Cutting performance evaluation of Actuated Disc Cutting by linear cutting test

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ABSTRACT: This paper presents an investigation into Actuated Disc Cutting (ADC). The ADC is based on the undercutting mechanism and involves several cutting parameters. To enable an experimental analysis of ADC, a new lab-scaled rock-cutting system is introduced. This system facilitates the undercutting concept of rock cutting based on the traditional Linear Cutting Machine (LCM) system. The cutting parameters in ADC, such as eccentricity, linear velocity, and RPM are simulated by the introduced cutting system. The paper also introduces calculation methods for cutter forces and specific energy of ADC based on the system. A series of undercutting tests were performed on a designed hard rock specimen under different cutting conditions. The effects of cutting parameters on cutter forces and specific energy were discussed, and the optimal cutting conditions in ADC were analyzed. The proposed lab-scaled rock-cutting system and calculation methods can be utilized for future studies in this field.

Keywords: Actuated disc cutting, undercutting, LCM, Cutting efficiency.

1 INTRODUCTION

Mechanical rock excavation techniques, such as Tunnel Boring Machines (TBM), roadheaders, continuous miners, and others, have become increasingly popular in many civil and mining projects. This trend is particularly evident in urban areas, where environmental considerations are paramount. Despite extensive research and remarkable developments in cutting efficiency and machine design, traditional mechanical excavation methods still face difficulties. For instance, conventional cutting tools are prone to high cutter forces and excessive wear when excavating hard rock. These problems may be inherent in the fundamental mechanism by which the cutting tool excavates the rock. Traditional rock cutting relies on two mechanisms: indenting, used by TBM disc cutters, or dragging, used by pick cutter.

As a promising alternative to traditional rock cutting methods, the concept of undercutting disc cutter (UDC) has been proposed. The UDC combines the advantages of both rolling and dragging mechanisms in rock cutting. The undercutting concept enables a rolling disc to be dragged across the rock surface like a pick cutter, reducing the required cutter force. In recent years, the undercutting disc cutter (UDC) technique has been studied as the form of oscillated undercutting (ODC) and actuated disc cutting (ADC). The ODC involves oscillation of the disc cutter at small amplitudes, facilitated by an internal motor. The ADC, on the other hand, builds on the ODC concept by adding a free rotational mechanism in a secondary axis that is not concentric with the main rotational axis.

In this study, a series of undercutting tests were performed on a designed hard rock specimen (rock-like material) under different cutting conditions. The paper also introduces calculation methods for three directional cutter forces and specific energy of ADC based on the traditional linear cutting machine test. The effects of cutting parameters on the cutter forces and specific energy were thoroughly discussed, and the optimal cutting conditions in ADC were analyzed.

2 METHODOLOGY

2.1 Testing system

Figure 1 shows the actuated undercutting test system utilized in this study, which was adapted from the conventional LCM system. The load cell, capable of recording forces in three orthogonal axes, has a 20-ton capacity. The vertical motor manages the penetration depth, while the horizontal motor drives the linear motion at a maximum velocity of 100 mm/s. Additionally, an electric motor with a maximum RPM of 800 and a torque of 1000 Nm acts as the system's rotational motor. A small-scaled ADC was used for the cutting tests, and the scaling ratio was determined through dimensional analysis, as displayed in Table 1. The laboratory experiment employed a 60 mm ADC to cut a concrete block with a uniaxial compressive strength of 20 MPa and a density of 2.1 g/cm^3. Assuming a constant gravitational acceleration, the ratio of the other dimensional variables can be determined for the use of a 500 mm ADC to cut a rock with a density of 2.6 g/cm^3. The strength of the laboratory-tested material is estimated to be 10.3 times weaker than the actual condition. Therefore, the 20 MPa laboratory specimen corresponds to approximately 206 MPa in actual cutting operations.

Figure 1. Linear cutting machine with ADC.

Table 1. Dimensional analysis to determine scaled condition in the cutting test.

Parameter	Dimension	Scaled value	Actual value	Ratio
Length	[L]	60	500	0.120
Gravity	[LT-2]	9.81	9.81	1.000
Density	[ML-3]	2.1	2.6	0.808
Time	[T]	-	-	0.346
Mass	[M]	-	-	0.001
Strength	[ML-1T-2]	-	-	0.097

2.2 *Cutting conditions*

The fundamental mechanics of ADC has been introduced in previous studies (Dehkhoda & Detournay, 2017, 2019, Jeong et al., 2021). The system consists of a main and a secondary axis, where the former is the center of rotation, and the latter is the center of the disc. Eccentricity (e) is defined as the distance between the disc center and the point of system rotation. The system revolves at a constant angular velocity (w) around the primary axis. The undercutting disc is attached to a cartridge and moves with a constant linear velocity (v) parallel to the cutting direction. The movement of a disc is determined by the product of translation and actuation relative to the main axis. The disc rotates freely around its axis, cutting the rock surface at a constant penetration depth (p). The parameters e, w, v, p, and the radius of the undercutting disc (d) define the trajectory of the undercutting disc, as well as the geometry of the cut rock surface. Additionally, the disc can be tilted (tilt angle α) throughout the cutting process to avoid excessive friction on the flat surface of the disc. The schematic mechanism can be seen in Figure 2. In this study, diameter of ADC, penetration depth (p), and RPM were fixed as 60 mm, 4 mm, and 70, respectively. A total of nine cases were performed with various linear velocities (v) of 20 mm/s, 30 mm/s, and 40 mm/s, and eccentricity (e) of 3.75 mm, 5.60 mm, and 7.50 mm.

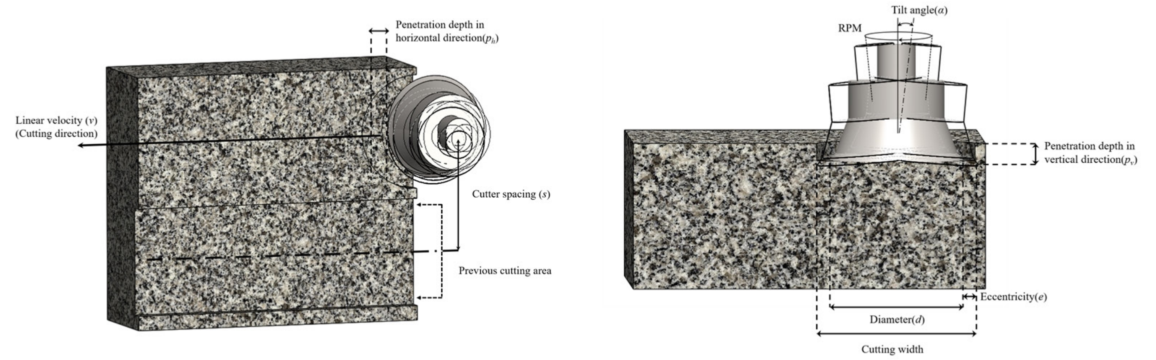


Figure 2. Cutting parameters of an actuated undercutting disc.

3 RESULTS

3.1 *Cutter forces*

The undercutting test system uses a load-cell to obtain real-time data on three-directional cutter forces. The normal force is measured perpendicular to the rock surface, while the cutting and side forces are perpendicular to the normal force and each other on the cutting surface. Figure 3 provides an example of the measured forces acting on an actuated disc during rock cutting. The three orthogonal cutter forces were periodic, and they exhibited peak values during cutting. The magnitudes of the three force components were similar. For a disc cutter, the normal force is typically about 10 times greater than the rolling force and side force, which is a key characteristic of ADC cutter forces. Table 2 presents the results of cutter force at different cutting conditions.

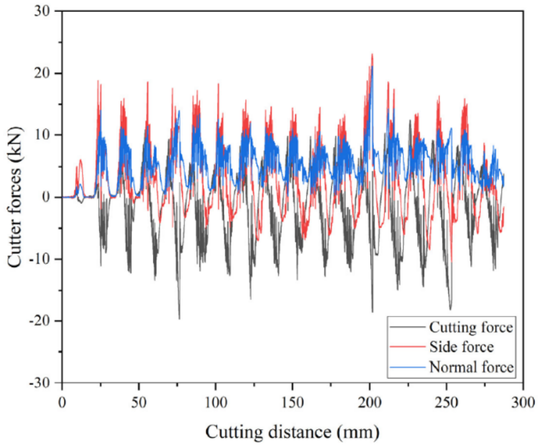
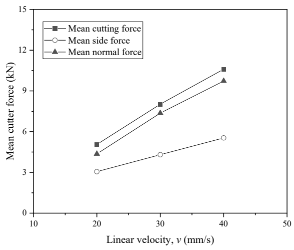
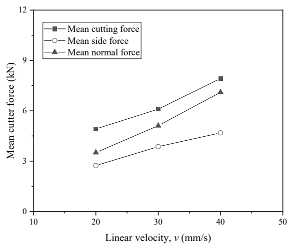


Figure 3. An example of cutter forces of ADC.

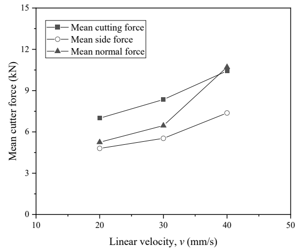
Figure 4 illustrates the effect of linear velocity (v) on the cutter force acting on the ADC. The findings suggest a linear increase in cutter forces as a function of linear velocity. It is noteworthy that linear velocity governs the depth of cutter penetration (in the cutting direction) per revolution of the cutting surface, provided that all other cutting parameters remain constant. The observed positive relationship between penetration depth and cutter forces has been extensively demonstrated through theoretical, experimental, and numerical research in rock cutting engineering. As such, the observed results can be deemed reasonable.



(a) e = 3.75 mm



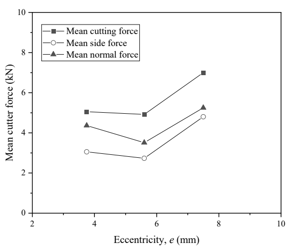
(b) e = 5.6 mm



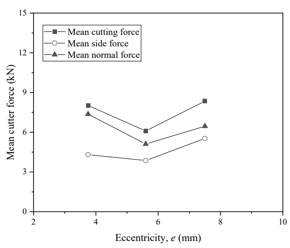
(c) e = 7.5 mm

Figure 4. Effect of linear velocity on the cutter force of ADC at different eccentricities.

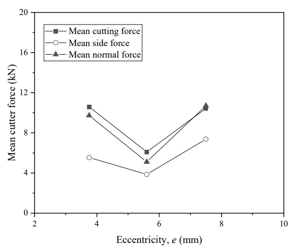
Figure 5 presents the effect of eccentricity (e) on the cutter forces of the ADC. The results indicated that the cutter forces were minimum at 5.6 mm of eccentricity for all cutting conditions. It implies that the cutting efficiency can be optimized at a specific eccentricity value in ADC rock cutting when the other cutting parameter is constant.



(a) v = 20 mm/s



(b) v = 30 mm/s



(c) v = 40 mm/s

Figure 5. Effect of eccentricity on the cutter force of ADC at different linear velocities.

3.2 *Specific energy*

In case of ADC, the cutting path is helical shape. In order to calculate the work, the continuous change in cutting path and direction of cutting and side forces should be considered. In Figure 6, the conceptual diagram for calculation method of work done by ADC to calculate the specific energy.

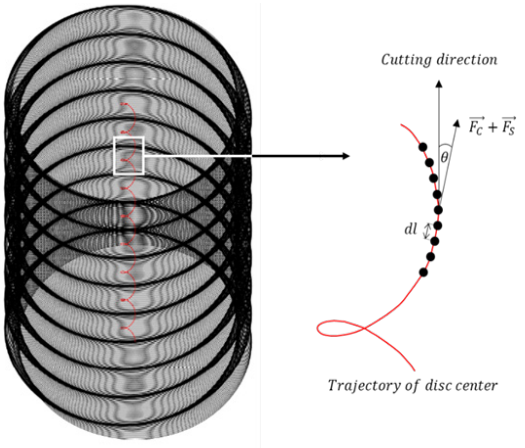


Figure 6. Conceptual diagram to calculate specific energy of ADC.

Figure 7 illustrates the effect of penetration depth (p) on the specific energy of the ADC, with varying linear velocities. Specifically, it is evident that at linear velocities of 30 and 40 mm/s, the specific energy increased as the penetration depth increased. In contrast, at a velocity of 20 mm/s, the specific energy exhibited a minimum value at a particular penetration depth of 4 mm. These results suggest that there may be an optimal value for penetration depth that can optimize the specific energy, particularly at a linear velocity of 20 mm/s. However, it is unclear whether the specific energy would be lower at smaller penetration depths for linear velocities of 30 and 40 mm/s, as there is limited test data available. Notably, the distinct trends observed in specific energy concerning linear velocity indicate that the optimal penetration depth value may vary based on linear velocity.

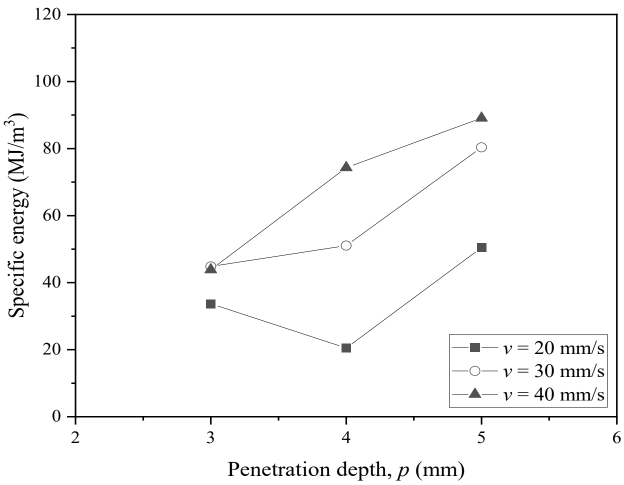


Figure 7. Effect of penetration depth on specific energy.

The effect of eccentricity on the specific energy of the ADC is illustrated in Figure 8. The e/p ratio concept was introduced to present the effect of eccentricity on the specific energy. Notably, at a linear velocity of 20 mm/s, the specific energy decreased with increasing e/p ratio. In contrast, for linear velocities of 30 and 40 mm/s, the specific energy values exhibited a minimum at 1.4 of e/p ratio. It is important to note that as the eccentricity of the ADC increases, it cuts a larger volume of rock in rotational motion when other cutting parameters are constant. These findings indicated that the cutting efficiency of the ADC increases with eccentricity until it reaches a certain limit value under the given cutting conditions. Beyond this limit value, the required cutter forces will drastically increase. Therefore, it is possible to optimize (or minimize) the specific energy for a particular cutting condition by selecting an appropriate eccentricity value.

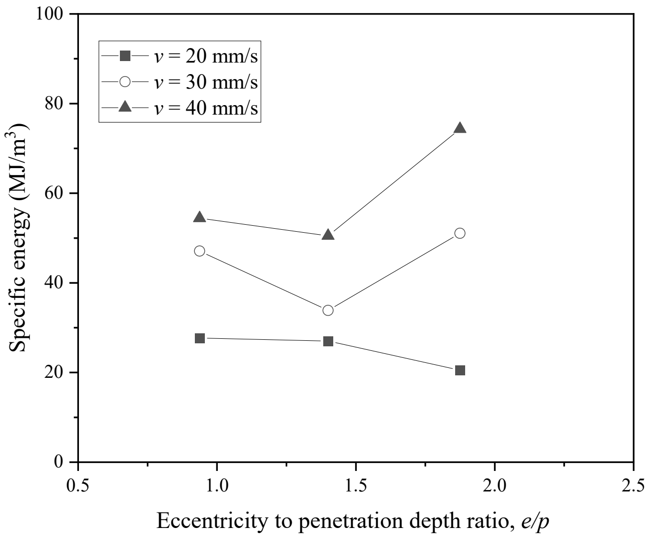


Figure 8. Effect of e/p ratio on specific energy.

4 CONCLUSIONS

This study introduces the testing method that enables evaluating cutting performance based on the undercutting method using an actuated disc cutter (ADC). Due to the fact that an ADC has a different cutting mechanism than disc or pick cutting, the testing parameters and performance evaluation are also different. Unlike the conventional method, ADC operates on non-linear trajectories in which the cutting direction changes throughout the test. As a result, a new approach for calculating cutting force and specific energy is introduced that considers the resultant force and its orientation relative to the cutting direction. The results indicated that the cutting performance of ADC was affected by different cutting parameters of ADC, and the efficient cutting condition can be determined by using a function of e/p ratio. However, future work using a more extensive database is necessary to confirm the current findings.

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