsequently, the test data were transferred to the computer and displayed on the screen.

For the test platform, the cutterhead was the key component. Because the full-scale roadheader cutterhead for rock breaking in the laboratory was expensive and time and labor consuming, a scaled cutterhead was designed and manufactured, which is shown in Figure 2. According to the similarity theory, the prototype and the model must satisfy equilibrium equations, geometric equations, physical equations, and displacement boundary conditions. To balance the reliability of the test results and the cost and time of the test, a similarity ratio of 1:2.5 was selected in the study. The scaling process based on the principle of homogeneity and Buckingham’s pi theorem has been detailed by Liu et al.
Based on the cutterhead prototype (Roadheader EBZ160B) and the similarity theory, the model cutterhead was 302 mm long and up to 362 mm in diameter. It comprised 38 point attack picks, which were arranged in a three-start helix, with 13 picks on two helixes each and 12 picks on the third helix. The bit of the pick was made of cemented carbide, which was characterized by high thermal hardness and good resistance to wear and brittleness. The pick body was made of C45 alloy steel, which was characterized by good comprehensive mechanical properties (strength, toughness, hardenability, weldability, and processing formability) but poor resistance to wear, corrosion, and oxidation.

In the tests, the advance speeds were controlled at 400 mm/min and each advancing test was performed for approximately 50 seconds to ensure that the entire cutterhead was involved in the rock-breaking process. The rotational speed of the cutterhead was 80 rpm. Maintaining the advance speed and rotation constant, the effect of the predrill holes on the rock-breaking performance was analyzed and compared. In this study, Portland cement #42.5, grade B gypsum powder, and river sand were used as raw materials for preparing artificial rocks. According to the similarity theory, a similarity ratio of 1:2.5 was selected. Table 1 lists the rock parameters of the prototype and model.

2.2 Effect of predrill hole number on rock breaking

To investigate the effect of hole number on rock-breaking performance, rock specimens containing different numbers of holes were designed and predrilled, as shown in Figure 3. Because the cutterhead was 302 mm long and up to 362 mm in diameter, the rock specimens measured 500 mm (high) × 500 mm (wide) × 400 mm (thick). The hole ratio \( \eta \) is defined as \( \eta = 100n(D_{\text{hole}}/D_{\text{max}})^2\% \), where \( n \) is the number of holes, \( D_{\text{hole}} \) the diameter of the hole and \( D_{\text{max}} \) the maximum diameter of the cutterhead. In this study, the maximum value of the hole ratio \( \eta \) was controlled to approximately 20%, considering the significant amount of time and labor required to drill dense holes in actual working conditions. The diameter of the hole was set as 45 mm, and the holes were distributed in
TABLE 1  Rock parameters of the prototype and the model (average values)

|                  | Prototype | Model |
|------------------|-----------|-------|
| Density $\rho$ (kg/m$^3$) | 2532      | 2532  |
| Compressive strength $\sigma_C$ (MPa) | 71.5      | 28.6  |
| Tensile strength $\sigma_T$ (MPa)   | 6.75      | 2.70  |
| Elasticity modulus $E$ (GPa)       | 38.5      | 15.4  |
| Poisson’s ratio $\mu$              | 0.19      | 0.19  |

the center and along a circle of diameter 292 mm. The numbers of holes were 1, 5, 9, and 13, which corresponded to hole ratios $\eta$ of 1.6%, 7.7%, 13.9%, and 20.1%, respectively.

Figure 4 presents the rock-breaking experimental processes of the cutterhead and the fracture pit patterns. Prior to cutting, the cutterhead was aligned with the center of the rock by adjusting the position of the rock such that the pre-drill holes were uniformly distributed in the fracture pit, as required by the design.

Figure 5 shows the cutting torque curve of the cutterhead during the entire process. It comprises four phases: preparation, cutting, stable, and shutdown. During the preparation phase, the cutterhead was pushed to establish contact with the rock. Subsequently, the cutterhead cut the rock gradually until the entire cutterhead was surrounded by the rock—this phase is called the cutting phase. Next, the cutterhead continued to move forward, and the cutting torque stopped increasing significantly but fluctuated stably—this is known as...
the stable phase. Finally, the motor was turned off, and the cutting torque decreased rapidly—this is called the shutdown phase.

Because the cutting phase is the most important for the rock-breaking performance, the average cutting torque $T$ and thrust force $F$ during the cutting phase were computed and compared, as shown in Figure 6, to analyze the effect of predrill hole number on rock-breaking performance.

As shown, as the number of the predrill holes increases, the cutting torque and thrust force decrease remarkably. For example, the cutting torque decreased from 1280 (without predrill hole) to 1080 N m (with five holes), and the thrust force decreased from 7820 to 5510 N. These corresponded to decrease rates of 15.6% and 29.5%, respectively, whereas the hole ratio $\eta$ of the rock specimen with five holes was 7.7%.

Specific energy ($SE$) is an important index for measuring the rock-breaking performance of mechanical excavations; it is defined as the energy required for a unit volume of rock fragmentation. During the cutting phase of the cutterhead, the specific energy can be computed using the formula below:

$$SE = \frac{W_T + W_F}{V} = \frac{P \cdot t + F \cdot l}{V}$$

where $SE$ is the specific energy (kW h/m$^3$), $W_T$ the work by the cutting torque (kW h), $W_F$ the work by the thrust force (kW h), $V$ the volume of the broken rock (m$^3$), $P$ the cutting power, $v_R$ the cutterhead rotation speed (RPM), $T$ the cutting torque (N m), $F$ the thrust force (N), $t$ the cutterhead advance time (h) and $l$ the cutterhead advance length (m).

Figure 7 illustrates the effect of hole number on the specific energy of rock breaking. Because the energy consumed by the cutting is significantly greater than the advancing, the curve trend of the specific energy is similar to that of the cutting torque. Compared with the $SE$ of the rocks without predrill holes, the energy decrease rates $\epsilon_E$ of the rocks with 1, 5, 9, and 13 holes were 10.2%, 15.7%, 23.5%, and 39.6%, respectively. Moreover, the corresponding normalized effect indexes $\eta_E$ were 6.37, 2.04, 1.69, and 1.97, respectively.
2.3 Effect of predrill holes arrangement on rock breaking

To investigate the effect of hole arrangement on rock-breaking performance, Figure 8 is presented to illustrate the design and predrill of rock specimens with different arrangements of nine holes. The diameter of the holes was 45 mm; in type 9-1, one hole was distributed in the center, and eight holes were distributed along a circle of diameter 292 mm. In type 9-2, one hole was distributed in the center, and eight holes were distributed along a circle of diameter 180 mm. In type 9-3, one hole was distributed in the center, and eight holes were arranged alternately along the circles of diameters 180 and 292 mm, respectively. In types 9-4 and 9-5, nine holes were equally spaced in a square of side lengths 180 and 292 mm, respectively. In type 9-6, nine holes were arranged in a cross shape of side length 292 mm. Overall, the arrangement of the
nine holes included circle (types 9-1 and 9-2), stagger (type 9-3), square (types 9-4 and 9-5), and cross (type 9-6).

Figure 9 shows the effect of predrill hole arrangement on the experimental cutting loads. The curves of cutting torque and thrust force exhibited similar trends, indicating a clear correspondence between the cutting torque and thrust force.

### FIGURE 9
Effect of predrill hole arrangement on experimental cutting loads

In the six arrangement types, type 9-2 indicated the minimum cutting torque and thrust force, of which the values were 690 N·m and 3211 N, respectively. Meanwhile, type 9-5 indicated the maximum cutting torque and thrust force, of which the values were 1006 N·m and 5014 N, respectively. It was clear that the same number and diameter of predrill holes but different hole arrangements affected the cutting loads significantly.

Figure 10 presents the effect of predrill hole arrangement on the experimental cutting specific energy. Among the six arrangement types, type 9-2 indicated the minimum cutting specific energy, the value of which was 3.37 kWh/m³, a decrease of 46.2% compared with type 0 (without predrill holes). Meanwhile, type 9-5 consumed the most cutting specific energy of 4.92 kWh/m³, which was a decrease of 21.5% compared with type 0. It is noteworthy that the maximum energy decrease rate was more than twice the minimum energy decrease rate under different predrill hole arrangements. Type 9-2 indicated the minimum cutting torque, thrust force, and specific energy, signifying that it was the most reasonable among the six arrangement types, which could serve as a reference for future studies.

### FIGURE 10
Effect of predrill holes arrangement on experimental cutting specific energy

### FIGURE 11
Numerical model of rock breaking by the cutterhead

3 | NUMERICAL MODELING

#### 3.1 | Numerical model

To investigate the fracture mechanism of rocks containing predrill holes, numerical models were developed. In this study, computer program ANSYS/LS-DYNA, a nonlinear finite element software for analyzing geometric nonlinearity, material nonlinearity, and contact nonlinearity, was used. It is a powerful tool for simulating rock cutting. Figure 11 shows the numerical model of rock breaking by the cutterhead. The sizes of the rock and cutterhead in the numerical model were the same as those in the experiments. It is noteworthy that the rock specimen shown in Figure 4A was fixed in a metal box. Correspondingly, normal constraint conditions were set at the upper, bottom, left, right, and back...
boundaries of the numerical model. MAT 145 in LS-DYNA is an advanced constitutive model for geomaterials with solid theoretical background; therefore, it was adopted to simulate the rock. Moreover, the cutterhead was regarded as a rigid body, and MAT 020 in LS-DYNA was selected as the cutterhead in this study. Element type solid 164 was used for the models, and the cutterhead and rock specimen without predrill holes were divided into 20,827 and 64,656 elements, respectively.

For the cutterhead-rock contact, the “ERODING_NODES_TO_SURFACE” contact type was selected, and the “element birth and death” technique was realized through APDL programming. The program can automatically calculate the stress and damage status of each element after each loading step.

3.2 Comparison between experimental and numerical results

Figure 12 presents the rock-breaking numerical process of the cutterhead (A) and the fracture pit pattern (B). During the numerical simulation, the rock elements were continuously broken and deleted with the rotation and advancement of the cutterhead, thereby forming a fracture pit pattern. The numerical process and fracture pit pattern are similar to the experimental results shown in Figure 4, thereby verifying the feasibility of the numerical investigation.

According to the experimental arrangements shown in Figure 8, numerical models were developed to further validate the numerical results. Figure 13 illustrates the effect of predrill hole arrangement on the numerical cutting loads. The curves of the numerical cutting loads were similar to the experimental curves shown in Figure 9. Moreover, in the six arrangement types, type 9-2 indicated the minimum cutting torque and thrust force, the values of which were 670 N m and 3648 N, respectively. Meanwhile, type 9-5 indicated the maximum cutting torque and thrust force, the values of which were 958 N m and 5734 N, respectively.

Figure 14 shows the effect of predrill hole arrangement on the numerical cutting specific energy. In the six arrangement types, type 9-2 indicated the minimum cutting specific energy, the value of which was 3.28 kWh/m³, a decrease of 42.2% compared with type 0. Meanwhile, type 9-5 consumed the most cutting specific energy of 4.69 kWh/m³, a decrease of 17.4% compared with type 0. According to the
experimental arrangements shown in Figure 8, type 9-2 indicated the minimum cutting specific energy, the value of which was 3.37 kWh/m³, a decrease of 46.2% compared with type 0 (without predrill holes). Type 9-5 consumed the most cutting specific energy of 4.92 kWh/m³, a decrease of 21.5% compared with type 0. It was observed that the numerical results agreed well with the experimental results.

To investigate the fracture mechanism of the rocks containing predrill holes, the law of stress changes in rocks is particularly important. Figure 15 presents the effect of predrill hole arrangement on the equivalent stress contours of the rocks when the cutterhead began to advance for 1 second.

Under the action of the cutterhead, stress concentration areas of different sizes were generated in the rocks. Moreover, the stress concentration areas of types 9-2 and 9-4 were larger compared with those of types 9-1 and 9-5. Comparing types 9-1 and 9-2, the circumferential holes of type 9-1 were farther from the central hole; therefore, the stress in the rock could not propagate effectively. Meanwhile, the circumferential holes of type 9-2 were closer to the central hole, and the stress could propagate from the central hole to the circumferential holes; therefore, the holes affected each other, thereby forming a larger area of stress concentration.

Figure 16 shows the effect of predrill hole arrangement on the maximum principal stress contour of the rocks at the advance time of 1 second. In ANSYS/LS-DYNA software, the maximum principal stress areas of a rock are either positive or negative; a positive value indicates the tensile status and a negative value the compressive status.

It is noteworthy that the rock elements around the central hole were in contact with the cutterhead; therefore, those elements were subjected to compressive stress and generated a squeeze zone (blue color). Meanwhile, the elements around the squeeze zone suffered from the tensile status and formed a tensile stress zone (green and red color). In type 9-1, the tensile stresses (green color primarily) propagated to the inner edge of the circumferential holes. In type 9-2, the compressive stresses around the central holes arrived at the surface of the circumferential holes, and the compressive stresses changed into tensile stresses (free surface effect\(^4\)), which then continued to propagate outward, thereby forming a wider range of green tensile stress zone. The tensile strength of the rock was only 10% of its compressive strength; therefore, a larger tensile stress zone implied that it was easier to fracture the rock. As shown in Figure 16, the tensile stress zone of type 9-2 was the largest among the six types, which explain why the type 9-2 has the minimum cutting loads and specific energy shown in Figures 13 and 14.

Compared with type 9-2, the peripheral of four holes in types 9-3 and 9-4 was slightly farther away from the central hole; therefore, the exerted free surface effect was worse. Type 9-5 was similar to type 9-1, in that the free surface effect could not be effectively exerted because the circumferential holes were distant from the intermediate action zone. In type 9-6, the tensile stress zone was primarily distributed in a cross shape around the holes, and the tensile stress zones between the holes did not penetrate each other to form a larger stress concentration zone.
3.3 | Effect of confining pressure on rock breaking

With increasing coal mining depth, the effect of confining pressure on the mining process became more prominent. Based on the numerical model shown in Figure 11, the rock-breaking model containing five holes under a confining pressure of 10 MPa was developed to study the effect of confining pressure. Figure 17 presents the equivalent stress contours at the center cross-section of the rock without and with a 10 MPa confining pressure. It is noteworthy the equivalent stress contour under the confining pressure was more complex because the contour was due to the combination of the confining pressure effect and the cutterhead action. Specifically, the stress concentration zones around the holes were larger and more obvious in Figure 17B.

To study the effect of the 10 MPa confining pressure on the cutting performances, the average cutting torque and thrust force were calculated. Specifically, the cutting torque and thrust force were 1028 N m and 6879 N, respectively which were 8.9% and 8.6% higher than those without confining pressure, respectively. Therefore, the effect of confining pressure on rock breaking cannot be ignored; hence, the subsequent simulations were simulated under a confining pressure of 10 MPa.

3.4 | Effect of distance between the circumferential holes and the central hole on rock breaking

According to the analysis above, rock models with different arrangements of five holes under a confining pressure of 10 MPa were developed to analyze the effect of distance between the circumferential holes and the central hole on rock
breaking. As shown in Figure 18, in addition to one central hole, the other four holes were evenly arranged along circles of diameters of 292 and 180 mm.

The cutting loads and specific energy of the rock models presented in Figure 18 were calculated from simulations and shown in Table 2. Specifically, the specific energy consumption of types 5-1, 5-2, and 5-3 were 5.03, 4.30, and 4.35 kWh/m³, respectively. Compared with type 0 (without predrill holes), the specific energy consumptions decreased by 28.1%, 38.6%, and 37.9%, respectively. Furthermore, the normalized effect indexes of the specific energy consumption $\eta_E$ were 3.65, 5.02, and 4.93, respectively. It is noteworthy that the cutting loads and specific energy consumption of types 5-2 and 5-3 were similar, whereas the values of type 5-1 were greater than those of the two types above. This indicates that it is reasonable to design the distance between the circumferential holes and the central hole to be half the maximum diameter of the cutterhead $D_{\text{max}}$.

Figure 19 shows the equivalent stress contours of a rock containing five holes under a confining pressure of 10 MPa at the advance time of 1 second. Under the action of the cutterhead, stress concentration areas of different sizes were generated in the rocks. Moreover, the distance between the circumferential holes and the central hole was large in type 5-1, although the stress on the rock could propagate to the circumferential holes; with continuous stress attenuation, the stress concentration area was primarily green, and the corresponding stress range was 12-18 MPa. Meanwhile, for types 5-2 and 5-3, the distance between the holes was relatively small, and the stress on the rock propagated to the circumferential holes easily. In addition to the green stress concentration area, many red stress concentration areas appeared around the holes under the interaction between the holes, and the red stress concentration area corresponded to a stress range of 24-30 MPa.

Figure 20 presents the maximum principal stress contours of a rock containing five holes under a confining pressure of 10 MPa at the advance time of 1 second. As previously described in Section 3.2, the maximum principal stress of a rock is either positive or negative, in which a positive value

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**TABLE 2** Cutting loads and specific energy of different rock models

| Rock models | $T$ (N m) | $F$ (N) | $SE$ (kWh/m³) | $\epsilon_E$ (%) | $\eta_E$ |
|-------------|-----------|---------|---------------|-----------------|---------|
| Type 0      | 1430      | 10 053  | 7.00          | —               | —       |
| Type 5-1    | 1028      | 6879    | 5.03          | 28.1            | 3.65    |
| Type 5-2    | 879       | 4567    | 4.30          | 38.6            | 5.02    |
| Type 5-3    | 889       | 4586    | 4.35          | 37.9            | 4.93    |
indicates the tensile status and a negative value the compressive status. Specifically, the red areas in Figure 20 are all positive, and the stress range is 0.4-3 MPa, which is defined as the tensile stress zone.

3.5 Study on the optimal arrangement of predrill holes

The experimental study above shows that the corresponding normalized effect index $\eta_E$ decreases as the number of holes increases. For the rock containing five pre-drill holes, the specific energy consumption decreased by 15.7%, which is considered significant. However, whether the comprehensive energy efficiency and the cutting effect of the rock with four or six pre-drill holes are better necessitates further study. In this study, the numbers of holes selected were four, three, two and six, seven, and eight, which were centered on five holes and changed gradually. Accordingly, the rock models with four, three, and two holes under a confining pressure of 10 MPa are shown in Figure 21. It is noteworthy that the models of types 4-1, 3-1, and 2-1 have a central hole, and those...
of types 4-2, 3-2, and 2-2 have no central hole. Therefore, the effects of the hole number and central hole will be studied.

Figure 22 illustrates the effect of predrill hole arrangement on the numerical cutting loads under a confining pressure of 10 MPa. As the number of predrill holes in the rock decreased, the cutting loads exhibited an increasing trend. Specifically, from types 4-1 to 3-1 and in type 2-1, the cutting torque increased from 926 N m to 963 N m and 1058 N m, respectively, and the thrust force increased from 4901 N to 5606 N and 5785 N, respectively. Moreover, at the same hole number, the rock containing a central hole had a smaller cutting load. Specifically, the values of the latter for types 4-1, 3-1, and 2-1 were smaller than those for types 4-2, 3-2, and 2-2, respectively.

Figure 23 illustrates the effect of predrill hole arrangement on the numerical cutting specific energy under a confining pressure of 10 MPa. It is noteworthy that the cutting specific energy of the rock with predrill holes was smaller than that of the rock without the holes. Furthermore, a fewer number of predrill holes resulted in a smaller energy decrease rate. Specifically, from type 4-1 to types 3-1 and 2-1, the energy decrease rate decreased from 35.3% to 32.7% and 26.1%, respectively. Moreover, at the same number of holes, the rock containing a central hole exhibited a higher energy decrease rate. Specifically, the energy decrease rate of type 4-1 was higher than that of type 3-2, and those of types 3-1 and 2-1 were higher than those of types 3-2 and 2-2, respectively. Our findings suggest that the central hole is crucial during the rock-breaking process.

Figure 24 shows the equivalent stress contours of rocks containing four, three, and two holes under a confining pressure of 10 MPa at the advance time of 1 second. Under the action of the cutterhead, stress concentration areas of different sizes were generated in the rocks. Overall, each stress concentration area included the predrill holes; the stress concentration around the hole was the most obvious, as shown in red, and the corresponding equivalent stress range was 24-30 MPa. The blue area represents the fracture pit boundary, corresponding to an equivalent stress range of 0-0.6 MPa.

Figures 22 and 23 show that the central hole of the rock is crucial during the rock-breaking process. Therefore, the central hole was arranged in the rock models with six, seven, and eight predrill holes to further analyze the effect of hole number on the rock-breaking performance. Figure 25 presents the rock models with six, seven, and eight holes under...
a confining pressure of 10 MPa. The circumferential holes were arranged evenly along a circle of diameter 180 mm, which was approximately half the maximum diameter of the cutterhead $D_{\text{max}}$.

Figure 26 presents the equivalent stress contours of rocks containing six, seven, and eight holes under a confining pressure of 10 MPa at the advance time of 1 second. Overall, the stress concentration areas of the rocks with six, seven, and eight holes were larger compared with those of the rock models shown in Figure 24. Specifically, in Figure 26, the stress concentration area spread radially along the circumferential holes. When the number of holes was 8, the stress concentration area between the holes was completely penetrated.

According to the previous analysis, as the number of predrill holes increased, the cutting loads and energy consumption of the cutterhead decreased continuously. However, the optimal number of holes should be further studied. Figure 27 shows the effect of predrill hole number on the numerical cutting specific energy under a confining pressure of 10 MPa. Compared with type 0 (without hole), the energy decrease rate increased with the number of holes. When the number of the holes increased from zero to three, the energy decrease rate increased rapidly; when the number of holes increased from three to nine, the increasing trend of the energy decrease rate decelerated. Specifically, when the number of holes increased from two to three, the energy decrease rate increased from 26.1% to 32.7%, with a difference of 6.6%. Meanwhile, when the number of holes increased from eight to nine, the energy decrease rate increased from 51.8% to 53.2%, with a difference of 1.4%. It is noteworthy that the normalized effect index $\eta_E$ decreased as the number of holes increased. The slowest decline occurred when the number of holes increased from five to six. Therefore, for the overall rock-breaking performance of the cutterhead, the optimal number of predrill holes was six, and the optimal arrangement was type 6-1, considering the energy efficiency and cutting effect.
4 | DISCUSSIONS AND CONCLUSIONS

In this study, laboratory tests and numerical simulations were conducted to analyze the dynamic characteristics of the cutterhead for breaking rocks containing different numbers and sizes of predrill holes. Based on different parametric analyses, the following conclusions were obtained.

1. The computer program ANSYS/LS-DYNA, a nonlinear finite element software, was used to simulate the rock-breaking process by the cutterhead, and the numerical results indicated consistency with the experimental results. These results revealed that the cutting torque, thrust force, and specific energy decreased as the number of the predrill holes increased. When the number of predrill holes was nine, type 9-2 indicated the minimum cutting load and specific energy. The central hole and circumferential holes of type 9-2 affected each other, thereby forming a larger area of stress concentration. A larger tensile stress zone implied that it was easier to fracture the rock. The tensile stress zone of type 9-2 was the largest among the six types; hence, type 9-2 exhibited the minimum cutting load and specific energy.

2. The confining pressure significantly affected the rock-breaking process. The results demonstrated that the equivalent stress contour of the rock model under the confining pressure was more complex because the contour was owing to the combination of the confining pressure effect and the cutterhead action. Under the confining pressure of 10 MPa, the values of the cutting torque and thrust force were 8.9% and 8.6% higher than those without confining pressure, respectively.

3. It was evident that more and larger predrill holes resulted in a lower energy consumption. However, this implied that more time and energy were required to drill the holes. Therefore, an optimal design of predrill holes should be selected by considering the effectiveness of energy. In this study, the optimal design for a cutterhead with a maximum diameter of 262 mm was the rock specimen containing six holes with a diameter of 45 mm according to arrangement type 6-1. In the future, for other sizes of cutterheads, the optimal predrill holes parameters of rocks can be compared with the parameters used in this study, that is, the diameter of the hole was set as 12.5% of the maximum diameter of the cutterhead, and the number of holes was set as six, with one central hole and five circumferential holes. Moreover, the circumferential holes were arranged evenly along a circle, of which the diameter was approximately half of the maximum diameter of the cutterhead.

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