

Article

Spacing Optimization of the TBM Disc Cutter Rock Fragmentation, Based on the Energy Entropy Method

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Abstract: We used the hyperbolic Drucker–Prager and damage-failure models to simulate a three-dimensional rock fragmentation with a tunnel boring machine (TBM) disc cutter through ABAQUS. The energy entropy method was proposed to identify the optimal disc cutter spacing. In order to verify the results of the numerical simulation, previous linear cutting machine (LCM) test data were referred to. The results of the numerical simulation were verified by comparing the mean rolling force and the specific energy against the corresponding values from the LCM tests. The proposed energy entropy method showed a good agreement with the LCM test results, thus proving its usefulness in analyzing rock fragmentation for various disc cutter spacings. The comparison between energy entropy and the specific energy showed that both methods provide similar conclusions with regard to optimal spacing. The results of this research showed that energy entropy can predict the performance of TBM disc cutters and could help improve their design.

Keywords: rock fragmentation; tunnel boring machine; specific energy; energy entropy



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1. Introduction

Given their advantages of high speed and safety, tunnel boring machines (TBMs) have been widely used in modern tunnelling projects and underground space development. Disc cutters tend to break most often during the process of tunnelling with TBMs, and their performance directly influences the cost and time expended to construct the tunnel. Local geological conditions determine the selection of a TBM for a tunnelling project. An optimal penetration and spacing of the disc cutters are crucial for raising the efficiency of tunnelling with TBMs [1,2].

Unpredictable and complex underground environments make it difficult to determine the optimal penetration and spacing for the tunnelling process [3]. However, in-situ data are typically scarce and difficult to obtain, and thus, it is impossible to work under optimal settings. Chang and Rostami [4] proved that the full-scale linear cutting machine (LCM) test is a reliable and accurate approach for evaluating optimal cutting settings. The LCM test can exclude the scale effects and the results can be directly applied to the performance assessment of TBMs in real practice. Therefore, various experimental and theoretical studies have been based on the LCM test [5–8].

Although full-scale tests, such as the LCM test, offer many obvious advantages, they are expensive and time-consuming [2]. Given the increasing capabilities of computers, many researchers have used numerical methods to analyze the mechanism of TBM rock fragmentation. These numerical simulation methods include the finite element method, discrete element method, finite difference method and boundary element method. Using the 2D discrete element method, Gong et al. [6] studied the effect of joint spacing and orientation on rock fragmentation. Cho et al. [2] selected a linear Drucker–Prager constitutive

model to simulate the LCM test, using AUTODYN-3D finite element analysis software. They summarized the actual chipping mechanism and also developed a corresponding experimental platform. Hasanpour et al. [7] created a three-dimensional model of a TBM using the finite difference analysis software FLAC3D. They analyzed the trend in the local directional pattern variations at different locations around the tunnel circumference. Huo et al. [8] studied the optimum spacing of the disc cutters at different positions on the TBM cutter head, using realistic failure process analysis software. Lu et al. [9] analyzed the effects of different loading methods on the efficiency of TBM rock breaking. Shen et al. [10] simulated a tunnelling process using an arbitrary Lagrangian–Eulerian method, which combines the merits of both the Lagrangian and the Eulerian approaches. Wen and Zhang [11] used a particle flow code method to study the rock-breaking efficiency of the disc cutters on composite rocks. Some researchers predicted the performances of TBMs with mathematical methods, based on actual engineering data [12–14].

Specific energy (SE) is an indicator of rock fragmentation and is also an important parameter for the TBM disc cutter design and performance prediction. SE is defined as the energy required to excavate a unit volume of rock. Many researchers have developed theoretical methods and conducted experiments with regard to the SE of TBM disc cutters [15–18]. However, the rock fragmentation volume is difficult to measure accurately, and thus, there is much uncertainty with regard to SE values. Therefore, this study aims to identify another index that can predict the performance of TBMs and serve as a guide for the TBM disc cutter design.

Based on the second law of thermodynamics, the concept of entropy is a function of the state that describes an irreversible process. Shannon was the first to apply the entropy concept to information theory, and defined this terminology as information entropy, which indicates the average information content without redundancy [19]. Energy entropy is widely used in the mechanical fault diagnosis and risk identification. It is also easily calculated by computer. In this study, we use energy entropy to determine the optimal penetration and spacing of the TBM disc cutters. The remainder of this paper is organized as follows. Section 2 presents the simulation models and methods, including the material model and the energy entropy model. The simulation results and the energy entropies of the different disc cutter spacings, are presented in Section 3. Section 4 validates the established energy entropy indicator, by comparing the simulation results against the measured data from an experiment. Section 5 concludes this article.

2. Methodology

2.1. Modeling a Disc Cutter

Disc cutters are usually made of tungsten carbide, which is known for its high durability. By the end of the 1970s, the constant cross-section (CCS)-profile cutter rings replaced their V-shaped counterparts because of their long-term durability and high cutting efficiency.

In order to verify the simulation results easily, we employed a rigid body material model to simulate disc cutters. This can be considered as reasonable because this article focuses on the rock fragmentation mechanism rather than the durability of the cutter tip. For our research, we modeled CCS disc cutters of a diameter of 432 mm (17 in) and a thickness of 80 mm (Figure 1). The mechanical parameters of the disc cutters are shown in Table 1.

Table 1. Mechanical parameters of the disc cutters.

Density, $\text{kg}\cdot\text{m}^{-3}$	Young's Modulus, GPa	Poisson's Ratio
7850	210	0.3

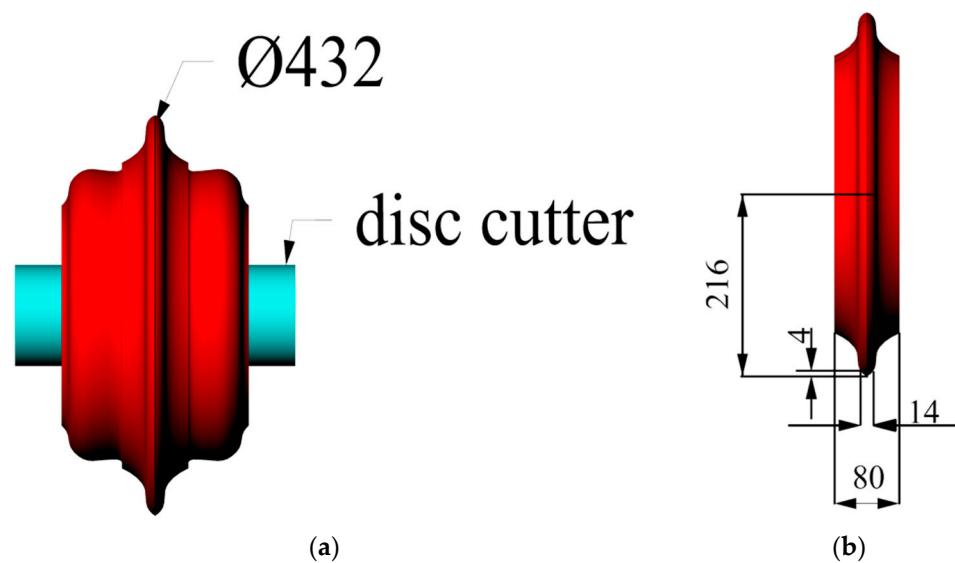


Figure 1. (a) The geometry model of a disc cutter. (b) CCS-profile cutter used in this research (unit: mm).

2.2. Modeling Rock Specimens

During a TBM excavation, the rock in the tunnelling face experiences yield, damage, and failure. The rock material properties directly affect the load on the disc cutters. Therefore, it is crucial to select the correct constitutive model. As the extended Drucker–Prager model can not only describe the isotropic hardening or softening of the material, but can also simulate its creep and non-elastic deformation, it has been widely used in rock-cutting simulations [2,20,21]. In this research, we employed the extended hyperbolic Drucker–Prager model to simulate the rock specimen.

2.2.1. Constitutive Equation

The hyperbolic yield criterion of the extended Drucker–Prager model is a continuous combination of the maximum tensile stress condition (Rankine; tensile cutoff) and the linear Drucker–Prager condition at a high confining stress [2,20,21]. It can be written as

$$F = \sqrt{l_0^2 + q^2} - p \tan \beta - d = 0 \quad (1)$$

where $l_0 = d|_0 - p_t|_0 \tan \beta$ and $p_t|_0$ is the initial hydrostatic tension strength of the material, p is the equivalent pressure stress, q is the von Mises equivalent stress, β is the friction angle measured at high confining pressure, $d(\bar{\sigma})$ is the hardening parameter, and $d|_0$ is the initial value of d . The typical yield surface of the hyperbolic Drucker–Prager model is shown in Figure 2.

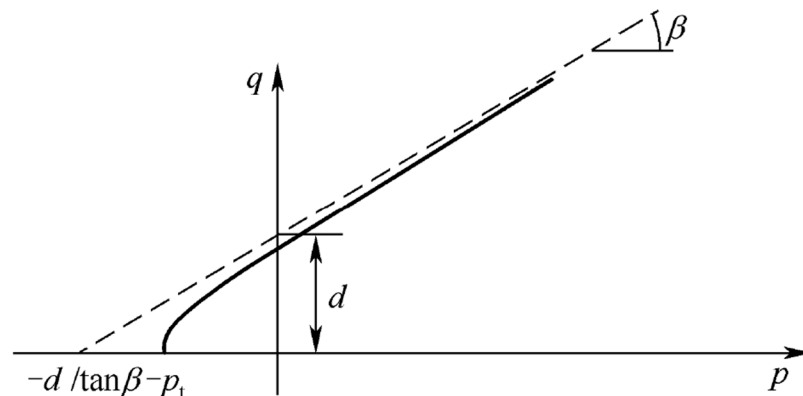


Figure 2. Typical yield surface of the hyperbolic Drucker–Prager model.

The flow rule is derived from the plastic potential, and the flow potential in the hyperbolic Drucker–Prager model is

$$G = \sqrt{(\varepsilon \bar{\sigma}|_0 \tan \psi)^2 + q^2} - p \tan \psi \quad (2)$$

where ε is the eccentricity, a parameter that defines the rate at which the function approaches the asymptote, $\bar{\sigma}|_0$ is the initial yield stress, and ψ is the dilation angle.

The hardening law of the hyperbolic Drucker–Prager model is consistent with the linear Drucker–Prager model. Both the isotropic hardening and softening are allowed in these two models. The hardening parameter $d(\bar{\sigma})$ can be obtained from the test data as follows:

- (1) If hardening is defined by the uniaxial compression yield stress, σ_c :

$$d(\bar{\sigma}) = \sqrt{l_0^2 + \sigma_c^2} - \frac{\sigma_c}{3} \tan \beta \quad (3)$$

- (2) If hardening is defined by the uniaxial tension yield stress, σ_t :

$$d(\bar{\sigma}) = \sqrt{l_0^2 + \sigma_t^2} + \frac{\sigma_t}{3} \tan \beta \quad (4)$$

- (3) If hardening is defined by the cohesion, c :

$$d(\bar{\sigma}) = \sqrt{l_0^2 + c^2} \quad (5)$$

2.2.2. Damage Law

When the TBM cuts the rock, some elements/terms will disappear or completely fail during the simulation process, due to the damage and fracture of the rock. In order to accurately represent the failure of these elements during the numerical simulation, we employed the damage-failure model for the simulation. Figure 3. illustrates the characteristic stress-strain behavior of an element undergoing damage. The solid curve in the figure represents the damaged stress-strain response, while the dashed curve is the response in the absence of damage. Moreover, the element experiences the following three stages from the initial damage to the final failure [2,20,21].

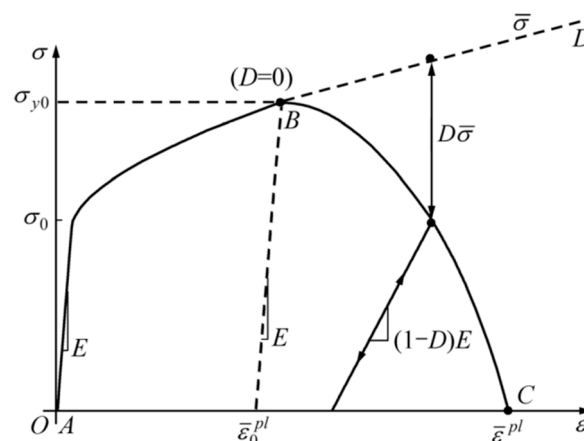


Figure 3. Stress-strain curve of the damaged failure model.

- Stage 1: Seen as A–B in the figure, this stage contains the material response before the failure of the element.
- Stage 2: Denoted as B, this is the initial point of the element failure, which is determined by the initial damage criterion.
- Stage 3: Denoted as B–C in the figure, it shows the damage evolution of the element [22].

In this figure, σ_0 is the initial yield stress of the material, and σ_{y0} is the yield stress at the onset of damage, whereas $\bar{\epsilon}_0^{pl}$ is the equivalent plastic strain at the onset of the damage, and $\bar{\epsilon}^{pl}$ is the equivalent plastic strain at the failure. D is the overall damage variable, which captures the combined effect of all active damage mechanisms, and it can be computed in terms of the individual damage variables. When $D = 1$, the element fails, and the corresponding term will be deleted from the simulation model.

Many researchers [23,24] have reported that chip forming is dominated by tensile fracture. In our research, we employed the tensile failure criterion to define the failure of the rock specimen, and we defined the damage evolution based on the energy dissipated during the damage process.

In order to verify the accuracy of the numerical simulation, we selected Hwangdeung granite as the specimen. The findings of the numerical simulation can be checked using the results of the LCM tests from previous research [2]. Table 2 shows the mechanical parameters of Hwangdeung granite. [2]

Table 2. Mechanical parameters of Hwangdeung granite.

Density, $\text{kg}\cdot\text{m}^{-3}$	Young's Modulus, GPa	Poisson's Ratio	Uniaxial Compressive Strength, MPa	Brazilian Tensile Strength, MPa	Model I Fracture Toughness, $\text{MPa}\cdot\text{m}^{-1/2}$
2600	23.01	0.18	183	9.8	0.99

2.3. Development of the Numerical Models

During the TBM excavation process, the geological conditions in the direction of the tunnelling are complex and liable to change, and various factors influence the efficiency of TBM tunnelling. Therefore, it is impossible to include and correctly simulate all of the factors in the numerical simulation. We assumed the mechanism of rock fragmentation, while using a single disc cutter, as shown in Figure 4 [25], whereas Figure 5 shows the mechanism of rock fragmentation when using two disc cutters. These images explain the cracking and chipping process of the rock when using the disc cutters. The process of the rock specimen cut by the TBM disc cutter can be divided into four steps, including the formation of a fracture zone by the normal force of the TBM disc cutter, the development of crack extensions, the penetration of lateral cracks produced by the adjacent TBM disc cutters, and the rock body broken away. With the development of numerical simulation methods, the rock fragmentation process cut by a TBM disc cutter can be easily simulated, based on a finite element method. The actual cutting process is a three-dimensional procedure, as shown in Figure 6. In our research, we focused on the three-dimensional rock fragmentation process and attempted to simulate the process of dynamic chipping.

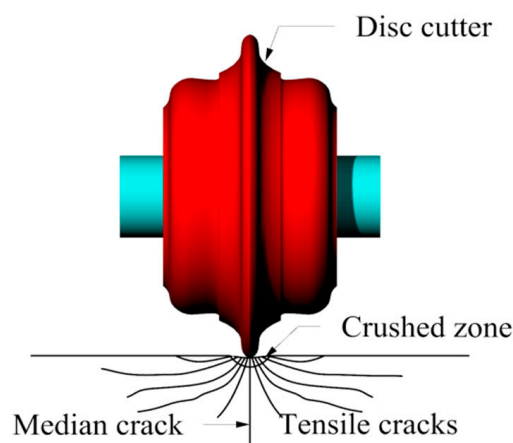


Figure 4. Development of the crushed zone and the cracks when using a single disc cutter.

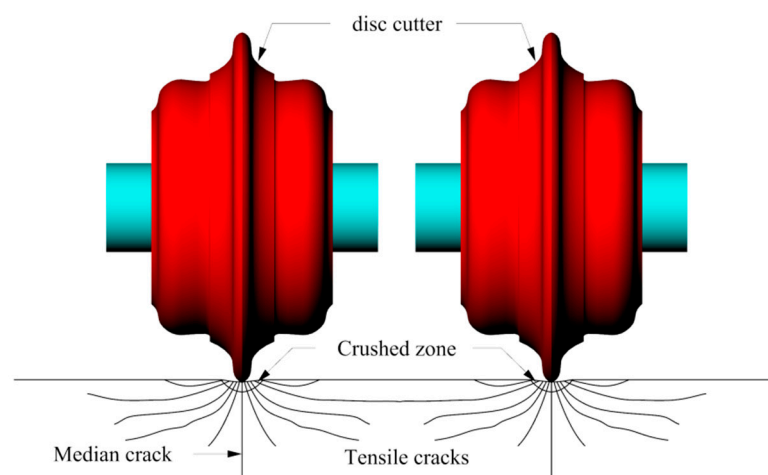


Figure 5. Development of the crushed zones and the cracks when using two disc cutters.

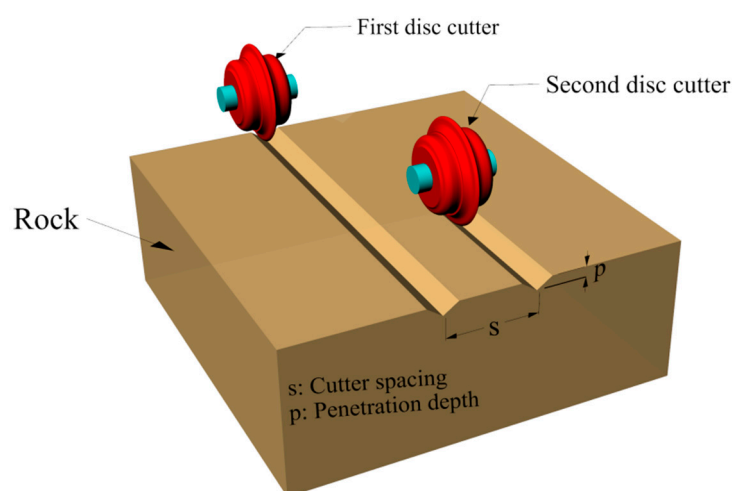


Figure 6. Three-dimensional rock-cutting geometry.

We employed ABAQUS to construct the three-dimensional models of the disc cutters and rock specimen. The rock specimen was modeled as a rectangular parallel pipe with 3D stress elements. We employed the rigid body material model to simulate the disc cutter. For simplicity, we set the disc cutter under rigid body constraints, and thus, the elements of the disc cutter also experienced 3D stress. Table 3 shows the results for the generated mesh from this simulation. We used the principle of relative motion to simulate the process of the TBM cutting rock. The rock specimen model was fixed in all directions, and the disc cutter model moved in the horizontal direction (x-direction) with a constant velocity for linear cutting. Simultaneously, the cutter was fixed to maintain a given penetration depth in the vertical direction (y-direction), and it was rotated at a constant angular velocity. The penetration depth of the disc cutter is 4 mm, the angular velocity is 9.3 rad/s, and the cutting speed is 4 m/s.

Table 3. Mesh results from the simulation.

Part	Number of Elements	Element Shape	Element Type
Rock specimen	60,000	Hex	C3D4
Disc cutter	8546	Tet	C3D4R

In order to match the actual TBM tunnelling conditions, we created two analysis steps. In the first analysis step, the first disc cutter was operational and the other was fixed. In the second analysis step, the first disc cutter 1 was fixed, whereas and the second was operational.

2.4. Constructing the Energy Entropy Function

Meshing is the most important aspect in the finite element calculation, as it determines the accuracy of the numerical simulation. The energy entropy function is also based on the mesh. For this research, we supposed n meshes of the rock specimen. Therefore, the total strain energy of rock specimen Q can be calculated using the following equation:

$$Q = \sum_{i=1}^n q_i \quad (6)$$

where q_i denotes the strain energy of the i th element, and n denotes the total number of elements.

In order to construct the energy entropy function, we should calculate the ratio of each element's energy to the total strain energy. As each element's strain energy is always non-negative, the ratio is also non-negative.

$$\lambda_i = \frac{q_i}{Q} \quad (7)$$

$$\begin{cases} \sum_{i=1}^n \lambda_i = 1 \\ \lambda_i \geq 0 \end{cases} \quad (8)$$

where λ_i denotes the ratio of the i th element's strain energy to the total strain energy. Thus, λ_i ($i = 1, 2, \dots, n$) reflects the distribution of the strain energy in the TBM cutting system [26].

Therefore, we can define the energy entropy of each element using

$$S_i = -\lambda_i \ln \lambda_i \quad (9)$$

where S_i denotes the energy entropy of the i th element in the rock specimen.

Finally, to calculate the energy distribution of the different TBM cutting set-ups, we employed the total strain energy entropy S to indicate the energy distribution.

$$S = \sum_{i=1}^n S_i = \sum_{i=1}^n \lambda_i \ln \lambda_i \quad (10)$$

As the total energy entropy S can reflect the rock specimen's energy distribution for different cutting conditions, we can employ this index to predict the cutting performance of the TBM and improve the design of the TBM disc cutters, based on the maximum entropy principle.

3. Results

3.1. Effect of the Different Cutter Spacings on the Chipping Failure

When the penetration of disc cutters is 4 mm, Figures 7 and 8 show the equivalent plastic strain diagrams of the different disc cutter combinations for a spacing of 48 mm. In Figure 7, when the first disc cutter completes the operation, due to its crushing and shearing effects on the surrounding rock, the equivalent plastic strain in the rock fragmentation zone occurs at the bottom and sides of the cutter. Moreover, the equivalent plastic strain zone produces pre-shredding in this part of the rock, which helps the second disc cutter. As shown in Figure 8, the rock fragmentation increases with the second disc cutter compared to that for the first one. Given the pre-shredding caused by the first disc cutter, the rock

failure force of the second disc cutter extends to the broken locations, causing the rock to collapse. This is the overall effect of the two disc cutters working in combination. This phenomenon can be verified through the change in mass of the rock using a numerical test (Figure 8).

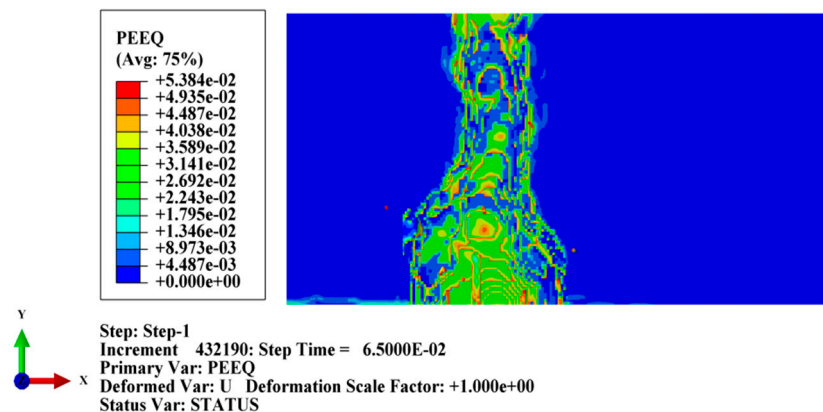


Figure 7. Equivalent plastic strain in the rock fragmentation zone with the first disc cutter.

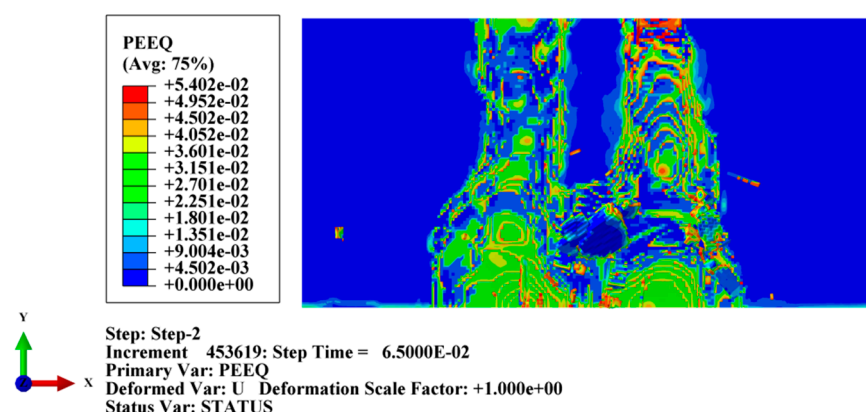


Figure 8. Equivalent plastic strain in the rock fragmentation zone with the second disc cutter.

In order to research the effect of the different cutter spacings on the rock fragmentation, we employed the same numerical method to simulate the effect of the disc cutter spacings of 28 mm, 40 mm, 48 mm, 60 mm, and 72 mm, as shown in Figure 9. The results show that if the disc cutter spacing is too large (more than 40 mm), the rock between the two disc cutters is not completely broken. However, if the spacing is too small (less than 40 mm), the rock will be overbroken, leading to energy wastage. Therefore, if the disc cutter spacing is optimal, it neither wastes energy nor overcuts the rock.

3.2. Comparison with the LCM Results

We collected the LCM test data from a previous experimental study to verify the results of the numerical simulation. The Hwangdeung granite was used in this test, and the penetration depth was 4mm [4]. The numerical simulation models were constructed using the same conditions as those in the LCM test set-up [4]. Taking the disc cutter spacing as 48 mm, as an example, the x-directional (rolling) force during the numerical simulation was obtained. In the numerical simulation models, the determination of the time step is crucial, because the time step will affect the rolling force value. If the time step is too long, the rolling force value will be less than the experimental value. Moreover, if the time step is too short, the cost of the numerical calculations will increase. In this model, the automatic time step was selected. The rolling force is shown in Figure 10. The rolling force fluctuates with the step times. If the rock elements encountered the cutter tip or attained the tensile stress

level, these elements were deleted through the “delete” option. Therefore, the mean rolling force can be calculated using the peak value during the numerical simulation process.

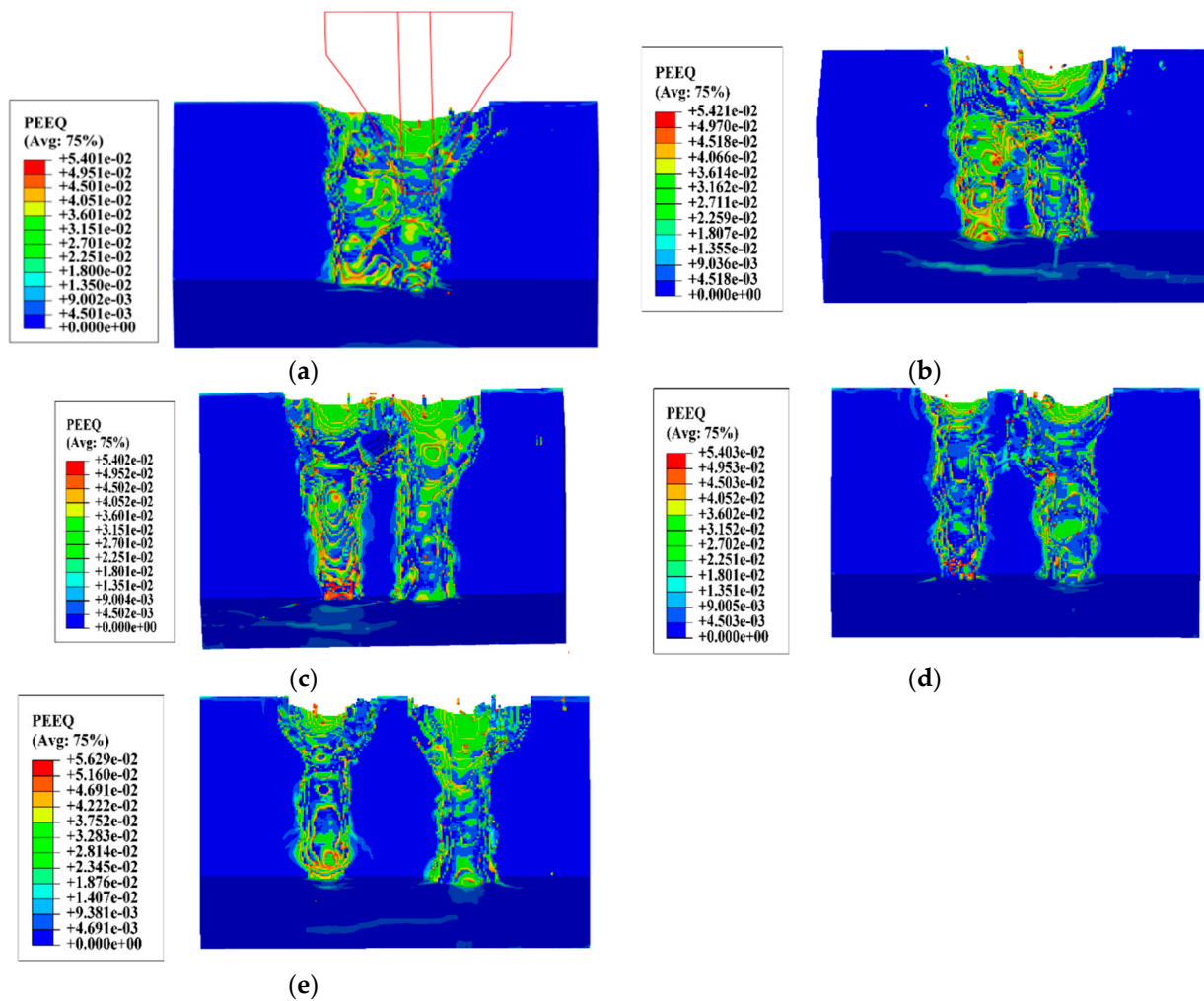


Figure 9. Effect of the cutter spacing on the chipping failure: (a) Disc cutter spacing at 28 mm; (b) Disc cutter spacing at 40 mm; (c) Disc cutter spacing at 48 mm; (d) Disc cutter spacing at 60 mm; (e) Disc cutter spacing at 72 mm.

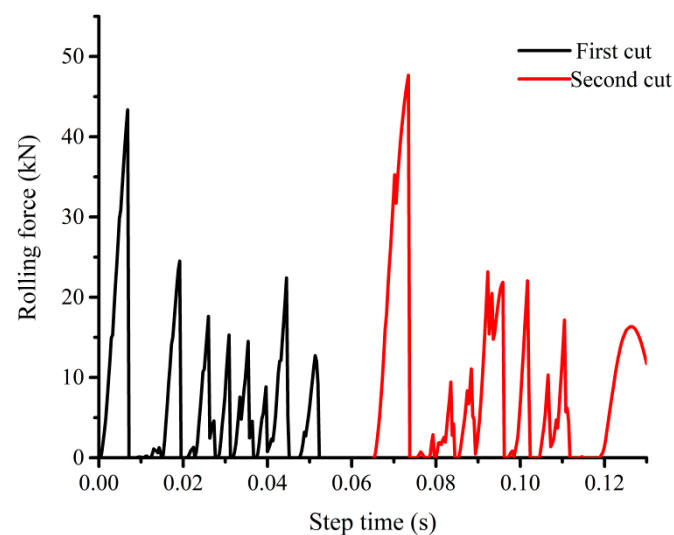


Figure 10. Rolling force with the disc cutter spacing of 48 mm.

The mean rolling force was determined from the numerical simulations and the LCM tests. The disc cutter spacing of 72 mm was not considered in the LCM tests. Therefore, Figure 11 does not show the mean rolling force for the disc cutter spacing of 72 mm. However, the average error of the mean rolling force between the numerical simulation and the LCM test is 7.67%, which means that the results of the numerical simulation are roughly consistent with the experimental (LCM test) results.

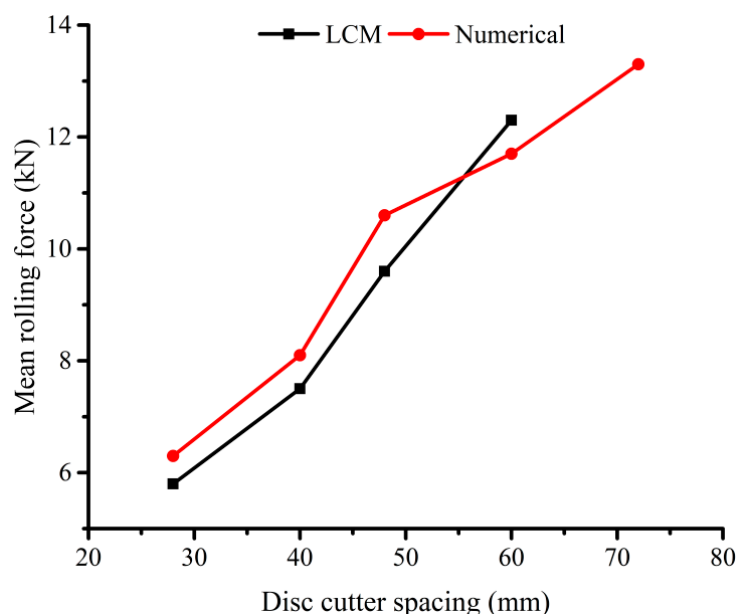


Figure 11. Mean rolling force for the various disc cutter spacings.

3.3. Effect of the Cutter Spacing on the Energy Entropy

In order to determine the optimal disc cutter spacing, we calculated the energy entropy when using the disc cutter spacings of 28 mm, 40 mm, 48 mm, 60 mm, and 72 mm. Figure 12 shows the change in the energy entropy of the rock specimen during the numerical simulations with various disc cutter spacings. According to the principle of maximum entropy, as entropy increases, the cutting system becomes increasingly unstable. Therefore, when the energy entropy is at its maximum, the best cutting-crushing effect is achieved. The optimal value can be determined by the fitting method. Based on Figure 12, the best cutting-crushing effect is observed for an optimal spacing of about 43 mm.

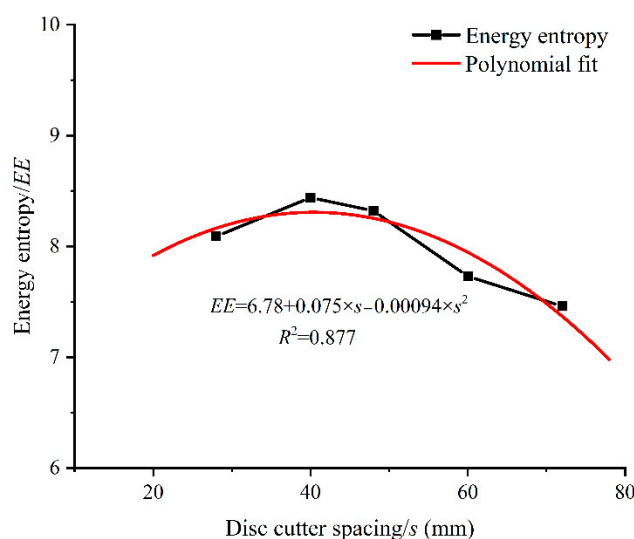


Figure 12. Energy entropy of the various disc cutters spacing.

4. Discussion

4.1. Comparison with the Specific Energy

This research compares the results of the energy entropy method with those of the SE method. The SE under various disc cutter spacings can be calculated using Equation (11).

$$SE = (MRF \times l_x) / (w_r / \rho_r) \quad (11)$$

where SE is the specific energy, MRF represents the overall mean rolling force, l_x is the distance cut by the disc cutter, w_r represents the rock debris mass, and ρ_r denotes the density of Hwangdeung granite.

The change in the rock mass as per the numerical simulation, is shown in Figure 13. For the first cut, all of the cases show the same change in reduction. For the second cut, the reduction in the rock mass is at its least when the disc cutter spacing is 28 mm, whereas the reduction is the largest for the disc cutter spacing of 48 mm.

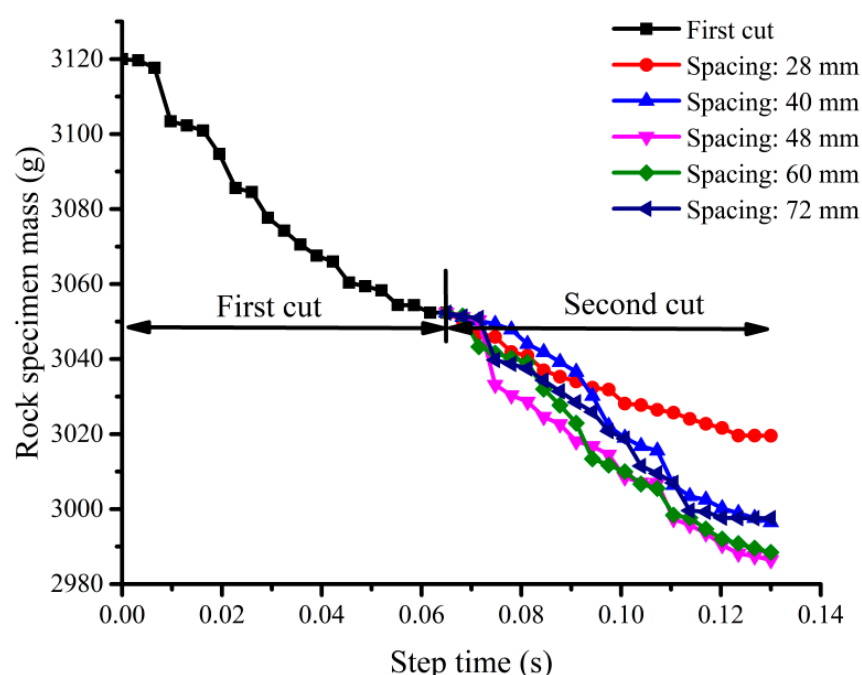


Figure 13. Change in the rock mass as per the numerical simulations for the various disc cutter spacings.

Figure 14 shows the values of energy entropy and the SE obtained from the numerical simulations and the LCM test data for various disc cutter spacings. This figure shows that the trends of energy entropy and the SE are similar and that they have the same optimal value. Therefore, our proposed method to predict the cutting performance of the TBM was successfully verified.

4.2. Summary of the Proposed Energy Entropy Method

The energy entropy method calculated the strain energy of each element, following which the energy entropy of the rock specimen was determined. As the entropy can reflect the energy distribution, the optimal disc cutter spacing can be determined, based on the maximum entropy principle. Our proposed method shows a good agreement with the minimum SE values determined by the previous studies. This index can thus be employed to predict the cutting performance of the TBM and improve the design of the TBM disc cutters.

Notably, this paper demonstrated the accuracy of the energy entropy method via numerical simulations; the method has not been verified from the viewpoint of the theory of mechanics. Therefore, future studies can focus in this particular direction.

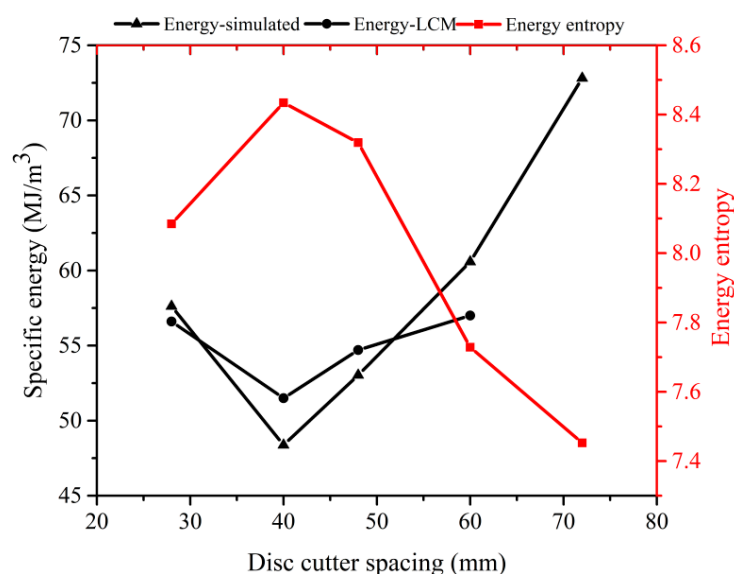


Figure 14. Results of the numerical simulations and the LCM tests of the different disc cutter spacings.

5. Conclusions

We used ABAQUS to simulate three-dimensional rock fragmentation when using TBM disc cutters. We employed the hyperbolic Drucker–Prager and the damage-failure models for the simulations. The energy entropies for the various disc cutter spacings were calculated using the proposed method. The results indicated an optimal spacing of 43 mm for a penetration depth of 4 mm.

In order to verify our proposed energy entropy method, we calculated the SE variance via the numerical simulations for the various cutter spacings. A comparison of the results of the energy entropies and the SE, revealed the optimal spacing for the TBM disc cutters. We also analyzed the effect of the boundary conditions and the rock properties on the simulation results. We concluded that it is necessary to build upon the numerical model so that it can also consider the anisotropic and discontinuous nature of the rock.

The energy entropy method has not been verified from the viewpoint of the theory of mechanics. The changing patterns of the numerical simulations and tests at different depths and velocities also need to be discussed. Therefore, future studies will focus on these particular directions.

The results of the proposed energy entropy method showed a good agreement with those of the LCM tests, thus offering novel ideas for analyzing rock fragmentation for various disc cutter spacings. The results of this research can help predict the performance of TBMs and guide improvements to the TBM disc cutter design.

Author Contributions: C.X.: Conceptualization, methodology, writing—original draft. Y.Z.: data curation, software. D.S.: writing—review and editing. X.L.: funding acquisition, resources, validation, writing—review and editing. W.G.: writing—review and editing. E.W.: supervision, writing—review. All authors have read and agreed to the published version of the manuscript.

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References

1. Acaroglu, O.; Ozdemir, L.; Asbury, B. A fuzzy logic model to predict specific energy requirement for TBM performance prediction. *Tunn. Undergr. Space Technol.* **2008**, *23*, 600–608. [\[CrossRef\]](#)
2. Cho, J.-W.; Jeon, S.; Yu, S.-H.; Chang, S.-H. Optimum spacing of TBM disc cutters: A numerical simulation using the three-dimensional dynamic fracturing method. *Tunn. Undergr. Space Technol.* **2010**, *25*, 230–244. [\[CrossRef\]](#)
3. Han, M.D.; Cai, Z.X.; Qu, C.Y.; Jin, L.S. Dynamic numerical simulation of cutterhead loads in TBM tunnelling. *Tunn. Undergr. Space Technol.* **2017**, *70*, 286–298. [\[CrossRef\]](#)
4. Chang, S.-H.; Choi, S.-W.; Bae, G.-J.; Jeon, S. Performance prediction of TBM disc cutting on granitic rock by the linear cutting test. *Tunn. Undergr. Space Technol.* **2006**, *21*, 271. [\[CrossRef\]](#)
5. Bilgin, N.; Feridunoglu, C.; Tumac, D.; Cinar, M.; Palakci, Y.; Gunduz, O.; Ozyol, L. The Performance of A Full Face Tunnel Boring Machine (TBM) in Tarabya (Istanbul). In *Underground Space Use. Analysis of the Past and Lessons for the Future*; CRC Press: Boca Raton, FL, USA, 2005.
6. Gong, Q.M.; Jiao, Y.Y.; Zhao, J. Numerical modelling of the effects of joint spacing on rock fragmentation by TBM cutters. *Tunn. Undergr. Space Technol.* **2006**, *20*, 183–191. [\[CrossRef\]](#)
7. Hasanpour, R. Advance numerical simulation of tunneling by using a double shield TBM. *Comput. Geotech.* **2014**, *57*, 37–52. [\[CrossRef\]](#)
8. Huo, J.Z.; Sun, W.; Guo, L.; Li, Z.; Zhang, X. Numerical simulation of the rock fracture process induced by multi-disc-cutters and cutters spacing design. *J. Harbin Eng. Univ.* **2012**, *33*, 96–99.
9. Lu, F.; Zhang, C.; Sun, J.; Tian, J.X.; Liu, M.; Wu, Y.H. Experimental study on rock-breaking simulation of double disc cutter of TBM. *Chin. J. Eng. Des.* **2016**, *23*, 41–48.
10. Shen, J.; Jin, X.; Li, Y.; Wang, J. Numerical simulation of cutterhead and soil interaction in slurry shield tunneling. *Eng. Comput. Int. J. Comput. Aided Eng.* **2009**, *26*, 985–1005. [\[CrossRef\]](#)
11. Wen, S.; Zhang, C. Experimental and simulation study on rock-breaking efficiency of disc cutters on composite rocks. *Int. J. Rock Mech. Min. Sci.* **2022**, *153*, 105089. [\[CrossRef\]](#)
12. Arbabsiar, M.H.; Farsangi, M.A.E.; Mansouri, H. A new model for predicting the advance rate of a Tunnel Boring Machine (TBM) in hard rock conditions. *Rud. Geološko-Naft. Zb.* **2020**, *35*, 57–74. [\[CrossRef\]](#)
13. Zhabin, A.; Polyakov, A.; Averin, E. Scale factors for conversion of forces on disc cutters for the main domestic and foreign methods. *Min. Miner. Depos.* **2017**, *11*, 50–55. [\[CrossRef\]](#)
14. Arbabsiar, M.H.; Farsangi, M.A.E.; Mansouri, H. Fuzzy logic modelling to predict the level of geotechnical risks in rock Tunnel Boring Machine (TBM) tunnelling. *Rud. Geološko-Naft. Zb.* **2020**, *35*, 1–14. [\[CrossRef\]](#)
15. Yagiz, S. A model for the prediction of tunnel boring machine performance. In Proceedings of the 10th IAEG Congress, London, UK, 6–10 September 2006.
16. Wang, L.; Kang, Y.; Cai, Z.; Zhang, Q.; Zhao, Y.; Zhao, H.; Su, P. The energy method to predict disc cutter wear extent for hard rock TBMs. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2012**, *28*, 183–191. [\[CrossRef\]](#)
17. Gong, Q.M.; Zhao, J. Development of a rock mass characteristics model for TBM penetration rate prediction. *Int. J. Rock Mech. Min. Sci.* **2009**, *46*, 8–18. [\[CrossRef\]](#)
18. Gertsch, R.; Gertsch, L.; Rostami, J. Disc cutting tests in Colorado Red Granite: Implications for TBM performance prediction. *Int. J. Rock Mech. Min. Sci.* **2007**, *44*, 238–246. [\[CrossRef\]](#)
19. Xu, C.; Hu, C.; Liu, X.; Wang, S. Information Entropy in Predicting Location of Observation Points for Long Tunnel. *Entropy* **2017**, *19*, 332. [\[CrossRef\]](#)
20. Tham, C.Y. *Reinforced Concrete Perforation and Penetration Simulation Using AUTODYN-3D*; Elsevier Science Publishers: Amsterdam, The Netherlands, 2005.
21. Su, C.; Wang, Y.; Zhao, H.; Su, P.; Qu, C.; Kang, Y.; Huang, T.; Cai, Z.; Wang, L. Analysis of Mechanical Properties of Two Typical Kinds of Cutterheads of Shield Machine. *Adv. Sci. Lett.* **2011**, *4*, 2049–2053. [\[CrossRef\]](#)
22. Cheng, R.L. Numerical simulation on optimal penetration of TBM disc cutter's rock fragmentation. *J. Cent. South Univ. Sci. Technol.* **2017**, *48*, 936–943.
23. Sanio, H.P. Prediction of the performance of disc cutters in anisotropic rock. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **1985**, *22*, 153–161. [\[CrossRef\]](#)
24. Liu, H.Y.; Kou, S.Q.; Lindqvist, P.A.; Tang, C.A. Numerical simulation of the rock fragmentation process induced by indenters. *Int. J. Rock Mech. Min. Sci.* **2002**, *39*, 491–505. [\[CrossRef\]](#)
25. Rostami, J.; Ozdemir, L. New model for performance production of hard rock TBMs. In Proceedings of the Rapid Excavation and Tunneling Conference, Boston, MA, USA, 13–17 June 1993; p. 793.
26. Chen, J.J.; Cao, Y.B.; Duan, B.Y. Informational Entropy of Structure and Maximum Entropy Principle. *Chin. J. Appl. Mech.* **1998**, *15*, 116–121.