

# SIMULATION ANALYSIS OF ROCK BRAKING MECHANISM OF TUNNEL BORING MACHINE

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Original scientific paper

Aiming at answering the questions of wear and failure of hob in the rock breaking process, the rock breaking process was simulated in different broken rock conditions by using finite element method. The relationship between normal force, lateral force, rolling force and time was obtained by rock breaking simulation analysis on the single edge disc cutter. The rock stress was analysed by setting different cutting depth when the stress reaches the maximum compressive strength of the rock. The best cutter space was also obtained in a certain depth by analysing the stress state of the cutter in different cutter space. The paper concluded with the effect of the disc cutter cross section shape on the wear. Therefore the study provided references for the wear and the optimized design of hob on Tunnel Boring Machine.

**Keywords:** rock broken mechanism; stress analysis; simulation; tunnel boring machine (TBM)

## Simulacijska analiza mehanizma loma stijena stroja za bušenje tunela

Izvorni znanstveni članak

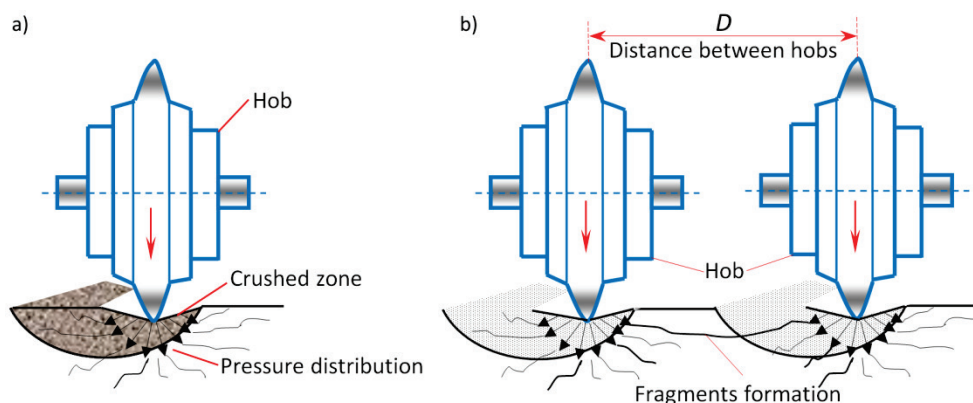
U svrhu odgovora na pitanja trošenja i oštećenja odvalnog glodala u postupku loma stijene, simulirao se postupak loma stijene pri raznim stanjima loma primjenom metode konačnih elemenata. Odnos između normalne sile, lateralne sile, sila pri valjanju i vremena dobiven je analizom simulacije loma stijene strojem za rezanje s jednom oštricom. Naprezanje stijene se analiziralo na različitim dubinama kad naprezanje dostigne maksimalnu tlačnu čvrstoću stijene. Najbolji prostor za rezanje postignut je na određenoj dubini analizom stanja naprezanja oštrice stroja u različitim prostorima. Učinkom oblika poprečnog presjeka oštrice na trošenje završen je ovaj rad. Istraživanje je pružilo reference vezano za trošenje i optimizirani dizajn glodala na stroju za bušenje tunela.

**Ključne riječi:** analiza naprezanja; mehanizam loma stijene; simulacija; stroj za bušenje tunela (TBM)

## 1 Introduction

The process of hob cutting was divided into two stages: hob intruded into rock body and rock fragments formed between two hobs [1÷3]. Firstly, hob was intruded into rock by thrust. High stress crushed area and radial cracks were formed on the tool nose and tool sides [4].

When hob continuously rolled tunnel face under thrust and torque, hob expanded its crushed area and extended the crack. When one or more cracks extended to the cracks caused by adjacent hob, rock fragments formed, as shown in Fig. 1.



**Figure 1** The rock crack process of hobs: (a) Pressure distribution in single hob; (b) Fragments formation of rock between adjacent hobs

Numerical modelling methods have been introduced to investigate the mechanism of TBM rock fragmentation. If numerical modelling could accurately simulate the process of rock fragmentation, this would be useful in carrying out performance assessment of TBMs. Bilgin et al. [6] employed Franc2D/L (2D linear elastic FEM software) to investigate the effect of lateral stress on the cutting efficiency of two materials (plaster and concrete) using chisel-type cutters. Liu et al. and Kou et al. [5] used the rock-tool interaction code RT2D to model the rock fragmentation process induced by single and double indenters. This model accommodates heterogeneous rock properties, and dynamic cracking patterns were observed.

Baek and Moon [7] and Park et al. (2006) employed a heterogeneous model, using the finite difference method (FDM) based FLAC2D (Fast Lagrangian Analysis of Continua in two-Dimensions), to analyse the influence of confining pressure and cutter spacing on the chipping mechanism of rock. Gong et al. [3, 4] studied the effect of joint spacing and orientation on rock fragmentation using the 2D discrete element method (DEM) based Universal Distinct Element Code (UDEC).

But the study mainly focuses on the effect of the disc cutter cross section shape on the wear and optimization of cutter space by using finite element method. It is divided into four main sections; the first is entitled the relations

between the broken angle degree of hob and rock stress. The second section, the rock broken mechanism of single-edge cutter is simulated. The third part, rock broken process of double-edges cutter is analysed. Finally, in section fourth, some conclusions from this study are given.

## 2 The relations between the broken angle degree of hob and rock stress

When the indenter is spherical (Fig. 2a), invasion degree is associated with the radius of ball under radial stress of the indenter and is given as follows [10]:

$$p(r) = \frac{4G\sqrt{a^2 - r^2}}{\pi(1-\nu)R} \tag{1}$$

where  $G$  is shear modulus;  $\nu$  is Poisson ratio;  $R$  is radius of ball;  $r$  is breaking zone.

The max radial stress is expressed:

$$p_{\max} = \frac{3F_n}{2\pi a^2} \tag{2}$$

When the indenter is flat (Fig. 2b), the relationship between the degree of intrusion and pressure is given:

$$F_n = \frac{4Gaw}{(1-\nu)} \tag{3}$$

The radial stress of the indenter is expressed as follows [10]:

$$p(r) = \frac{F_n}{2\pi a\sqrt{a^2 - r^2}} \tag{4}$$

When the indenter is conical (Fig. 2c), the relationship between invasion degree and pressure is [11]:

$$\frac{F_n}{Ew^2} = \frac{\tan \alpha}{\pi(1-\nu^2)} \tag{5}$$

The radial stress of the indenter is:

$$p(r) = \frac{E \cot \alpha}{\pi(1-\nu^2)} \cos^{-1} \left( \frac{a}{r} \right) \tag{6}$$

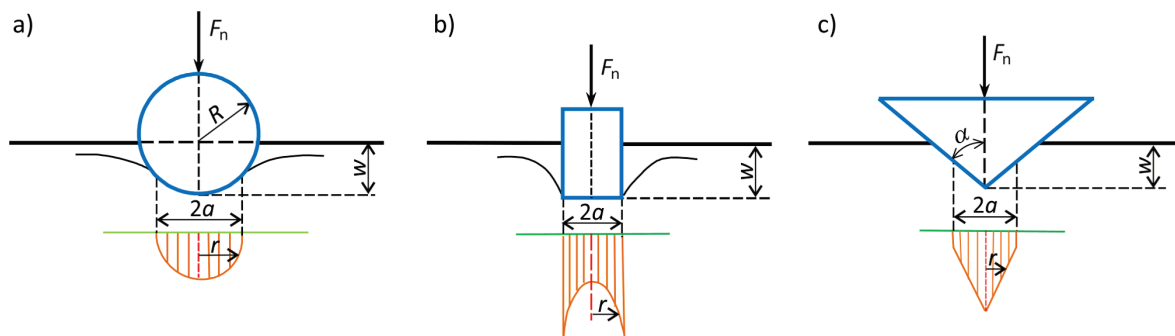


Figure 2 Stress distribution of rock

The intrusion degree of spherical indenter is greater than the two others under the same invasive pressure [10]. Therefore the arc cutter ring is used as excavation in the following research.

## 3 Simulation of rock broken mechanism of single edge cutter

### 3.1 The modelling process of rock breaking and simulation analysis

According to rock breaking feature of disc cutter, some assumptions are given as follows. The rock material property is continuous, small deformation and isotropic. The cutter with 432 mm diameter is used as simulation model dimension, which is one of the most common engineering tools imports it into ABAQUS. The size and structure of the model is shown in Fig. 3. Diameter is 432 mm and thickness is 80 mm. The material of disc cutter is AISI4340 steel. In actual working conditions, rocks can be considered as a rectangular whose bottom and sides are 200 × 300 × 100 mm.

Table 1 The parameter of Colorado red granite

Density (kg/m <sup>3</sup> )	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Shearing strength (MPa)	Modulus of elasticity (GPa)	Poisson ratio	Broken angle (°)	Internal friction angle (°)
2730	183	6,78	22,8	42,3	0,18	140	43,5

In this study, the material property was defined based on Tab. 1. Using the combination of two failure criteria of Ductile Damage and Shear Damage the failure criteria was defined. The explicit dynamic as analysis type and two analysis steps were used in ABAQUS. The cutting velocity and depth of cut were given in step 1. In step 2, angular velocity was  $\omega = 6$  rad/s and longitudinal velocity was  $v_2 = 1300$  mm/s. The duration time is 0,01 s and 0,04 s respectively. Some parts were divided to reduce calculation on surface of rock and the C3D8R was used as unit type in mesh processing. The friction coefficient is 0,4 between rock and disc cutter. The analysis steps and breaking rock process are shown in Fig. 3 and Fig. 4.

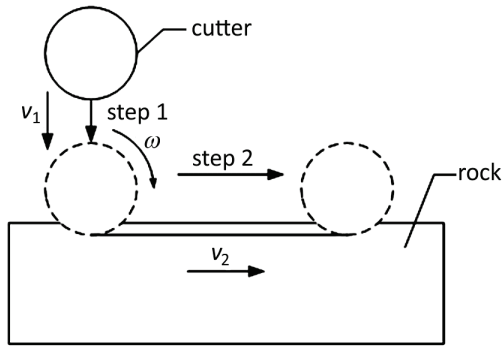


Figure 3 The analysis steps diagram

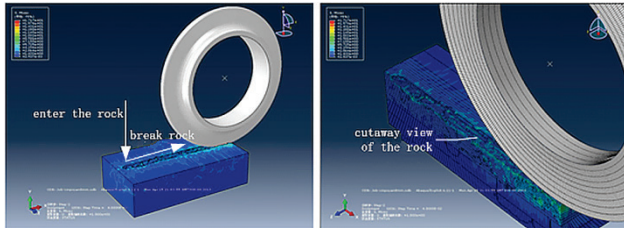


Figure 4 Hob broken rock rendering

It can be seen from Fig. 5 that normal force increases as cutting depth increases and stabilizes at around 78 kN. The rolling force stabilizes at around 24 kN and lateral force always stabilizes at 0.

The stress distribution on the rock is clearly visible, while the force of the cutter can also be determined. The simulation results provide reference for the study of rock

breaking mechanism and the simulation data can provide basis study for engineering practices.

### 3.2 Stress analysis of single-edge cutter in different cutting depth

Set respectively cutting depth as 1 mm, 2 mm, 3 mm, 4 mm. The stress distributions in different cutting depth are shown in Fig. 6.

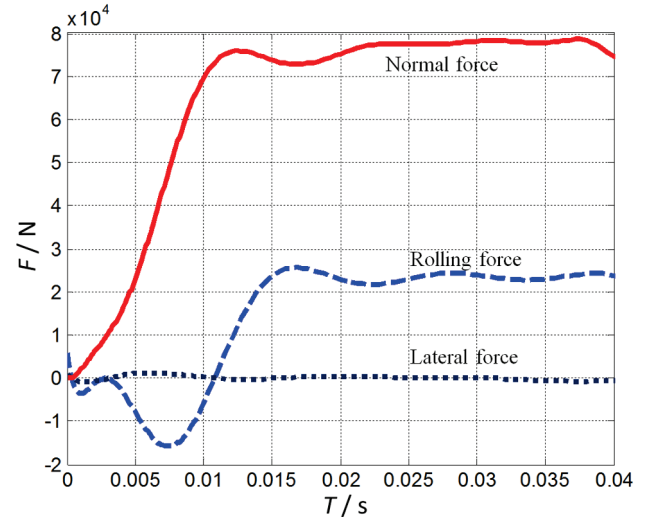


Figure 5 Change curves of normal force, rolling force and lateral force

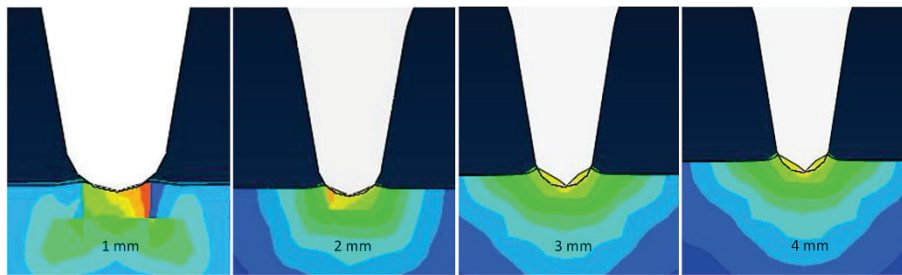


Figure 6 The compressive stress distribution of different cutting depth

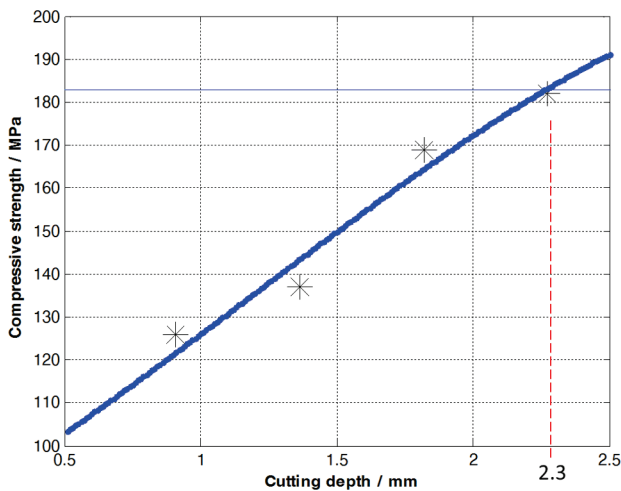


Figure 7 The maximum compressive stress corresponding to different cutting depth

It can be noticed from Fig. 7 that compressive stress gradually increases with the increase of cutting depth. The

maximum stress is on the nose of tool. Some non-symmetrical stress results from non-evenness in material. Stress reduces gradually as stress is far from the cutter. By analysis, when the intrusion depth is 2,3 mm, the stress that the cutter rolls the rock is 183 MPa, which reaches the value of uniaxial compression.

### 3.3 The shear stresses of single edge in different cutting depth

It can be seen from Fig. 8 and Fig. 9 that the maximum shear stress increases as the depth of cut increases. When it reaches a certain depth of cut, it will remain a small certain range. The volume with which the cutter is in contact with the rock is gradually increasing, the compression on the rock increases, so the shear stress increases. When the cutting depth reaches a certain range, the compression on the rock remains, so the shear stress remains constant.

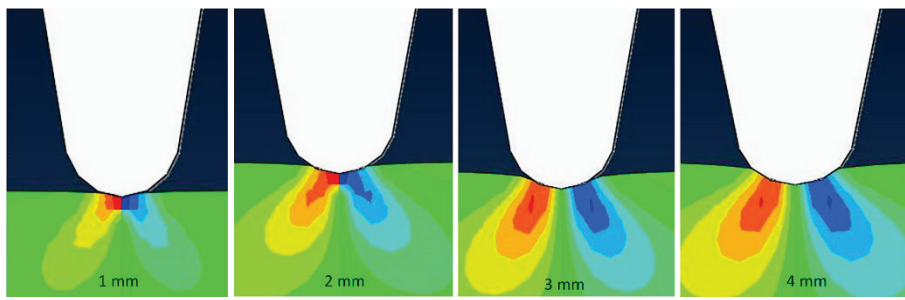


Figure 8 Shear stress distribution in different cutting depth

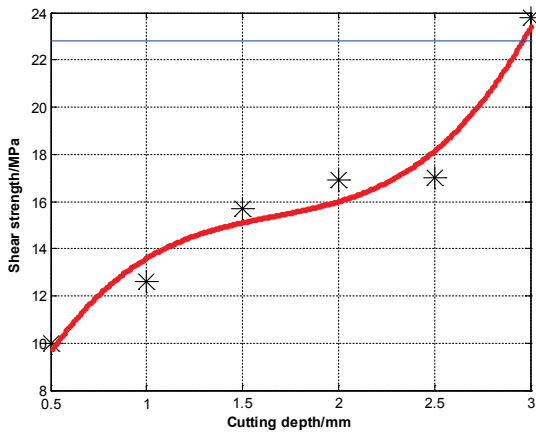


Figure 9 Corresponding maximum shear stress in different cutting depth

#### 4 Rock broken process of double-edge cutter and simulation analysis

##### 4.1 Compressive stress analysis in different cutter space

The reasonable cutter space could ensure good rock breaking efficiency and breaking rock cost. Cutting energy and vertical force and rock breaking volume are important indicators in practical engineering. Therefore, the cutter space is optimized by using simulation study.

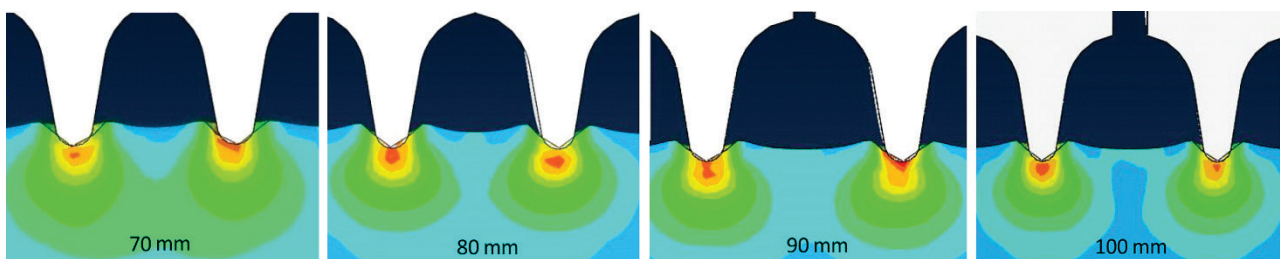


Figure 10 The compressive stress distribution in different cutter space

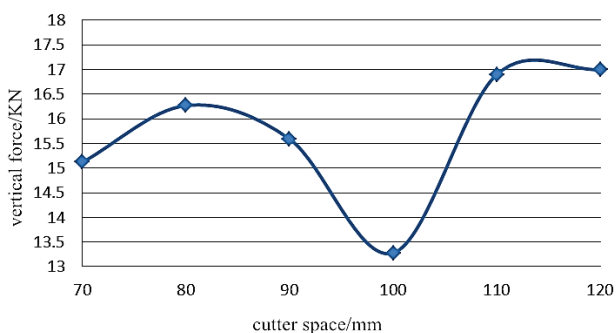


Figure 11 The vertical forces in different cutter space

It can be noticed in Fig. 11 that the vertical force is minimum, when the cutter space is 100 mm. When the

Cutting energy is the energy that breaking per unit volume rock needs. The formula is expressed as follows [13]:

$$E_s = \frac{W}{V} = \frac{W_v + W_r}{V} = \frac{F_v d + F_r l}{V}, \tag{8}$$

where,  $W$  is the total work by the cutter;  $W_v$  is the work by vertical force;  $W_r$  is the work by rolling force;  $F_v$  is average vertical force;  $F_r$  is average rolling force;  $d$  is cutting depth;  $l$  is cutting track of the cutter;  $V$  is the volume of the peeling rocks.

The process of invasion is only considered in the simulation, so  $l = 0$ ,  $F_v$  is the sum of the vertical force of the cutting edges. Cutter space that is less than 60 mm is rarely used, so cutter spaces of 70 mm, 80 mm, 90 mm, 100 mm, 110 mm, 120 mm are used respectively. The compressive stress distribution is shown in Fig. 10. When cutter space is 120 mm, the damage degree between two adjacent cutters does not cause seams connecting. Therefore, the reasonable cutter space is chosen in cutting process.

cutter spacing is 90 mm, the rock breaking volume is maximal, as shown in Fig. 12.

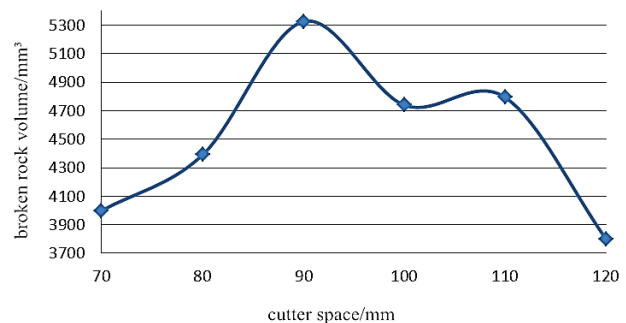


Figure 12 Broken rock volume in different cutter space



When the cutter spacing is 96 mm, the cutting specific energy is minimal, as shown in Fig. 13. Considering the hob vertical force, the volume of rock breaking, cutting specific energy factors, the reasonable cutter spacing is the range from 90 mm to 100 mm.

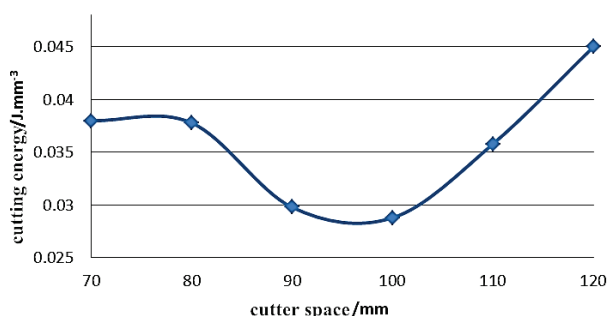


Figure 13 Cutting energy in different cutter space

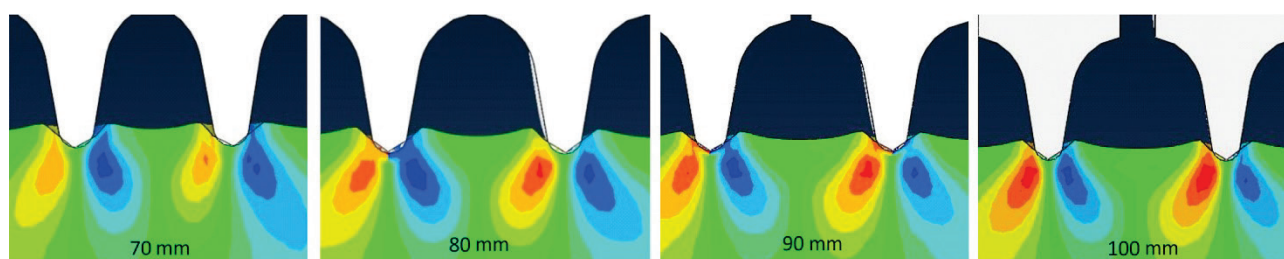


Figure 14 The shear stress distribution of different cutting width

## 5 Conclusions

(1) The model of breaking rock was established by using finite element method based on the analysis of breaking rock mechanism. The efficient ways of breaking rock were obtained by rock stress simulation in hob pressed into the rock in turn, and the destruction of rock was in the presence of both compressive failure and shear failure. The main destruction of rock was compressive failure with single hob. The main destruction of rock was shear failure with multiple hobs. It could be found that the main destruction of hard and brittle rock was shear failure but shear failure of softer rock was relatively small through rock breaking process of three hobs in different sequential angle.

(2) By analysis of single edge disc cutter breaking rock simulation, the relationship between vertical force, rolling force and time is obtained. The curved cross-section is better than flat cross-section and conical cross-section to excavate in rock breaking process. By setting different cutting depth, the numerical value of depth can be obtained at which the stress of rock reaches the compressive strength of rock. There is the best cutter space when the cutters break the rock in a certain depth.

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## 4.2 Shear stress distributions of different cutter space

Shear stress distribution of breaking rock of two cutters is shown in Fig. 14. The colour represents change of shear stress in different directions. The cutter space is set to 70 mm, 80 mm, 90 mm, 100 mm, 110 mm, 120 mm, corresponding to the shear stress distribution.

It can be seen in Fig. 14 that shear stress of breaking rock will gradually decrease with increase of cutter space. If the cutter spacing is too small, the effect of rock breaking is good, but it will increase the number of cutters on the cutter head, increase costs, increase at the same time energy consumption of the shield machine. Conversely, if the cutter spacing is too large, the shear stress is not enough to break rock, which will cause the phenomenon of rock ridge. Therefore, rational cutter space is chosen in the simulation study.

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