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EXPERIMENTAL RESEARCH ON THE ROCK FRAGMENTATION LOADS OF A WATER JET-ASSISTED CUTTING HEAD

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Original scientific paper

A test bed for rock fragmentation by cutting head was developed to investigate the load of water jet-assisted cutting heads. In this test bed, water jet was pumped into the center of the conical pick. In the case without water jet, the characteristic index of the cutting torque and pulling force increased with the rock compressive strength exponentially. No obvious relationship was observed between the characteristic indexes of the cutting torque and the rock compressive strength for the case with water jet, but the effect of the water jet on the pulling force of the cutting head was relatively stable. The cutting torque and pulling force were decreased by 20 % to 40 % when the rock compressive strength was lower than the water jet pressure. However, the water jet that assisted in rock fragmentation was less effective when the water pressure was lower than the rock compressive strength. The ratio between water jet pressure and rock compressive strength can help recognize the efficiency of water jets for rock fragmentation by cutting head.

Keywords: *characteristic indexes; cutting head; cutting torque; pulling force; rock fragmentation; water jet*

Eksperimentalno istraživanje opterećenja rezne glave s mlazom vode kod fragmentacije stijene

Izvorni znanstveni članak

U svrhu istraživanja opterećenja reznih glava opremljenih vodenim mlazom razvijena je oprema za ispitivanje fragmentacije stijene pomoću rezne glave. Vodeni mlaz se tu upumpavao u središte konusnog šiljka (pick). Bez vodenog mlaza, karakteristični indeks reznog momenta i vlačne sile eksponencijalno se povećao s tlačnom čvrstoćom stijene. Nije primijećena jasna povezanost između karakterističnih indeksa reznog momenta i tlačne čvrstoće stijene u slučaju s vodenim mlazom, ali je učinak vodenog mlaza na vlačnu silu rezne glave bio relativno postojan. Rezni moment i vlačna sila su se smanjili za 20 % do 40 % kada je tlačna čvrstoća stijene bila niža od tlaka vodenog mlaza. Ipak, vodeni mlaz koji je pomogao u fragmentaciji stijene, bio je manje učinkovit kad je tlak vode bio slabiji od tlačne čvrstoće stijene. Omjer između tlaka vodenog mlaza i tlačne čvrstoće stijene može pomoći kod prepoznavanja učinkovitosti vodenog mlaza kod reznih glava za fragmentaciju stijene.

Ključne riječi: *fragmentacija stijene; karakteristični indeksi; rezna glava; rezni moment; vlačna sila; vodeni mlaz*

1 Introduction

Coal, rock, concrete, and soil fragmentation is important in underground mining, civil engineering, constructional engineering, and so on [1÷3]. In rock fragmentation by roadheader, the performance of the cutting head has a significant effect on the tunneling efficiency and service life of the equipment [4, 5]. Decreasing the load of the cutting head can enhance the operational stability and rock fragmentation ability of a roadheader, and the cutting parameters of the conical pick are considered applicable in decreasing the pick load by experimental, theoretical, and numerical methods [6÷11]. The water jet technology has been wildly used in coal mining, tunnel excavation, agriculture, and so on [12, 13]. However, this technology can damage, fracture, and weaken coal or rock. When water jet is used to support the conical pick, the impact of the water jet on the rock decreases the pick load and lowers the pick temperature through heat exchange. Therefore, the use of water jets can improve the rock fragmentation ability of mechanical tools [14÷16]. Fenn [17] investigated the hard rock excavation using free-rolling cutters assisted by water jets and found that the forces on a free-rolling cutter can be reduced over 40 % by using four coherent water jets (1,2 mm in diameter) at the arc of contact between the cutting edge and the rock at pressures ranging from 5 to 40 MPa. Fowell et al. [18] reviewed the application of water jets in the industry and compared the results with laboratory findings; the water jet tool was compared in terms of jet positions and parameters to develop an outline for good practice. Hood et al. [19] reviewed rock cutting assisted by water jets and concluded that further improvement can be achieved for distances (i.e., from tip of the tool to the jet impingement point) lower than 3 mm. At this position, the jet can efficiently remove the volume of plasticized material near the tip to allow enhanced penetration and improved performance. Veenhuizen et al. [20] investigated rock drilling assisted by high-pressure water jets at 206 MPa and found that drilling efficiency can be increased by 1,5 to 1,6 times. Ciccu et al. [21, 22] investigated the excavating performance of a water jet-assisted PDC (polycrystalline diamond compact) cutter and observed decreased cutter wear, increased excavating speed, and more than 80 % increase in excavating depth. Li et al. [23] investigated the performance of PDC cutters that are resistant to the different combined loads of static thrust, impact, cutting, and water jet was investigated to verify the feasibility and efficiency of drilling hard rocks (e.g., Missouri red granite and Halston limestone) assisted by water jets; the combined mode of cutting and impact was effective on hard rock, and adjusting the direction of the water jets acting on rock to medium pressure can enhance penetration depth and critical impact spacing. Liu et al. [24, 25] used the numerical method to simulate rock fragmentation by conical pick assisted by water jet (CPW) and found the effect of water jet on rock breaking to be better when placed through the center of the conical pick than when placed in front of the conical pick. In addition, rock breaking by conical pick was more effective with a rear water jet than with a front water jet.

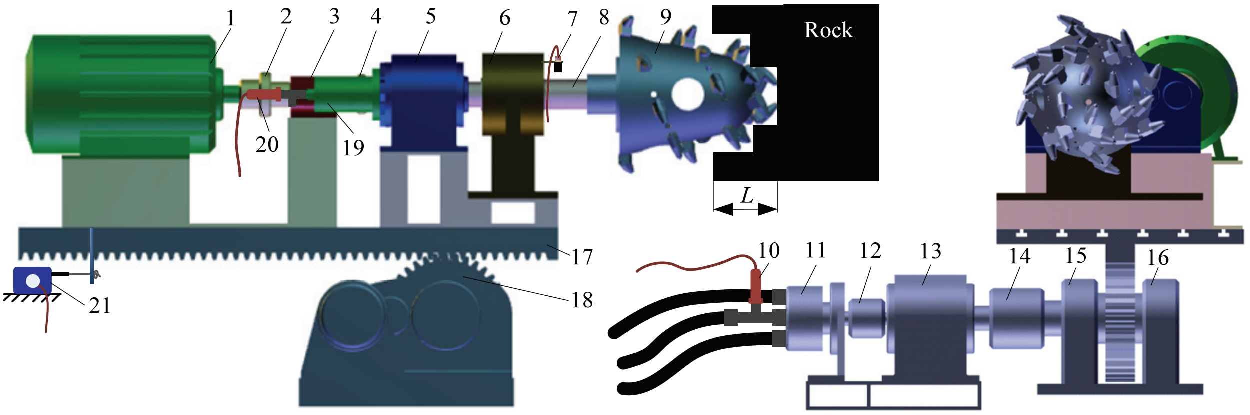
Previous studies have primarily focused on linear rock cutting using mechanical tools with and without water jet assistance, although the results promote the development of rock cutting assisted by water jet. Few studies have investigated the effect of rock properties on the fragmentation performance of rotating cutting heads assisted by water jets. However, the consideration of water jet pressure in improving the rock fragmentation performance of cutting heads still lacks basis. Hence, a test bed for rock fragmentation by cutting head is developed in this study. In this test bed, water jet is pumped into the center of conical picks. The effect of rock compressive strength on the cutting torque and pulling force of the cutting head with and without water jet assistance is also investigated. Rock fragmentation by water jet-assisted cutting head is analyzed to determine whether water jet pressure or rock compressive strength improves the rock fragmentation performance of the water jet-assisted cutting head.

2 Experiment setup

2.1 Test bed for rock fragmentation

Figure 1 shows the test bed for rock fragmentation by cutting head with and without water jet assistance. The main transmission system consists of parts that are numbered 1 to 6 and 8 to 9. This system is used to rotate the cutting head, with the rotation speed adjusted using the frequency converter. The gearbox with a transmission ratio of 8 is adopted to decrease the motor rotating speed and consequently enhance the power for rock fragmentation. A rotary seal device connected to the end of the gearbox output shaft is used to pump high-pressure water into the center of the conical pick of the cutting head.

The assist transmission system consists of parts that are numbered 11 to 18. This system is used to simulate the drilling condition of the roadheader. A constant power control system controls the traction motion of the cutting head. When rock strength changes during rock fragmentation, the pulling force and speed regulate each other and guarantee the operation of the traction motor throughout the rated power. The torque and oil pressure sensors are adopted to measure the cutting torque and pulling force of cutting head, respectively. In addition, the drilling depth of cutting head is measured by displacement sensor.



(a) Front view (b) Lateral view

1 - cutting motor; 2 - coupler I; 3 - torque sensor; 4 - coupler II; 5 - gearbox I; 6 - bearing block I; 7 - eddy current sensor; 8 - cutting shaft; 9 - cutting head; 10 - oil pressure sensor; 11 - hydraulic motor; 12 - coupler III; 13 - gearbox II; 14 - coupler IV; 15 - bearing block II; 16 - bearing block III; 17 - traction platform; 18 - driving gear; 19 - rotary seal device; 20 - water pressure sensor; 21 - displacement sensor

Figure 1 Transmission system of the test bed for rock fragmentation

2.2 Rotary seal device

The rotary seal device is essential for rock fragmentation by water jet-assisted cutting head. This device mainly consists of the shell, rotating shaft, four seal sleeves, and seal rings (Fig. 2). It is assembled at the end of the output shaft of gearbox I (Fig. 1).

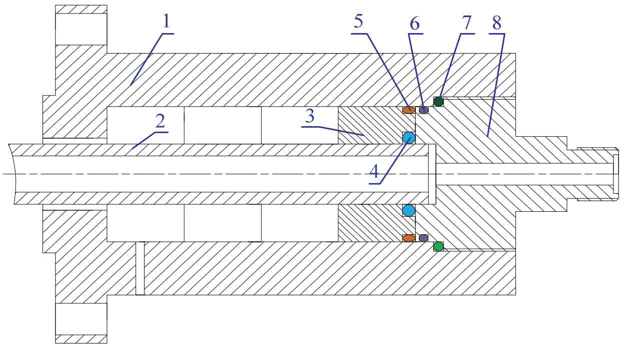
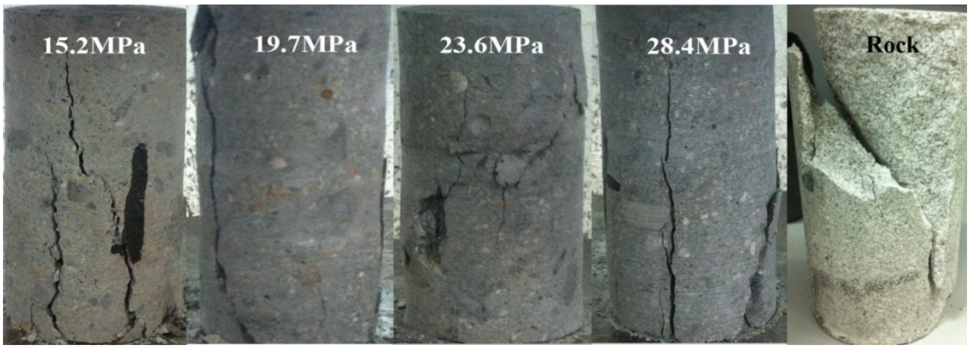


Figure 2 Rotary seal device for high-pressure water: 1 – shell, 2 – rotating shaft, 3 – seal sleeve, 4 – dynamical seal ring, 5 – static seal ring I, 6 – static seal ring II, 7 – static seal ring III, 8 – water inlet

This setup allows the device to be easily dismounted and replaced and can decrease pressure loss when the water flows into the seal and output shaft. The device exhibits a long service life because its low rotation speed is consistent with the output shaft of gearbox I. In addition, the four seal sleeves also can enhance the service life of the rotary seal device. The seal shaft diameter is equal to ∅25 mm, the rotation speed of the seal shaft ranges from 50 to 100 r/min, and the sealing medium pressure is no more than 40 MPa.

2.3 Preparation of artificial rock

For simulation experiments on rock fragmentation by mechanical actions, the failure patterns and characteristics of the simulation materials should be similar to those of the prototype material as much as possible. The usual shale, sandstone, and limestone found in underground roadways consist of aggregate and cement, the structures and mechanical properties of which are similar to those of sand, cement, and gypsum. In this study, the raw materials for propagating the artificial rock include Portland cement #42.5, grade B gypsum powder, and river sand. The artificial rock is prepared as follows: cement, gypsum, and sand are weighed according to the mass ratio of the raw materials. The raw materials are mixed for approximately 3 min to 5 min using a concrete mixer with the required amount of water. The mixed materials are then poured into a mold, pressed, and cured for approximately one month at 20 °C. As shown in Table 1, the mechanical properties of the artificial rock with different mass ratios include density (ρ), elasticity modulus (E), comprehensive strength (RCS), tensile strength (BTS), and Poisson ratio (υ). Uniaxial compression tests reveal that the failure patterns of the artificial rock are similar to those of the actual rock (Fig. 3).



(a) No. 1 (b) No. 2 (c) No. 3 (d) No. 4 (e) Actual rock

Figure 3 Compression failure of artificial rock and actual rock

Table 1 Mechanical properties of the artificial rock

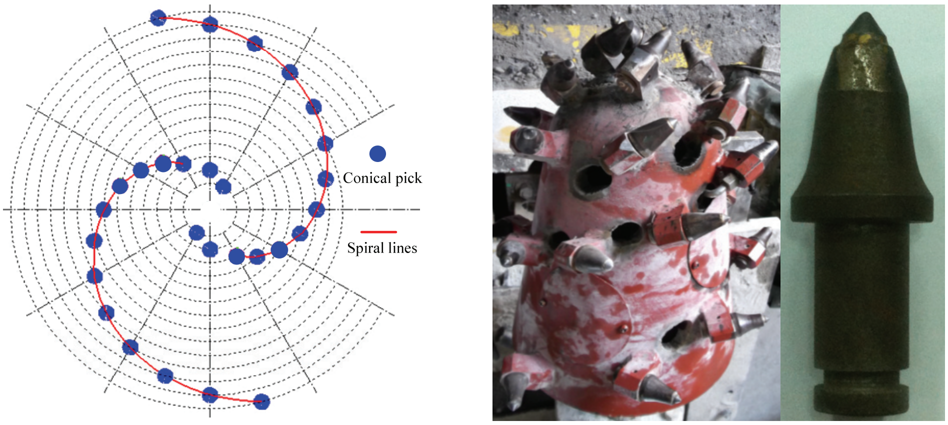
No.	ρ / kg/m^3	E / GPa	RCS / MPa	BTS / MPa	v
1	2548	15,2±0,5	28,4±0,4	2,7±0,10	0,21
2	2472	12,9±0,2	23,6±0,3	2,5±0,06	0,22
3	2436	7,8±0,1	19,7±0,3	2,1±0,04	0,19
4	2387	4,4±0,1	15,2±0,2	1,2±0,03	0,23

3 Effect of rock compressive strength on cutting torque

3.1 Cutting torque without water jet assistance

Experiments on rock fragmentation by cutting head without water jets were performed. The rock compressive strengths were 15,2; 19,7; 23,6 and 28,4 MPa. The rotation speed and initial pulling speed of the cutting head were 100 r/min and 2,4 m/min, respectively. Fig. 4 shows the pick arrangement and cutting head without water jets.

Fig. 5 shows the cutting torque versus the drilling depth of the cutting head with different rock compressive strengths. Rock compressive strength only slightly influences the overall trend of the cutting torque versus the drilling depth. The cutting torque increases with the drilling depth until the traction ability of the assist transmission system reaches its limitation. The number of picks in rock cutting increases with the drilling depth, causing the cutting torque to increase with the drilling depth for the same artificial rock. The rock cutting experiments [7, 26] show that the cutting resistance of the conical pick increased with the rock compressive strength; hence, the cutting torque was proportional to the rock compressive strength at the same drilling depth. The least squares method was adopted to regress the cutting torque before the traction reached its limitation linearly. The regression coefficients were 0,995; 0,986; 0,979 and 0,974, which correspond to the rock compressive strengths of 15,2; 19,7; 23.6 and 28,4 MPa, respectively. The regression lines are thus reliable and accurately match the variation trend of the cutting torque before reaching the traction limitation. The slope of the fitting line can be regarded as the characteristic index of cutting torque (CIT).



a) b)

Figure 4 a) Pick arrangement of cutting head without water jets; b) Cutting head without water jets

Fig. 6 shows the relationship between the CIT and rock compressive strength. The CIT exponentially increases with rock compressive strength and is a parameter for approximately estimating the trend of the cutting torque. The CIT without water jet assistance could serve as a reference index for investigating the cutting torque of the water jet-assisted cutting head.

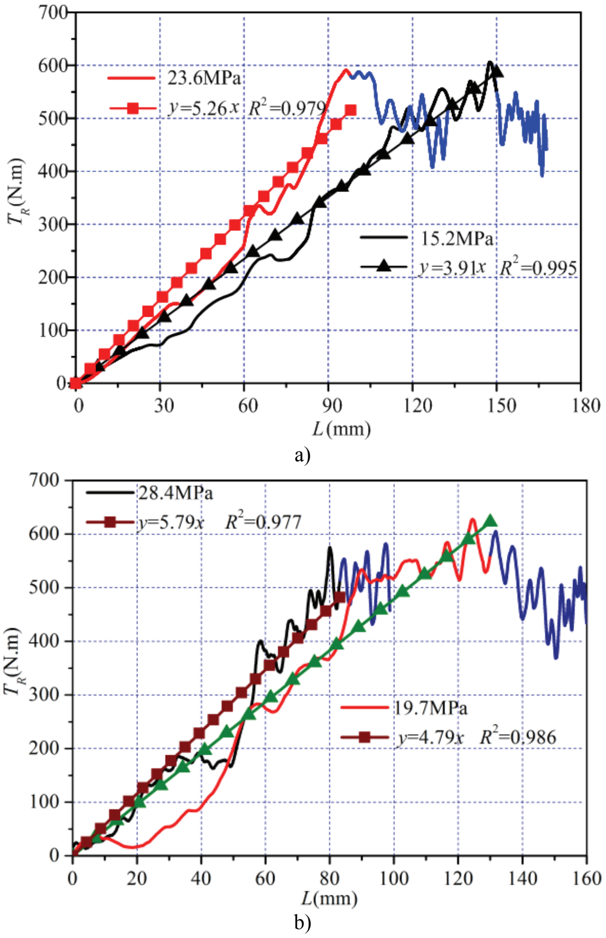


Figure 5 a) Cutting torque without water jet with rock compressive strengths of 15,2 and 23,6 MPa; b) Cutting torque without water jet with rock compressive strengths of 19,7 and 28,4 MPa

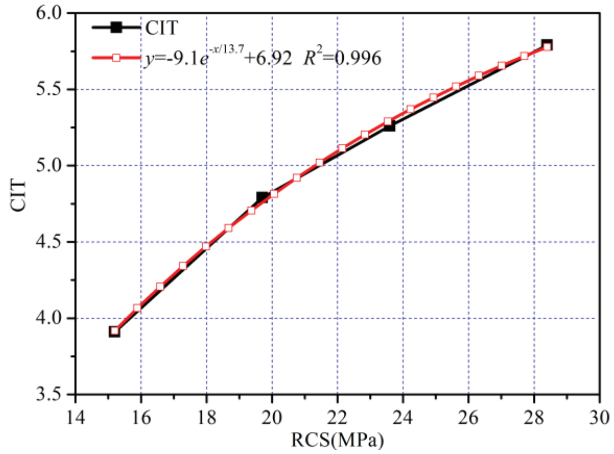


Figure 6 CIT without water jet versus rock compressive strengths

3.2 Cutting torque with water jet assistance

The water jet-assisted cutting head was adopted to execute rock fragmentation experiments with different compressive strengths. Fig. 7 shows the assistant mode of the water jets and the conical pick arrangement. The rock compressive strengths were 15,2; 19,7; 23,6 and 28,4 MPa. The rotation speed and pulling speed of the cutting head were 100 r/min and 2,4 m/min, respectively. The inlet pressure of the CPW was 22 MPa, and the diameter and nozzle were both 0,7 mm.

Under different rock compressive strengths, the cutting torque with water jet assistance changed with the drilling depth (Fig. 8). The overall trend of the cutting torque with water jet assistance is similar to that of the cutting torque without water jet assistance (Fig. 5). The cutting torque increased with drilling depth until the traction ability of the assist transmission system reached its limitation in the constant power control system.

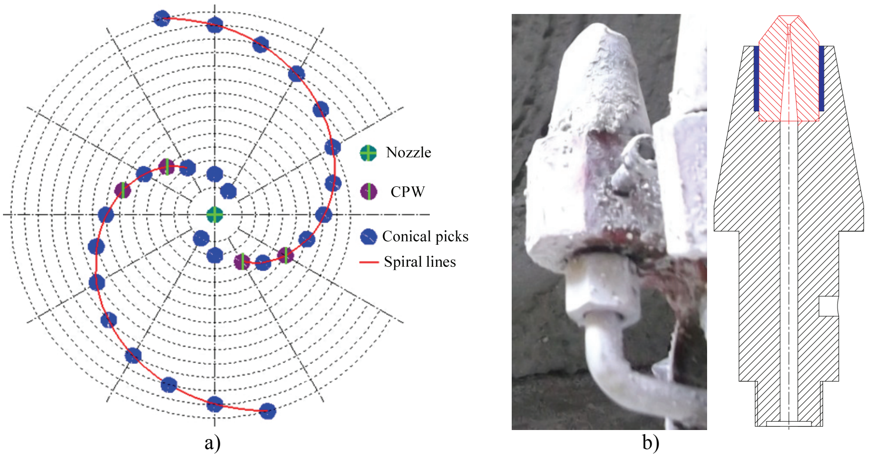


Figure 7 a) Pick arrangement of the water jet-assisted cutting head; b) The conical pick assisted by water jet

For the maximum drilling depth without water jet assistance, the cutting torque of the water jet-assisted cutting head decreased by 26,2 % and 26,7 % when the rock compressive strengths were 15,2 and 19,7 MPa, respectively, and by 4,91 % and −1,7 % when the rock compressive strengths were 23,6 and 28,4 MPa, respectively. In accordance with the rock fragmentation process by CPW [27, 28], the cutting force obviously decreased, thus proving the difficulty of breaking high-strength rocks by CPW. This phenomenon can be explained as follows. The impact of water jet at 22 MPa can damage rocks with low compressive strengths of 15,2 and 19,7 MPa (Fig. 9). This condition caused the cutting torque with water jet assistance to obviously decrease. Rock strength can be weakened by water jet impact at low speed [29, 30]. However, the cutting torque with water jet assistance slightly increased when the rock compressive strength was 28,4 MPa. This result is attributable to the nozzle being the carbide tip of the conical pick in Fig. 7b. The poor sharpness of the nozzle decreased the rock fragmentation ability of the conical pick. When the water jet damaged the high-strength rock difficultly, the cutting torque was likely to increase because of the poor sharpness of the conical pick.

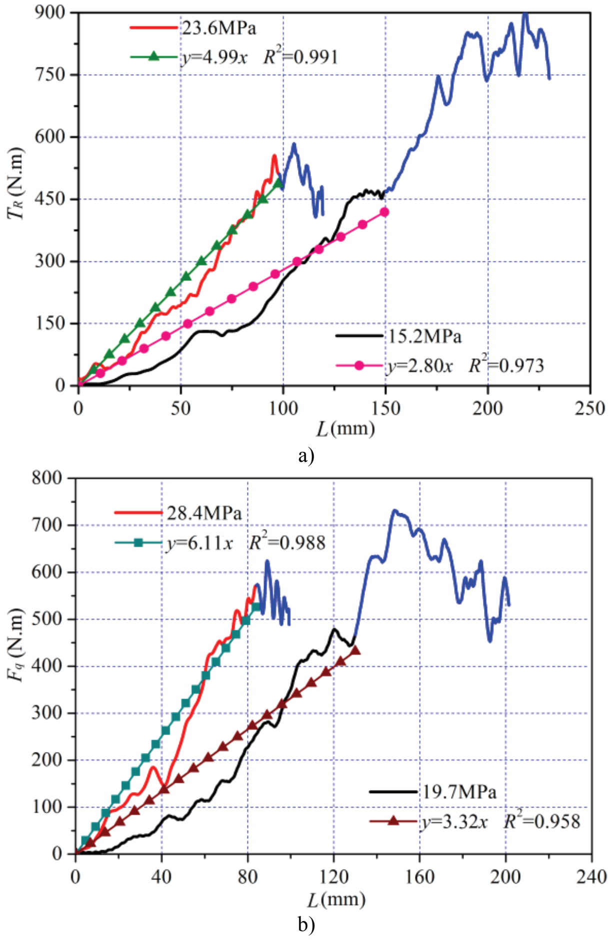


Figure 8 a) Cutting torque with water jet assistance with rock compressive strengths 15,2 and 23,6 MPa; b) Cutting torque with water jet assistance with rock compressive strengths 19,7 and 28,4 MPa

The least squares method was adopted to synthetically estimate the cutting torque with water jet assistance (22 MPa) and to linearly regress the cutting torque in the range of 0 to the maximum drilling depth without water jet assistance (Fig. 8). The regression coefficients of the fitting lines all exceeded 0,95, thus, the fitting line could be used to describe the overall trend of the cutting torque with water jet assistance. The ratio between the difference of two corresponding CITs (CIT with and without water jet assistance) and CIT without water jet assistance for the same artificial rock could be used to estimate the average percentage decrease of the cutting torque.

Fig. 10 shows the CIT with and without water jet assistance. The difference of the two corresponding CITs was small when the rock compressive strength was greater than the water pressure. Thus, the rock fragmentation performance of the water jet-assisted cutting head had an obvious boundary. No obvious relationship was observed between the CIT with water jet assistance and the rock compressive strength. Rock fragmentation performance improved when the rock compressive strength was lower than the water pressure. Related experiments have verified that rock fragmentation by water jet impact or hydraulic action is related to water jet diameter, water pressure, impact distance, water flow, inner crack pressure, and so on. However, water jet impact and hydraulic action in the present work both contributed to the rock fragmentation. The inner pressure and flow in the rock crack were extremely difficult to measure. Therefore, the ratio between the rock compressive strength and the water pressure (R_p) was regarded as the independent variable in the analysis of rock fragmentation performance. The ratio could then be used to determine the water pressure according to the rock compressive strength.

Fig. 11 shows the reduced percentages of cutting torque (RPT) with water jet assistance under different rock compressive strengths to water jet pressure. The reduced percentages of 28,3 %, 30,6 %, 4,3 %, and −5,2 % correspond to the ratios of 0,69; 0,895; 1,07 and 1,29, respectively. Therefore, the approximate R_p of 1 was regarded as the "boundary" for determining the efficiency of the rock fragmentation performance of the water jet-assisted cutting head. This phenomenon has been analyzed and is thus excluded in this discussion.

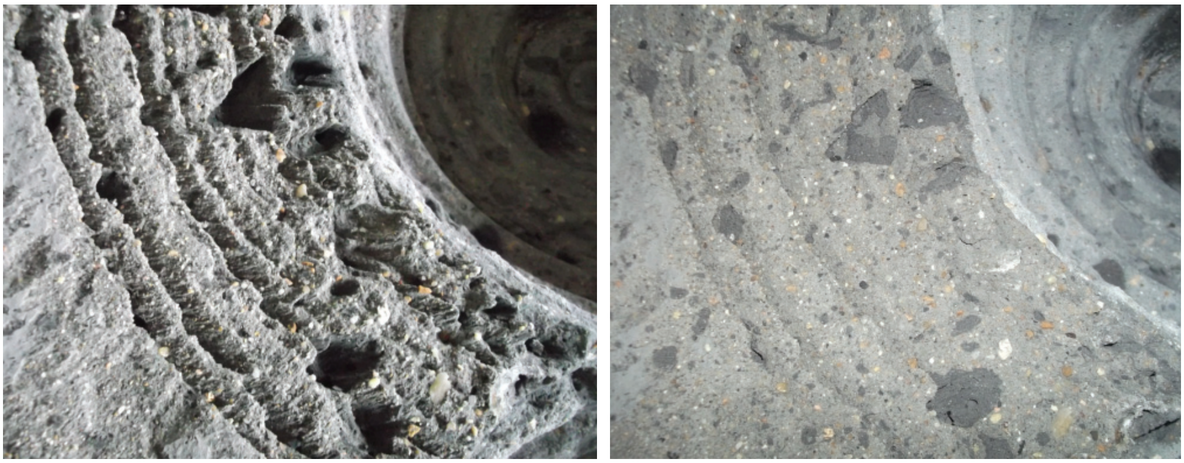

a) b)

Figure 9 a) Kerf formation by water jet impact with rock compressive strength of 15,2 MPa; b) Kerf formation by water jet impact with rock compressive strength of 19,7 MPa

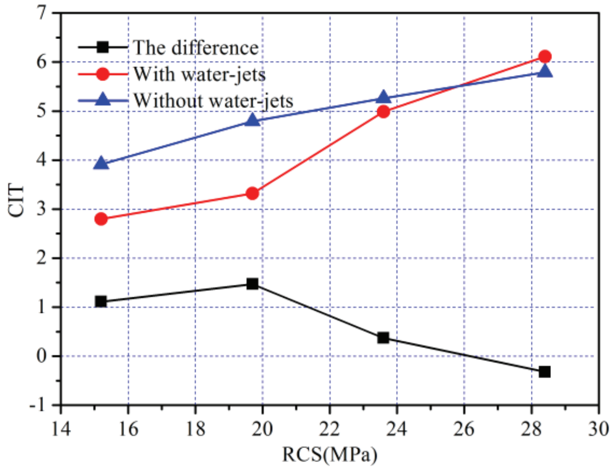


Figure 10 CIT with and without water jet assistance

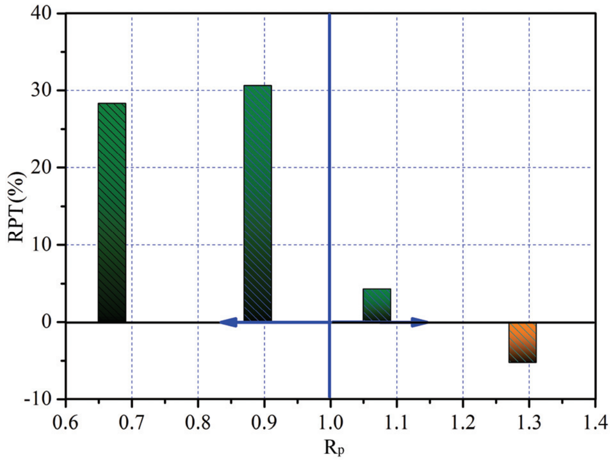


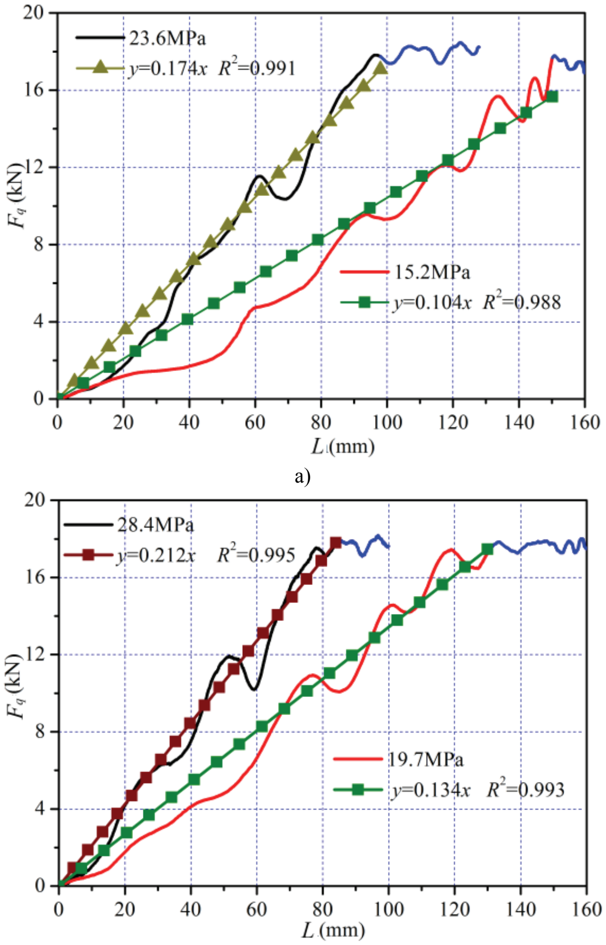
Figure 11 RPT under different R_p

4 Effect of rock compressive strength on pulling force

4.1 Pulling force without water jet assistance

The initial stage of rock fragmentation by cutting head is the drilling condition, which is the precondition for implementing pendular rock cutting. Pulling force in the drilling condition should be investigated for roadway construction. Fig. 12 shows the pulling forces versus the drilling depth with different rock compressive strengths.

Before reaching the traction limitation, the pulling force of the cutting head linearly increased with the drilling depth. This condition can be explained by the large volume of rock fragmentation by cutting head in unit time when the drilling depth was large. The increased rate of the pulling force versus the drilling depth was proportional to the rock compressive strength, thus indicating that the increased rate can reflect the load level with different rock compressive strengths. The regression coefficients of the fitting line all exceeded 0,95; hence, the regression line could match the variation trend of the pulling force before the traction limitation was reached. The characteristic index of pulling force (CIP) changed with the rock compressive strength, exponentially increasing with the compressive strength (Fig. 13). Thus, the pulling force increased with the rock compressive strength. The CIP without water jet assistance could serve as a reference index for investigating the pulling force of the water jet-assisted cutting head.



a)

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Figure 12 a) Pulling force without water jet assistance with rock compressive strengths of 15,2 and 23,6 MPa; b) Pulling force without water jet assistance with rock compressive strengths of 19,7 and 28,4 MPa

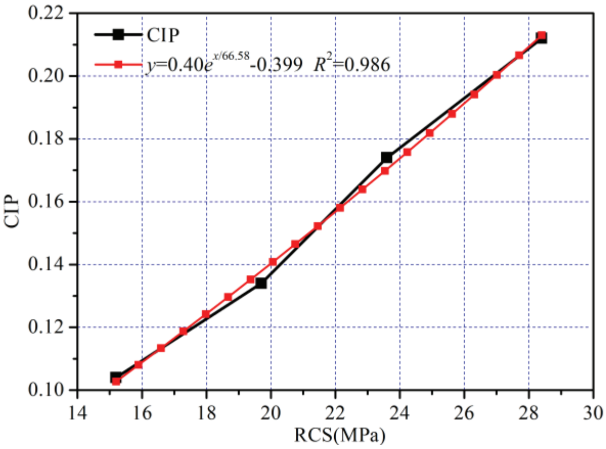
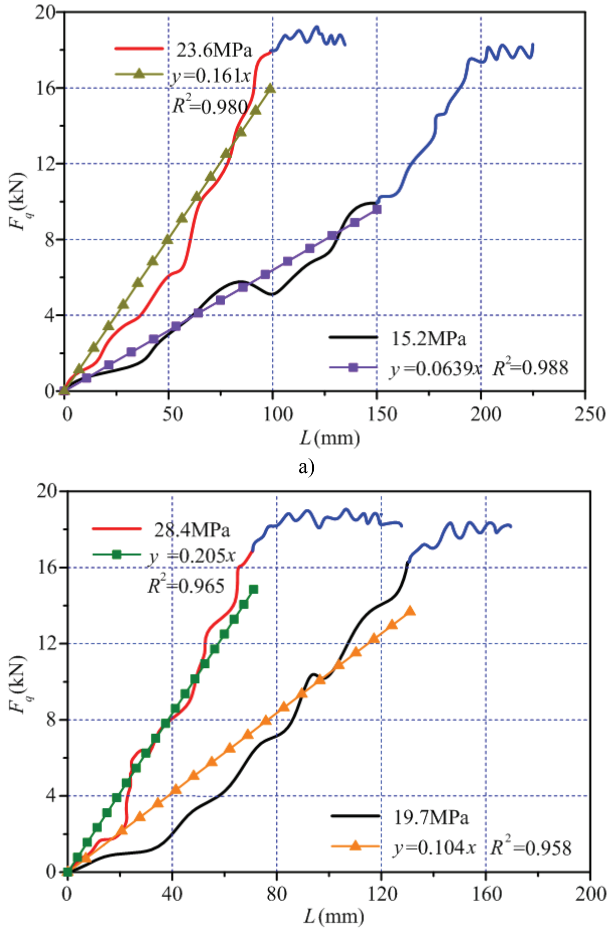


Figure 13 CIP without water jet assistance versus rock compressive strengths

4.2 Pulling force with water jet assistance

Fig. 14 shows the pulling forces versus the drilling depth under different rock compressive strengths for the water jet-assisted cutting head. The overall trend of the pulling force is similar to that of the cutting head without water jet. The pulling force increased with the drilling depth until the traction ability of the assist transmission system reached its limitation because of the constant power control system. The peak pulling force was approximately 18 kN, which is consistent with that of the cutting head without water jet. The reason was that the maximum pulling force produced by the assist transmission system was close to 18 kN. Similarly, the least squares method was adopted to linearly fit the pulling force in the range of 0 to the maximum drilling depth without water jet assistance (Fig. 14).



a)

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Figure 14 a) Pulling force assisted with water jet assistance with rock compressive strengths of 15,2 and 23,6 MPa; b) Pulling force assisted with water jet assistance with rock compressive strengths of 19,7 and 28,4 MPa

The decreased percentages were 38,5 %, 22,3 %, 7,5 %, and 3,3 %, which correspond to the rock compressive strengths of 15,2; 19,7; 23,6 and 28,4 MPa, respectively. Thus, the rock fragmentation performance in drilling was obviously improved when the rock compressive strength was lower than the water pressure. The reduction of cutting torque and pulling force assisted by water jets was not coincidental. The pulling force slightly decreased when the rock compressive strength was up to 28,4 MPa. Fig. 9 shows that obvious kerfs formed when the water jet hit the rock with low compressive strength; the angle between the kerfs and the drilling speed direction equals the complementary angle of the pick tilt angle [7, 31]. Several free surfaces of the rock with low compressive strength formed because of water jet impact, which transformed the rock closed cutting to a semi-enclosed or an open cutting by conical pick. When the depth of the kerfs was large, the rock between the two adjacent kerfs was broken down easily because of the extrusion action by the conical pick. The pulling force could obviously be decreased when the rock compressive strength was lower than the water jet pressure. According to the cutting and tilt angles of the conical pick, the effect of pick sharpness on the rotation cutting performance was larger than that of the drilling performance, causing the pulling force to decrease slightly when the rock compressive strength was higher than the water jet pressure.

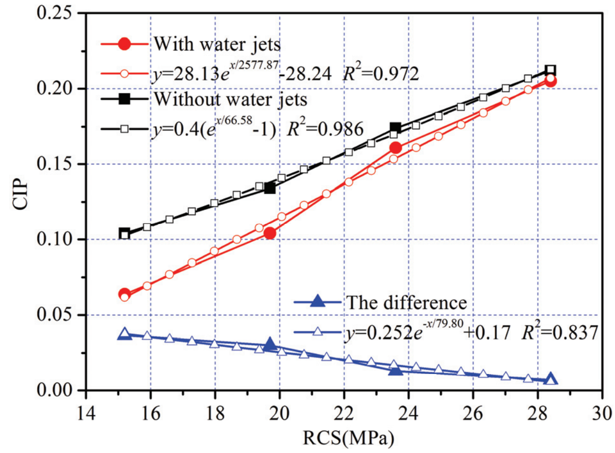

Figure 15 CIP with and without water jet assistance

Fig. 15 shows the CIP with and without water jet assistance. With different rock compressive strengths, the CIPs were all less than those without water jet assistance. The difference of the two CIPs decreased with the rock compressive strength. Their variation feature differed from that of the cutting torque with water jet assistance. Hence, the effect of the water jet on the pulling force of the cutting head was relatively stable.

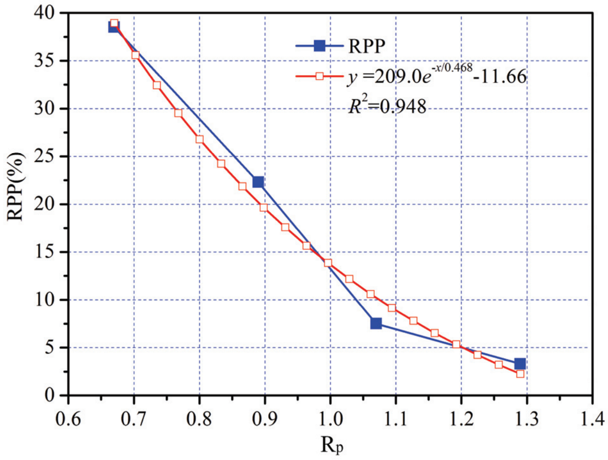

Figure 16 RPP versus R_p

Fig. 16 shows the relationship between the reduced percentage of pulling force (RPP) and R_p, with the former decreasing sharply and exponentially. Similar to the case of the cutting torque with reduced percentage, the drilling performance could not significantly be enhanced when the ratio exceeded 1. Therefore, R_p of approximately 1 was used to determine the water pressure according to the rock compressive strength.

5 Conclusion

Rock fragmentation experiments by cutting head with and without water jet were conducted based on the developed test bed. The effect of the compressive strength on the rock fragmentation performance of the two types of cutting head was investigated. The experiments led to the following conclusions:

(1) The test bed was developed for rock fragmentation by cutting head. A rotary seal device was designed to introduce high-pressure water into the center of the conical pick of the cutting head. The developed test bed was used to achieve rock fragmentation by water jet-assisted cutting head.

(2) The regression line was reliable and accurate and matched the variation trend of the cutting torque and pulling force before reaching the traction limitation. The slope of the fitting lines was regarded as the characteristic index of the rock fragmentation loads. The CITs and CIPs exponentially increased with the rock compressive strength without water jet assistance. However, no obvious relationship was observed between the CITs and rock compressive strength assisted by water jet. However, the effect of the water jet on the pulling force of the cutting head was relatively stable.

(3) The rock fragmentation loads of the cutting head decreased by approximately 20 % to 40 % when the water pressure was higher than the rock compressive strength. However, water jet assistance was less effective when the water pressure was lower than the rock compressive strength. The ratio between the rock compressive strength and water pressure can be used to recognize the efficiency of water jets for rock fragmentation by cutting head.

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