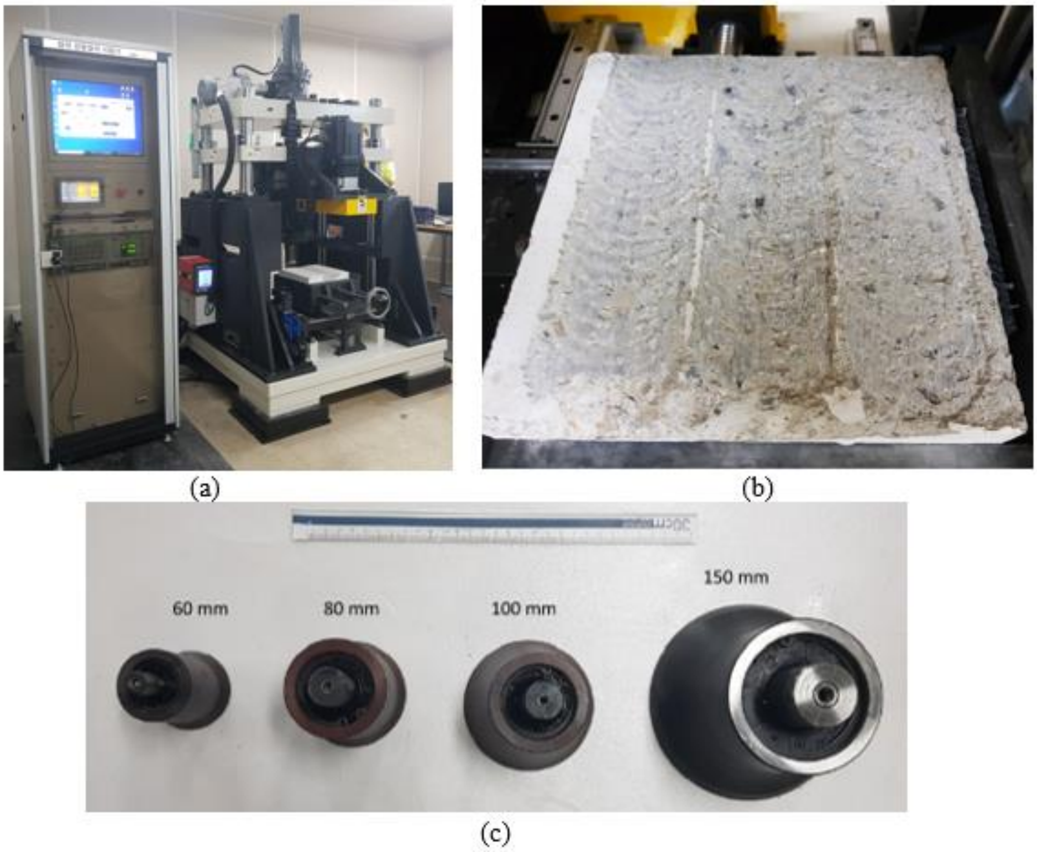

Fig. 2. Actuated undercutting testing system. (a) the machine, (b) typical of specimen after test, (c) scaled-down ADC in various sizes

Table 1. Scaled condition used in the experiment (ADC diameter = 60 mm, specimen density = 2.1 gr/cm^3)

Variable	Dimension	Measure		Ratio
		Scaled	Actual	
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 and stress	$ML^{-1}T^{-2}$	-		0.097

3. SPECIFIC ENERGY CALCULATION

The concept of specific energy is introduced to evaluate the rock cutting performance. The term specific energy refers to the work performed by a cutter to cut a unit volume of rock, as shown in Eq. (1).

$$SE = \frac{Work\ done}{Volume} \tag{1}$$

In standard disc and pick cutting, the cutting direction is linear, and the force can be represented by force dominant parallel to the cutting direction. Thus, the work performed by the cutter on a typical traditional cutting can be calculated using Eq. (2).

$$W = \overrightarrow{F_c} \cdot \vec{l} = |\overrightarrow{F_c}||\vec{l}|cos\theta \tag{2}$$

where F_C is the cutting force, l is the cutting length, and θ is the angle between the force direction and the cutting direction.

However, in actuated undercutting, the cutting force and side force play a significant role in the cutting operation. As a result, work is derived in a slightly more complex form by including side force. The DAQ system of the machine is capable of recording three-dimensional force at the rate of 1000 Hz. The quick data interval enables segmentation of the cutting trajectory into smaller linear segments every one millisecond. As a result, the work is denoted by Eq. (3).

$$W = \sum(|\overrightarrow{F_c} + \overrightarrow{F_s}| \cdot dl \cdot cos\theta) \tag{3}$$

where F_C is the cutting force, F_S is the side force, and dl is the cutting length in a small interval.

The cut volume is simplified and assumed to be cuboid in shape because the excavation produces a flat surface with straight side boundaries. Thus, as illustrated in Eq. (4), the cutting volume is theoretically estimated.

$$V_{cut} = (d + 2e)pl \tag{4}$$

where d is the diameter of the cutter, e is the eccentricity, p is the penetration depth, and l is the cutting length.

So, considering the work and volume calculations explained above, the specific energy can be denoted as Eq. (5). The schematic description of the calculation is depicted in Fig. 3.

$$SE = \frac{1}{V_{cut}}\sum(|\overrightarrow{F_c} + \overrightarrow{F_s}| \cdot dl \cdot cos\theta) \tag{5}$$

4. EXPERIMENT RESULT

This study used the ADC of 60 mm diameter, constant penetration depth (p) of 3 mm, and constant RPM of 70. 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. Cutter force in three orthogonal directions, namely cutting, side, and normal forces, were recorded throughout each test. The specific energy for each case was calculated based on Eq. (5). Representative cutter forces at a single case are depicted in Fig. 4; the experiment results are summarized in Table 2.

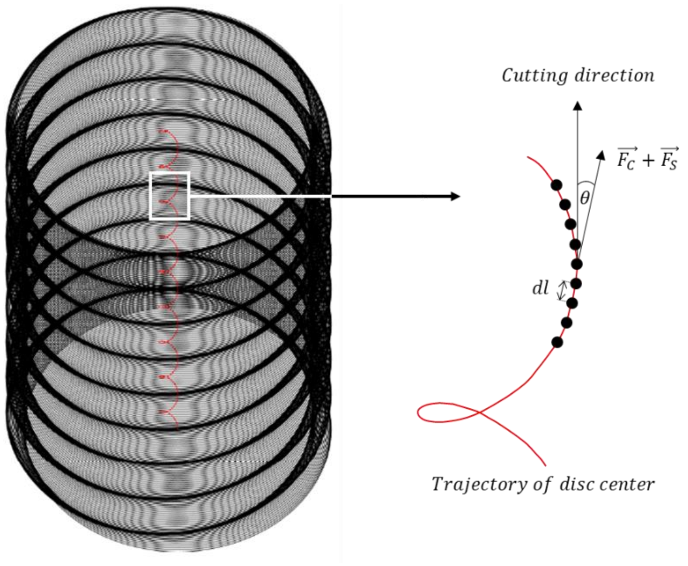

Fig. 3. Sample of cutting trajectory of ADC and specific energy calculation

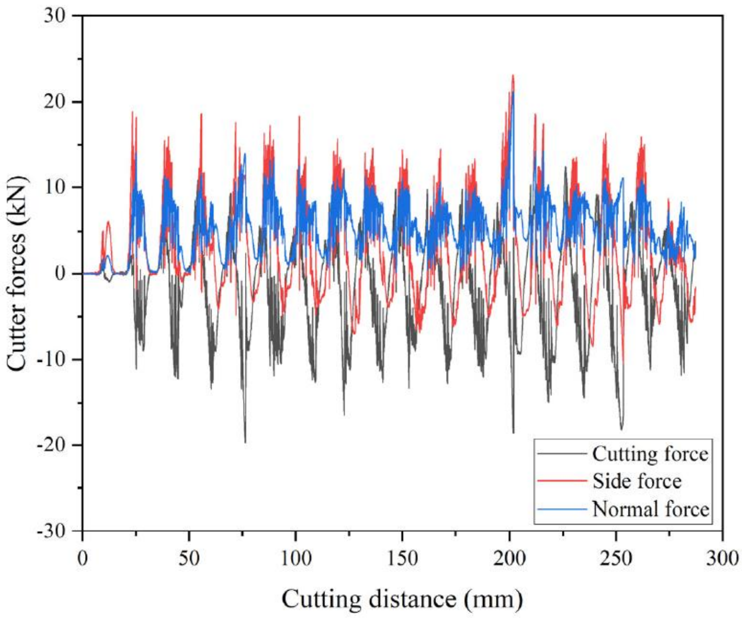

Fig. 4. Representative cutter forces of ADC at the case of *d* = 60 mm, *v* = 20 mm/s, *p* = 3 mm, *e* = 7.5 mm, RPM = 70

Table 2. Results of ADC test

Case	v (mm/s)	e (mm)	e/p	Mean cutter force (kN)			SE (MJ/m^3)
				Cutting	Side	Normal	
1	20	3.75	1.25	7.83	4.09	6.41	35.03
2	20	5.60	1.86	6.76	4.36	5.87	23.06
3	20	7.50	2.50	6.05	4.63	5.43	33.69
4	30	3.75	1.25	9.97	5.96	9.97	59.33
5	30	5.60	1.86	9.61	7.21	10.06	40.56
6	30	7.50	2.50	6.59	4.63	5.96	43.85
7	40	3.75	1.25	6.59	6.41	8.01	44.17
8	40	5.60	1.86	6.76	6.23	7.92	41.96
9	40	7.50	2.50	8.63	5.16	7.83	43.85

5. DISCUSSION

In traditional disc and pick cutting, the optimum cutting is usually expressed as a function of the *s/p* ratio, the ratio of line spacing between two cutters and penetration depth.

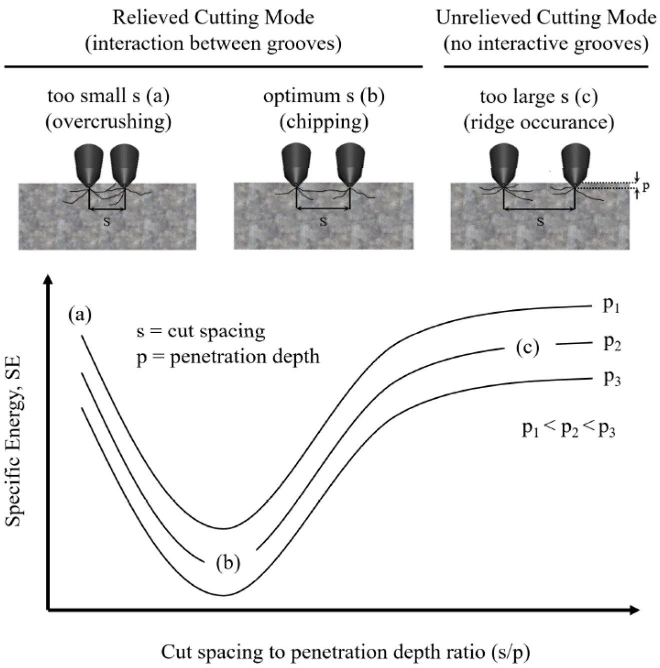

Fig. 5. The influence of line spacing and penetration depth on specific energy and cutting efficiency (modified from Bilgin et al. 2014)

Fig. 5 illustrates the influence of line spacing and penetration depth on specific energy and cutting efficiency (Bilgin et al, 2014). If the line spacing is too small (case a), the specific energy becomes extremely high, and the cutting becomes inefficient due to the over-crushing of the rock. If the line spacing is too large (case c), the specific energy is also high, and the process is inefficient because the tensile cracks from neighboring cuts cannot connect to form a chip (unrelieved cut). The lowest specific energy is attained by optimizing the *s/p* ratio, as illustrated in case b, which results in the most efficient cutting condition and produces the largest rock chips.

Undercutting with ADC, on the other hand, does not rely on neighboring cuts to produce chips. ADC enables the generation of tensile cracks in a direct manner, and the tensile cracks propagate directly towards the free surface. In this circumstance, the *s/p* ratio is irrelevant in determining the optimal cutting condition. Rather than that, we attempt to use the *e/p* ratio, which is the eccentricity to penetration depth ratio. Eccentricity is defined as the offset between the disc axis and the main rotational axis. Thus, the unit length of eccentricity contributes to the amount of rock excavated while also affecting the force being used to cut the rock. Therefore, the cutting efficiency will be specified by the minimum SE value under various *e/p* ratio settings.

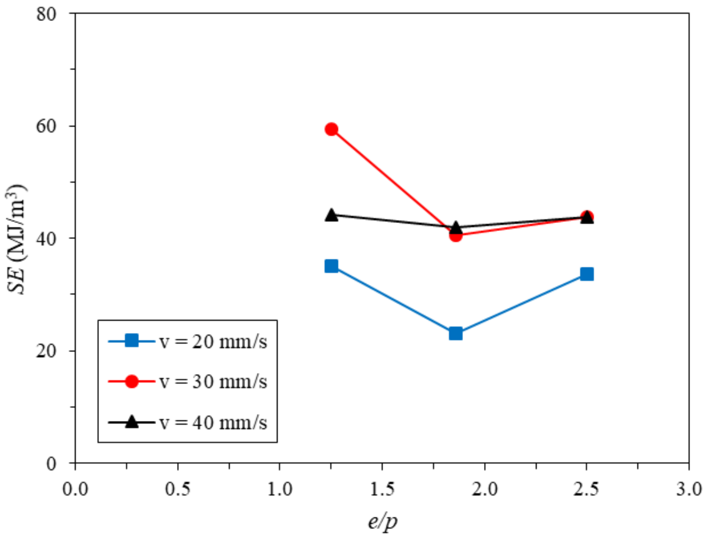

Fig. 6. Results of specific energy in various linear velocity and *e/p* ratio scenarios

Fig. 6 illustrates the influence of the *e/p* ratio and linear velocity on specific energy. The graph demonstrates that specific energy varies with the *e/p* ratio, with the lowest SE at *e/p* = 1.86. The results in this current study, however, are somewhat optimistic because the sampling data are limited. Nevertheless, the result indicates that using the *e/p* ratio as a parameter to define optimum cutting conditions could work. Additionally, Fig. 6 demonstrates that SE tends to decrease with decreasing cutting velocity, although this is obvious only for the case of 20 mm/s. Based on these findings, it is anticipated that cutting efficiency should be examined using the combination of *e/p* ratio and linear cutting velocity and potentially other cutting parameters such as rotational speed and tilting angle.

Another important issue is how the ADC performs compared to traditional disc and pick cutting. Table 3 summarizes the optimum ADC cutting condition from the current investigation compared to conventional disc and pick cutting. Based on work done by

Cho et al. (2003), at the optimum condition, disc cutting yielded SE values in the range of 35-42 MJ/m^3 from the laboratory cutting test and 37-43 MJ/m^3 from numerical simulation. In the case of pick cutting, Jeong et al. (2020a) reported SE values ranging from 37 to 68 MJ/m^3 in laboratory testing and 41 to 43 MJ/m^3 in numerical modeling. The optimal condition in the current study ranges from 23 MJ/m^3 to 42 MJ/m^3. Despite the fact that it is difficult to say if ADC performs better or not at the present study due to a lack of data, it is a solid indication, in which the SE value might drop as low as 23 MJ/m^3 with ADC. Future work using a more extensive database is necessary to confirm the current findings.

Table 3. Cutting efficiency of ADC compared to traditional disc and pick cutting

Optimum cutting configuration		SE (MJ/m^3)		Cutting mechanism	Reference
p (mm)	*s/p* or *e/p*	Laboratory	Numerical		
4	*s/p* = 10	41.70	43.10	Disc cutting	Cho et al. (2013)
6	*s/p* = 10	37.60	40.50		
8	*s/p* = 7.5	35.00	37.80		
5	*s/p* = 4	67.57	41.05	Pick cutting	Jeong et al. (2020a)
7	*s/p* = 3	42.17	40.99		
9	*s/p* = 3	33.12	42.08		
11	*s/p* = 3	31.10	43.10		
3	*e/p* = 1.86 (v = 20 mm/s)	23.06	-	Undercutting with actuated disc cutter	Present study
3	*e/p* = 1.86 (v = 30 mm/s)	40.56	-		
3	*e/p* = 1.86 (v = 40 mm/s)	41.96	-		

6. CONCLUSION

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 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 commonly used *s/p* ratio cannot be used to determine the cutting efficiency of ADC. Instead of that, the *e/p* ratio concept is proposed and tested using a simple laboratory test case. The efficient cutting condition can be portrayed from the result, but a more extensive database is needed to confirm the current finding. According to this study, ADC performs better than traditional cutting by exhibiting lower specific energy at its optimum cutting condition, although further research is required to provide more evidence.

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