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Effects of nozzle position and waterjet pressure on rock-breaking performance of roadheader

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ABSTRACT

The performance of roadheaders in cutting hard rocks can be improved using high-pressure waterjet technology. The optimum position of waterjet nozzles and the threshold pressure in rotary cutterheads have not been well studied. This study investigates the effects of the waterjet-nozzle position and waterjet pressure on the cutting torque and thrust force of scaled roadheaders with point-attack picks. The experimental results show that the waterjet helps in significantly reducing the cutting torque and thrust force. Moreover, the rock-breaking performance is the best when the nozzles are positioned at the center of the pick. For the center-positioned configuration with a pressure of 40 MPa, the specific energies of three types of rocks are reduced by 41.3, 28.3, and 20.1%. The effects of the nozzle position and waterjet pressure on the dust suppression and pick wear are also examined and a fine-dust suppression coefficient of over 70% is achieved.

1. Introduction

Roadheaders are one of the most widely used machines for fast roadway construction in soft-to-medium hard rocks owing to their advantages, such as high advance rates, good mobility, and versatility (Neil and Ozdemir, 1991; Copur et al., 1998; Bilgin et al., 2004). Hemphill (2012) and Bilgin et al. (2013) provided excellent reviews on the development and applications of roadheaders in the mining and tunneling industries and their operating principles. However, when cutting hard and abrasive rocks, cutters of a roadheader are subjected to high forces, excessive wear, and high temperature, resulting in reduced cutter life, compromised advance rates, increased machine downtime, and eventually, a higher project cost (Wang and Miller, 1976; Hood, 1985; Liu et al., 2014a). Previous researches have demonstrated that waterjets can help in significantly increasing the advance rates, reducing the dust generation, and extending the cutter life (Ozdemir and Evans, 1983; Tecen and Fowell, 1983; Fenn et al., 1985; Hood et al., 1992; Vasek, 1995; Yang et al., 2011; Jiang et al., 2015). The cutting forces can be reduced by a factor of two and the cutter life can be doubled with the assistance of waterjet. For hard-rock roadheaders, point-attack/conical picks are the most suitable type of cutter for efficient rock breaking. So far, the mechanism of waterjet-assisted cutting is not well understood. Dubungnon (1981), Hood (1985), and Summers (1995) believed that the waterjet could be used to either pre-weaken the rocks by cutting kerfs, or clean away the fragments at the pick–rock interface to avoid the energy-intensive grinding process, or both, depending on the pressure of the waterjet and the location of the nozzle with respect to the picks. In contrast, Fairhurst (1987) and Pierce et al. (1996) advised that the best application of the jet is to relieve the forces on the tool tip and not to remove the crushed rocks around the tip, which help in creating a tensile strength for chip generation. Nonetheless, researchers agree that for waterjets to be effective, they have to penetrate into the cracks initiated by the pick cutters and extend the cracks (Dubungnon, 1981; Hood et al., 1992). Over the past four decades, the influences of the waterjet pressure, water flow rate, positioning and standoff distance of jet nozzles, cutting velocity, and rock strength on the cutting thrust force and torque, dust generation, advance rate, and specific energy have been extensively investigated. The influences of the nozzle position and waterjet pressure on the cutting performance are summarized below.

The position of the waterjet nozzles with respect to the picks is of vital importance for improving the cutting efficiency. Generally, for point-attack picks, the following five arrangements exist: in front of the pick, impinging on the pick, through the pick, at the sides of the pick, and behind the pick. There is a controversy regarding the best position of the nozzles. Ropchan et al. (1980) found that placing the nozzle behind the conical picks is much more effective in reducing the normal and drag forces in the Dakota Sandstone because the jet placed in front of the picks could be constantly deflected and diffused by cut debris. Hood (1985) argued that it is important to position the waterjet at a distance within 1 or 2 mm from the leading face of the bit to substantially reduce the bit forces. Fowell et al. (1992) advised that

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impinging the jet within 1–2 mm of the pick tip has a clear advantage over other arrangements. Liu et al. (2014b) studied the performance of rock breaking using conical picks with the help of high-pressure water jet and found that the waterjet is most efficient when placed through the center of the conical pick. Hood et al. (1992) believed that these differences in opinion might be due to the different bit geometries. Previous studies focused on the relationship between the nozzle position and the single cutting tool. However, it is difficult to arrange a nozzle for each pick, because a cutterhead comprises approximately 30–40 picks. Further studies are required to determine the best position of the jet for all the cutterheads.

The waterjet pressure has an important influence on the rock-breaking process. The important uses of various types of plain-water jets for rock breaking can be classified into three groups. First, the mechanically assisted waterjets, wherein waterjets (below 100 MPa) are used along with rock cutters (Jiang et al., 2015). Second, the pulsed waterjets, wherein waterjets (up to 200 MPa) are used to apply cyclical, impact forces in the form of a sequence of generally short-duration stress pulses onto the rock (Dehkhoda and Bourne, 2014). Third, the super-high pressure continuous waterjets, wherein only the waterjets (up to 400 MPa) are used to cut the rocks (Louis et al., 2003). It is more cost effective to use a waterjet along with mechanical excavators (Fowell et al., 1986; Hood et al., 1992). For the waterjet to assist in the breaking of rocks, a given waterjet pressure must be exceeded. After reaching the threshold pressure, the cutting efficiency increases with the increase in the waterjet pressure until reaching the optimum pressure beyond which no further increase in the rock-breaking efficiency is observed (Pierce et al., 1996). The threshold and optimum pressures are governed by the cutter specifications and rock strength. Ropchan et al. (1980) found that a jet with a pressure of 35 MPa helped in improving the pick performance in softer sandstone; however, it was less effective for harder sandstone, shale, and limestone. The pressure should be increased to 70 MPa to observe the same effect. The same phenomena were observed by Dubungnon (1981) when cutting sandstone and granite of different strengths. The above research demonstrates the importance of the waterjet pressure. However, because of the complex mechanism observed in the waterjet-assisted cutting technology, the relationship between the rock-breaking performance and the waterjet pressure is unknown; moreover, the same applies for pulsed waterjets and super-high pressure continuous waterjets (Dehkhoda and Hood, 2014).

In this study, cutterheads with waterjet nozzles placed at different positions with respect to the picks are designed and manufactured to investigate the influence of the positions of the nozzles on the rock-breaking efficiency. Additionally, the effect of the waterjet pressure on the rock breaking performance is analyzed, and the threshold pressure of difficult rocks is obtained. Moreover, the reductions in the cutting torque, thrust force, specific energy, fine dust, and pick wear are examined.

2. Experiment procedures

2.1. Design of cutterheads

Given that developing a full-scale roadheader rock-breaking machine in a laboratory is very expensive and time and labor consuming, scaled cutterheads are designed and manufactured. Based on the similarity theory, the prototype and model must satisfy equilibrium equations, geometric equations, physical equations, and displacement-boundary conditions (Fumagalli, 1973). To balance the reliability of the test results and the cost and time of the test, a similarity factor of 2.5 is selected in the study. The scaling process based on the principle of Homogeneity and Buckingham's Pi theorem can be found in the found by Liu et al. (2009). Table 1 lists the relationship between the parameters of the model and its prototype. It should be noted that no attempts were made to simulate the rock material, as the purpose of the study is to investigate the effect of the waterjet on the cutting performance.

Fig. 1 shows the scaled cutterhead manufactured based on the parameters listed in Table 1. The length and diameter of the cutterhead are 302 and 362 mm, respectively (Fig. 1(a)). It comprises 38 point-attack picks and 6 waterjet nozzles, which are arranged in a three-start helix with 13 picks on each of the two helixes and 12 picks on the third helix. In the cutting process, picks at the front of the cutterhead help in breaking the rock first, and the waterjet nozzles at the front picks assist in rock breaking from the beginning. If the water nozzles are installed behind the cutterhead, the waterjets working as a coolant will not be able to effectively assist the rock breakage. Thus, on each helix, two picks at the very front of the cutterhead are equipped with a waterjet nozzle (Fig. 1(b)). Fig. 1(c) shows the structure of the pick. The bit of the pick is made of cemented carbide, which is characterized by high thermal hardness and good resistance to wear and brittleness. The pick body is made of C45 alloy steel, which is characterized by good comprehensive mechanical properties (strength, toughness, hardenability, weldability, and processing formability) but poor resistances to wear, corrosion, and oxidation (Yang et al., 2015). The major requirement of a nozzle is the efficient conversion of potential energy to kinetic energy. This is best achieved by a sudden, smooth contraction of the flow area from the supply line to the desired nozzle diameter. Fig. 1(d) shows the structure of the nozzle based on the studies conducted by McCarthy and Molloy (1974) and Mitsoulis and Hatzikiriakos (2003).

2.2. Waterjet positions

To investigate the influence of the nozzle positions on the rock-breaking efficiency, three types of position configurations of a waterjet nozzle with respect to the pick, namely, front, center, and rear, are designed, as shown in Fig. 2. For the cutterhead with the front-positioned nozzles (Fig. 2(a)), the nozzles are attached to the cutterhead and are separated from the pick holders. For the cutterhead with the center-positioned nozzles (Fig. 2(b)), the nozzles are countersunk into the picks and high-pressure water is made to flow through the picks. For the cutterhead with the rear-positioned nozzles (Fig. 2(c)), the nozzles are placed on the pick holders. The nozzle-to-pick standoff distances for the front and rear positioned configurations are approximately 18 mm.

The flow passage may affect the waterjet pressure at the nozzle to a certain extent, particularly when there are corners or sudden area changes in the flow passage. To study the difference due to the flow passage, the outlet pressure of the nozzle is computed using the following equation.

$$P = \rho Q^2 k/(2A^2) \tag{1}$$

where P is the outlet pressure (Pa), ρ is the density of water, Q is the flow rate (m^3/s), k is the resistance coefficient, and A is the nozzle area (m^2).

The ρ and A are constant, and the Qs of the three waterjet nozzle types are measured in the experiment using a flow meter and are close in value. Compared to the total pressure loss, the pressure loss due to the nozzle is negligible. This is because compared to the distance between the pump and the nozzle, the distance between the cutterhead body and the nozzle is short. Thus, the difference in k due to the waterjet positions is ignored in this study, and the pressure loss of the entire flow passage will be addressed in the future.

2.3. Rock specimens

In this study, Portland cement #42.5, grade B gypsum powder, and river sand are used as the raw materials for preparing artificial rocks. The raw materials are weighted based on the mass ratios of the cement, gypsum, and sand (C/G/S). The well-mixed materials are then poured into the molds and rock boxes, and subsequently, rodded and cured in accordance with the ASTM C192 standard. The height, width, and