Experimental investigation of multiple rock indentations on hard rock using a conical cutter at different cutting depths

Shaofeng Wang1,* Licheng Sun1, Shanyong Wang2
1 School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China
2 School of Engineering, University of Newcastle, Callaghan, NSW 2308, Australia
* Corresponding author: sf.wang@csu.edu.cn (Shaofeng Wang) ORCID: 0000-0001-9870-6463

Abstract. To apply roadheaders to deep hard rock mines, one must investigate the influence of multiple rock indentations and cutting depths on rock breakage. In this study, multiple rock indentations using a conical cutter were performed on hard rock samples at different cutting depths. The relationship between the cutting depth and the parameters reflecting the rock cuttability was regressed. The experimental results of the single and multiple rock indentations were compared. They showed that the failure pattern affects the cutting parameters. In the case of partial splitting, the cutting parameters increase with the increase of the cutting depth. Meanwhile, in the case of complete splitting, the force and the work required to break the rock did not show any obvious relationship with the cutting depth, but were directly proportional to the area of the formed fracture surface. Moreover, the free and fracture surfaces formed by multiple rock indentations facilitated the subsequent rock breakage.

1. Introduction
At present, roadheaders are widely used in coal mining due to their advantages of high efficiency and flexible application [1-5]. The cutterhead of a roadheader is regularly distributed with drag-type cutters, mainly conical cutters. During the cutterhead rotation, the cutter wear caused by the friction between the cutters and the rock is more uniform, which can increase the service life [3,6,7]. However, in non-coal mines dominated by hard rock, the application effect of a roadheader is poor due to the high strength and abrasiveness of the ore rock [8-11]. The capacity of the rotary and the thrust force will limit the roadheader application in hard rock mines [12]. Moreover, in field tests using roadheaders in hard rock mines, the cutter consumption rate is relatively high, which is not conducive to mining benefits [13,14].

The main factor affecting the roadheader application is the rock cuttability. The rock cuttability, which can be measured by the peak cutting force (PCF), insertion depth (ID), cutting work (CW), and specific energy (SE) during rock indentation, reflects the degree of difficulty of rock breakage [15-18]. Therefore, for different rock properties and cutting parameters, a large number of laboratory experiments and numerical simulations were performed to explore the factors affecting the rock cuttability through the PCF and other parameters. The experimental results showed that rock cuttability is related to rock properties and cutting operating parameters [19-23]. In addition to the physio-mechanical properties of rock, the stress condition in which the rock is located will also influence the rock cuttability. The rock cuttability increases with the decrease of the stress condition dimension of the rock. Previous studies on the influence of the cutting operating parameters on the rock cuttability mainly focused on the influence of the geometric parameters of cutters, cutting speed, and cutting depth on the rock breakage. However, in these experiments, the rock fragments peeled from the rock sample were regarded as a rock failure, which is different from the fact that the cutters repeatedly cut...
the pillar in the mining process. In other words, to more accurately simulate the rock breakage of the conical cutter on the roadheader, multiple rock indentations are required until the rock sample is completely split.

In this study, multiple rock indentations using a conical cutter were performed on the same rock sample at different cutting depths until the rock sample was completely split. The parameters that can reflect the rock cuttability were obtained through load–displacement curves. The relationships among the PCF, ID, CW, and SE and the cutting depth were regressed to investigate the influence of the cutting depths on the rock cuttability. In addition, the influences of multiple rock indentations and failure patterns on rock braking were explored by comparing the experimental results of a single rock indentation and multiple rock indentations.

2. Experiment description

2.1. Experimental preparation

In this experiment, TRW-300 was adopted to conduct the rock indentation using a conical cutter, which can carry large specimens and apply a static load of up to 3000 kN in the Z-direction. Figure 1 depicts the test apparatus and the loading mode. Granite samples of 200 × 200 × 150 mm size were processed to perform the multiple rock indentations. A set of standard cylinder and disc samples were prepared to measure the basic physical and mechanical properties of the rock material. Figure 2 and Table 1 show the typical test curves and the physio-mechanical properties, respectively.

![Experimental apparatus](image1)

**Figure 1.** Experimental apparatus, including (a) the TRW-300 test platform and (b) the loading mode.

![Typical test curves](image2)

**Figure 2.** Typical test curves, including (a) the Brazil split test curve and (b) the uniaxial compressive test curve.

| Density (g·cm\(^{-3}\)) | Elastic modulus (GPa) | BTS\(^{a}\) (MPa) | UCS\(^{b}\) (MPa) | Cohesion (MPa) | Friction angle (°) |
|-------------------------|-----------------------|-------------------|-----------------|----------------|-------------------|
| 2.66                    | 32.69                 | 8.42              | 156.3           | 18.14          | 63.86             |

\(^{a}\)Brazilian tensile strength. \(^{b}\)Uniaxial compressive strength.

2.2. Experimental process
The influences of the cutting depths on the rock cuttability and the damage caused by previous rock breaking on the next rock indentation were explored in this experiment. Six sets of tests with cutting depths \(d\) of 20 mm, 30 mm, 40 mm, 50 mm, and 60 mm were designed. In each set of experiments, the cut points were \(d\), 2\(d\), 3\(d\), etc. on the midcourt line of the rock sample surface with length and width of 200 mm until the rock sample was completely split. Figure 3(a) illustrates the experimental cutting sequence. The parameters reflecting the rock cuttability can be obtained from the force–displacement curves and the volume of the rock fragments during the rock indentation.

### 3. Experimental results

Figures 3(b)–(f) show the pick force–ID curves of the rock samples at different cutting depths and cutting numbers.

![Experimental results, including (a) the cutting sequence and the pick force–insertion depth curves at the cutting depths of (b) 20 mm, (c) 30 mm, (d) 40 mm, (e) 50 mm, and (f) 60 mm.](image)

The experimental results, including the PCF, ID, CW, and SE, were calculated and shown in Table 2 according to the abovementioned experimental curves.

### Table 2. Cutting parameters at different cutting depths and cutting numbers.

| Cutting depth–cutting number | Number of peaks | Pick force at first fracture (kN) | PCF (kN) | ID (mm) | Volume of fragments (cm³) | CW (J) | SE (J/cm³) | Failure pattern     |
|-----------------------------|-----------------|----------------------------------|----------|---------|--------------------------|--------|------------|-------------------|
| 20–1                        | 1               | 20.81                            | 20.81    | 1.09    | 40.0                     | 11.34  | 0.2832     | Partial splitting  |
| 20–2                        | 2               | 18.88                            | 23.91    | 1.72    | 29.7                     | 20.56  | 0.6913     | Partial splitting  |
| 20–3                        | 2               | 17.63                            | 41.95    | 2.79    | 142.3                    | 58.52  | 0.4113     | Partial splitting  |
| 20–4                        | 3               | 23.01                            | 62.42    | 3.20    | 123.9                    | 99.87  | 0.8062     | Partial splitting  |
| 20–5                        | 4               | 21.89                            | 96.00    | 4.83    | 127.6                    | 231.8  | 0.8973     | Partial splitting  |
| 20–6                        | 3               | 16.15                            | 92.46    | 4.30    | 282.2                    | 198.8  | 0.7045     | Partial splitting  |
| 20–7                        | 4               | 57.79                            | 128.05   | 4.38    | 2563.4                   | 280.4  | 0.1094     | Complete splitting |
| 30–1                        | 2               | 41.18                            | 68.64    | 2.65    | 38.5                     | 90.95  | 2.3648     | Partial splitting  |
| 30–2                        | 3               | 23.01                            | 71.83    | 3.23    | 54.3                     | 116.0  | 2.1382     | Partial splitting  |
| 30–3                        | 2               | 34.41                            | 127.90   | 4.45    | 317.1                    | 284.6  | 0.8973     | Partial splitting  |
| 30–4                        | 5               | 18.92                            | 90.85    | 4.56    | 2644.1                   | 207.1  | 0.0783     | Complete splitting |
| 40–1                        | 4               | 31.96                            | 97.15    | 5.02    | 326.8                    | 243.9  | 0.7461     | Partial splitting  |
| 40–2                        | 4               | 13.57                            | 78.64    | 4.65    | 188.0                    | 182.8  | 0.9727     | Partial splitting  |
| 40–3                        | 4               | 22.51                            | 118.17   | 5.83    | 2673.1                   | 344.5  | 0.1288     | Complete splitting |
4. Discussions

4.1. Influence of the cutting depths on the rock breakage
The cutting depth is one of the important factors affecting the rock breakage. The cutting parameters reflecting the rock cuttability change according to the cutting depth changes. Compared with the first rock indentation, the second rock indentation was affected by the fracture surface. When two adjacent rock indentations have their cutting points close to each other, the fracture surface formed by the latter indentation may develop toward that formed by the former. In this experiment, the distance between the first and second cutting points was higher than twice the cutting depth. Moreover, the experimental results showed no obvious size relationship between the first and second rock indentation data. Therefore, in this experiment, it is believed that the first rock indentation will not affect the second rock indentation. The experimental results of the first and second rock indentations with different cutting depths (when d = 60 mm, there was only one set) were taken to regress the relationship between the cutting depth and the PCF, ID, CW, and SE. Figure 4 illustrates the regressed curves.

![Figure 4](image-url)

Figure 4. Regressed curves of the (a) PCF, (b) ID, (c) CW, and (d) SE at different cutting depths. The regressed curves show that the change trends of the PCF, ID, and CW with the cutting depth were roughly the same, and they all presented a positive correlation with the cutting depth increase. The small PCF, ID, and CW can peel off the rock fragments from the rock sample when the cutting depth was 20 mm. The PCF, ID, and CW showed a basically gentle or slightly rising trend when the cutting depth was within the range of 30–50 mm. Meanwhile, the failure pattern changed from partial splitting to complete splitting when the cutting depth was increased to 60 mm. The PCF, ID, and CW required to break the rock also sharply increased to a high level. The rock cuttability decreased with the cutting depth increase. The decreasing trend for cutting depths d of 20–30 mm, 30–50 mm, and 50–60 mm was rapid, gentle, and rapid, respectively. However, the SE presented a trend that was first increasing, and then decreasing with the cutting depth increase, which was caused by the combined effect of the
CW value and the rock fragment size. At the cutting depth of 20–30 mm, the fragment size was small, and the SE was mainly affected by the CW. Hence, the SE increased with the cutting depth increase. The CW was in a relatively stable range when the cutting depth was 30–50 mm. At this time, the SE was mainly affected by the rock fragment volume. Therefore, the rock fragment volume gradually increased as the cutting depth increased, affecting the gradual SE decreases. At the cutting depth of 60 mm, although the CW will rise to a very high level, the SE will decrease to an extremely low level due to the tenfold increase in the rock fragment volume caused by the complete rock splitting.

When the distance between the cutting point and the free surface at both ends is quite different, the rock indentation will cause the fracture surface to develop toward the near free surface, and the failure pattern is partial splitting. The rock indentation will completely split the rock when the distance between the cutting point and the free surfaces at both ends is close. The larger the rock sample size, the greater the cutting depth at which complete splitting will occur. The rock failure pattern during ore mining by a mechanized cutter shows only partial splitting rather than complete splitting. Therefore, the complete rock splitting phenomenon with an extremely low SE when the cutting depth \( d \) is higher than 60 mm will not occur in the actual mining process. The excessively large cutting depth causes the PCF and the CW required to break the rock to be extremely large, seriously affecting the ability of the cutter to break the hard rock. When designing the row spacing of conical cutters on the cutterhead, the ideal row spacing should pursue lower PCF, ID, CW, and SE to improve the rock cuttability and the mining economic benefit. The experimental results showed that the rock breakage performance was the best when the cutting depth \( d \) was 50 mm.

4.2. Fracture surface

The experimental results demonstrated that the PCF, ID, CW, and SE values required for the rock breakage at different cutting depths were similar when the rock samples were completely split, indicating that the abovementioned parameters for complete rock splitting have no obvious relationship with the cutting depth. Figure 5 displays the rock failure images of five rock indentations with complete splitting.

![Figure 5. Rock failure images.](image)

The PCF and the CW were higher than those at the other cutting depths when the cutting depth \( d \) was 60 mm. At this time, the fracture surface area generated by complete splitting was large, showing that the PCF and the CW required for the rock failure were correlated with the size of the fracture surface area. This coincided with the argument in the Griffin–Irwin theory explaining that the energy used for the fracture surface formation in rock breakage is related to the area. This provides an idea for predicting the PCF and the CW by establishing a fracture surface model in future research. In addition, the PCF, ID, and CW required for complete rock splitting have a significant increase compared with those for partial splitting. The SE, however, will significantly decrease. Therefore, the rock breakage efficiency can be greatly improved by increasing the cutting depth to make the rock completely split.
under the condition that the power is sufficient, and the fragment size can meet the lumpiness requirement, which is especially suitable for rock breakage with a crushing hammer.

4.3. Influence of multiple rock indentations on rock breakage
This experiment can be regarded as a case under the same cutting conditions when the distance between the cutting point and the surface is the same. According to the experimental data, the experimental results of multiple rock indentations on the same rock sample at different distances between the cutting point and the surface were obtained when \( d = 20 \text{ mm} \) (Table 3).

**Table 3.** Experimental results of the multiple rock indentations on the same rock sample.

| Distances (mm) | Number of peaks | PCF (kN) | ID (mm) | Volume of fragments (cm\(^3\)) | CW (J) | SE (J/cm\(^3\)) | Failure pattern |
|----------------|----------------|----------|--------|-------------------------------|--------|------------------|----------------|
| 20             | 1.5            | 22.36    | 1.41   | 34.89                         | 15.95  | 0.4873           | Partial splitting |
| 40             | 2.5            | 52.19    | 3.00   | 133.08                        | 79.20  | 0.6088           | Partial splitting |
| 60             | 3.5            | 94.23    | 4.57   | 204.91                        | 215.31 | 1.2605           | Partial splitting |
| 80             | 4              | 128.05   | 4.38   | 2564.21                       | 280.43 | 0.1094           | Complete splitting |

Note: All data in this table are the average values obtained under the same cutting conditions.

The PCF, ID, and CW all linearly increased with the increase of the distance between the cutting point and the surface. In our previous research, the rock fragments formed by the rock indentation can be simplified as half of the ellipse cone. The increase of the distance between the cutting point and the surface would lead to the increase of the corresponding ellipse cone fragment model. The energy required to form a new fracture surface would also increase. Moreover, the number of peaks increased with the increase of the cutting numbers. In other words, the fracture surface formed by the rock indentation was affected by both the previously formed fracture surface and the free surface. Although the cutting depth remained the same, the area of the fracture surface increased, and the number of peaks increased as the distance from the cutting point to the free surface increased. The test data of the multiple rock indentations were compared with those of the single rock indentation at different cutting depths to explore the influence of multiple rock indentations on the rock breakage. Table 4 presents the experimental results of a single rock indentation at cutting depths \( d \) of 20 mm, 40 mm, and 60 mm.

**Table 4.** Experimental results of the single rock indentation.

| Cutting depth (mm) | Number of peaks | PCF (kN) | ID (mm) | Volume of fragments (cm\(^3\)) | CW (J) | SE (J/cm\(^3\)) | Failure pattern |
|--------------------|----------------|----------|--------|-------------------------------|--------|------------------|----------------|
| 20                 | 1.5            | 22.36    | 1.41   | 34.89                         | 15.95  | 0.4873           | Partial splitting |
| 40                 | 4              | 87.90    | 4.84   | 257.41                        | 213.38 | 0.8572           | Partial splitting |
| 60                 | 5              | 116.56   | 5.80   | 2998.22                       | 338.02 | 0.1127           | Complete splitting |

Note: All data in this table are the average values obtained under the same cutting conditions.

A comparison of the experimental results of the 40 mm distance in the multiple rock indentations and the 40 mm cutting depth in a single rock indentation showed that during multiple indentations, the PCF, ID, and CW of each rock indentation were lower than those of a single rock indentation. Therefore, when the rock breaking equipment is limited in power and cannot cut the rock at one time, the cutting depth can be reduced and cut several times to achieve the purpose of rock breaking. Different from the complete splitting when the cutting depth was 60 mm in a single rock indentation, the complete splitting occurred when the distance between the cutting point and the surface was 80 mm in multiple rock indentations. This indicates that the fracture surface formed by multiple indentations will affect the failure pattern by changing the fracture length required to penetrate from the cutting point to the rock surface.

5. Conclusions
In this study, multiple rock indentations using a conical cutter on the rock sample at different cutting depths were performed to investigate the influence of the cutting depths and the multiple rock indentations on the rock breakage. The influences of the cutting depths, failure pattern, and multiple rock indentations on the rock breakage were investigated. The following conclusions can be drawn from this study:
(a) The PCF, ID, and CW gradually increased with the increase of the cutting depth. On the contrary, the SE first increased, and then decreased. The rock was completely split when the cutting depth reached 60 mm. When the complete splitting occurred, the SE was extremely low due to the large volume of rock fragments, which helped improve the rock breakage efficiency. However, the ore will be stripped from the ore body instead of completely splitting in the actual mining process. Therefore, regardless of the complete splitting caused by the cutting depth higher than 60 mm, the row spacing was set to 50 mm to obtain larger fragments with smaller PCF and CW.

(b) In the multiple rock indentations performed using a conical cutter, the number of peaks increased as the cutting numbers increased. The PCF, ID, and CW of each rock indentation during multiple indentations were lower than those of the single rock indentation. These results show that multiple rock indentations are affected by both the previously formed fracture surface and the free surface. Moreover, the PCF, ID, and CW required for complete rock splitting were not significantly related to the cutting depth, but proportional to the area of the formed fracture surface. The fracture surface formed by multiple indentations will affect the failure pattern.

Acknowledgments
This study was funded by the National Natural Science Foundation of China (No. 51904333).

References
This study was funded by the National Natural Science Foundation of China (No. 51904333).

[1] Bilgin N 1977 Investigation into the mechanical cutting characteristics of some medium and high strength rocks (PhD thesis: University of Newcastle, Upon Tyne)
[2] Ocak I and Bilgin N 2010 Comparative studies on the performance of a roadheader, impact hammer and drilling and blasting method in the excavation of metro station tunnels in Istanbul, Tunn. Undergr. Space Technol. 25(2) 181–187
[3] Bilgin N, Copur H and Balci C 2013 Mechanical excavation in mining and civil industries (Boca Raton: CRC Press)
[4] Li X, Wang S and Wang S 2018 Experimental investigation of the influence of confining stress on hard rock fragmentation using a conical pick Rock Mech. Rock Eng. 51(1) 255–277
[5] Wang S, Sun L, Li X, Wang S, Du K, Li X and Feng F 2020 Experimental investigation of cuttability improvement for hard rock fragmentation using conical cutter Int J Geomech. 21(2) 06020039
[6] Dewangan S, Chattopadhyaya S and Hloch S 2015 Wear assessment of conical pick used in coal cutting operation Rock Mech. Rock Eng. 48(5) 2129–2139
[7] Nahak S, Chattopadhyaya S, Dewangan S, Hloch S, Krolezyk G and Legutko S 2017 Microstructural study of failure phenomena in WC 94%-CO 6% hard metal alloy tips of radial picks Adv. Sci. Technol.-Res. J. 11(1) 36–47
[8] Ergin H and Acaroglu O 2007 The effect of machine design parameters on the stability of a roadheader Tunn. Undergr. Space Technol. 22(1) 80–89
[9] Yang D, Li J, Wang L, Gao K, Tang Y and Wang Y 2015 Experimental and theoretical design for decreasing wear in conical picks in rotation-drilling cutting process Int. J. Adv. Manuf. Technol. 77(9-12) 1571–1579
[10] Dewangan S and Chattopadhyaya S 2016 Characterization of wear mechanisms in distorted conical picks after coal cutting Rock Mech. Rock Eng. 49(1) 225–242
[11] Cai X, Zhou Z and Du X 2020 Water-induced variations in dynamic behavior and failure characteristics of sandstone subjected to simulated geo-stress Int. J. Rock Mech. Min. Sci. 130 104339
[12] Goktan R and Gunes N 2005 A semi-empirical approach to cutting force prediction for point-attack picks J. S. Afr. Inst. Min. Metall. 105(4) 257–263
[13] Wang S, Li X, Yao J, Gong F, Li X, Du K, Tao M, Huang L and Du S 2019 Experimental investigation of rock breakage by a conical pick and its application to non-explosive mechanized mining in deep hard rock Int. J. Rock Mech. Min. Sci. 122 104063
[14] Wang S, Sun L, Huang L, Li X, Shi Y, Yao J and Du S 2019 Non-explosive mining and waste utilization for achieving green mining in underground hard rock mine in China Trans. Nonferrous Met. Soc. China.29(9) 1914–1928
[15] Bilgin N, Demircin M, Copur H, Balci C, Tuncdemir H and Akcin N 2006 Dominant rock properties affecting the performance of conical cutters and the comparison of some experimental and theoretical results Int. J. Rock Mech. Min. Sci. 43(1) 139–156
[16] Wang S, Li X, Du K and Wang S 2018 Experimental investigation of hard rock fragmentation using a conical pick on true triaxial test apparatus Tunn. Undergr. Space Technol. 79 210–223
[17] Wang S, Li X, Du K, Wang S and Tao M 2018 Experimental study of the triaxial strength properties of hollow cylindrical granite specimens under coupled external and internal confining stresses Rock Mech. Rock Eng. 51(7) 2015–2031
[18] Li X, Gong F, Tao M, Dong L, Du K, Ma C, Zhou Z and Yin T 2017 Failure mechanism and coupled static-dynamic loading theory in deep hard rock mining: A review J. Rock Mech. Geotech. Eng. 9(4) 767–782
[19] Balci C and Bilgin N 2007 Correlative study of linear small and full-scale rock cutting tests to select mechanized excavation machines Int. J. Rock Mech. Min. Sci. 44(3) 468–476
[20] Bakar M and Gertsch L 2013 Evaluation of saturation effects on drag pick cutting of a brittle sandstone from full scale linear cutting tests Tunn. Undergr. Space Technol. 34 124–134
[21] Li X, Wang S, Ge S, Malekian R, Li Z and Li Y 2018 A study on drum cutting properties with full-scale experiments and numerical simulations Measurement 114 25–36
[22] Bao R, Zhang L, Yao Q and Lunn J 2011 Estimating the peak indentation force of the edge chipping of rocks using single point-attack pick Rock Mech. Rock Eng. 44(3) 339–347
[23] Copur H, Bilgin N, Balci C, Tumac D and Avunduk E 2017 Effects of different cutting patterns and experimental conditions on the performance of a conical drag tool Rock Mech. Rock Eng. 50(6) 1585–1609