Optimum spacing of TBM disc cutters using an explicit finite element approach

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ABSTRACT: One of the major challenge in the production of TBMs is the design of the cutter-head. The main element affecting cutting efficiency is the choice of an adequate cutter spacing. Even a minor departure from the ideal spacing causes a decrease in cutting effectiveness. In this study, to model optimum cutter spacing, numerical tests are carried out. The three-dimensional dynamic failure seen in tests of the linear cutting machine (LCM) is simulated using LS-DYNA software. For the purpose of simulating the process of rock failure, we use a constitutive model based on the extended Drucker-Prager strength criterion and the Johnson-Holmquist-2 (JH-2) material model. The specific energy is obtained by the rolling force acting on the TBM disc cutter and the mass of rock debris obtained during the numerical test. The optimal cutter spacing calculated by numerical simulations agrees well with that established by LCM tests.

Keywords: TBM, Disc cutter, Specific energy, Optimum spacing, LS-DYNA.

1 INTRODUCTION

Compared to the traditional drill-and-blast approach, the tunnel boring machines (TBM) not only offers rapid advance rates and great working safety, but also reduced vibrations and a smaller damaged zone beyond the planned excavation limit. As a result, TBM has seen considerable use in the past and is anticipated to see increased use in the future while building tunnels (Friant and Ozdemir 1993). One of the most crucial challenges in the production of TBMs is the design of the cutter-head. Cutter-head diameter, cutter count, cutter forces and cutter spacing are the main design factors for TBM cutter-heads. The main element affecting cutting efficiency among them is the choice of an adequate disc cutter spacing. A minor departure from the ideal spacing causes a noticeable decrease in cutting effectiveness (Rostami and Ozdemir 1993). Testing using a full-scale linear cutting machine (LCM) has proved to be a reliable way to figure out the optimum distance between TBM disc cutters (Chang et al. 2006). The results of full-scale LCM tests have thus served as the foundation for a large number of experimental and theoretical studies (Roxborough and Phillips 1975 and Gertsch et al. 2007). Despite the fact that linear cutting tests have many benefits, they are uneconomical and require significant time. To overcome such issues, empirical models such as, CSM (Rostami and Ozdemir, 1993), NTNU (Bruland, 1998) are used to forecast TBM performance. The correctness and dependability of empirical prediction models is based on the quality and quantity of the available field data. In general, it is challenging to gather large amounts of high quality data. To determine the mechanism of rock fragmentation by TBM disc cutters, various numerical modelling techniques have been used. Numerical modelling provides a detailed insight into all the phases of rock fragmentation by disc cutters.

Specific energy determines the efficiency of the cutting process. There is a lot of uncertainty surrounding the specific energy values since it is challenging to estimate the rock fragmentation volume precisely. In this study, we use an explicit finite element approach using JH-2 material model (Johnson and Holmquist 1994) with extended Drucker Prager yield criteria to model the fragmentation process by TBM disc cutters. The separation criteria for rock fragments is satisfied when the displacement at the integration point exceeds the maximum allowable rigid body displacement or when damage = 1. Specific energy is then calculated using the mass of rock debris formed and mean rolling force acting on the disc cutter. The variation in specific energy in relation to the disc cutter spacing to penetration ratio is used to calculate the suitable disc cutter spacing for TBMs. We used the 3D FEM numerical code LS-DYNA to simulate the TBM disc cutter-induced rock failure process.

2 NUMERICAL MODELLING

2.1 Disc cutter

In most cases, tungsten carbide, which is renowned for its exceptional durability, is used to make disc cutters. Due to higher cutting efficiency, constant cross-section (CCS) cutter rings superseded their V-shaped counterparts. We modelled Robbins CCS disc cutters with 432 mm diameter and 80 mm thickness. The important disc cutter mechanical characteristics are density = 8000 kg/m^3, Poisson's ratio = 0.25 and young's modulus = 210 GPa. The disc cutter is modelled using hexahedron eight-node elements as shown in Figure 1. The CCS disc cutter is modelled as a rigid material as this study focuses on rock fragmentation for the determination of specific energy and the elastic modulus of disc cutters is much greater than the rock specimen.

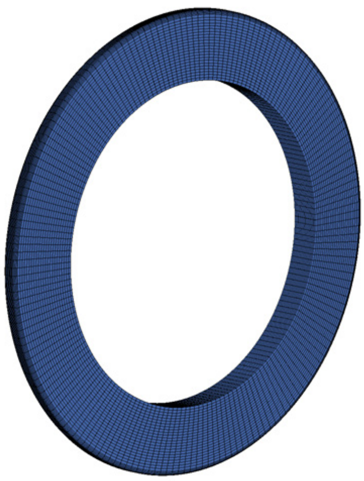

Figure 1. CCS disc cutter with 432 mm diameter.

2.2 Rock specimen

The finite element model of the rock is modelled using hexahedron eight node elements as shown in Figure 2. We use the properties of Barre granite in the material model defined for rock, as shown in table 1. The bottom nodes of the model were fixed and non-reflective boundary conditions were applied to the sides. Based on the convergence of specific energy to stable values, the minimum model dimensions are obtained. Specific energy does not vary significantly with depth. The depth is taken as 80 mm to determine the cutting forces for different disc cutter penetrations. The simulation time is taken as 4 seconds.

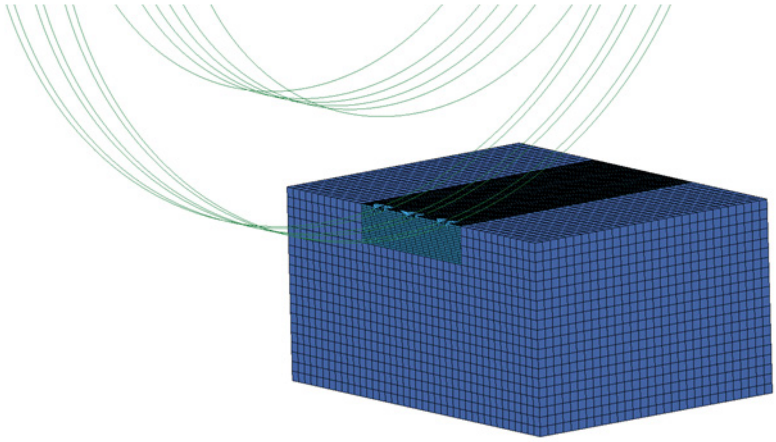

Figure 2. Finite element model of rock specimen with CCS disc cutters.

3 MATERIAL MODEL

3.1 Rock specimen

As the TBM disc cutter interacts with the rock, the rock mass initially yields. It is followed by the appearance of damage as plastic deformation accumulates. Finally, the disc cutters lead to rock failure. In order to properly represent the rock breaking process based on the user defined material subroutine, it is important to construct the appropriate framework. The material model should have three components: a constitutive equation that describes the stress-strain relationship, a damage law that describes how material stiffness degrades, and separation criteria that describes separation of rock fragments. In this numerical study, we use a constitutive model based on the Johnson-Holmquist-2 (JH-2) material model (Johnson and Holmquist, 1994) with extended Drucker Prager yield criteria. The separation criteria for rock fragments is satisfied when the displacement at the integration point exceeds the maximum allowable rigid body displacement or when damage = 1. Utilizing the user subroutine VUMAT, the rock material described is implemented in LS-DYNA. The parameters of the JH-2 model are shown in Table 1.

Based on the extended Drucker-Prager strength criterion, the JH-2 material model framework allows for the expression of the yield surface as a function of hydrostatic pressure, strain rate, and damage. The expression takes the following form:

$$\tau = f_c' \left[A(1-D) + B\left(\frac{p}{f_c'}\right)^N \right] \left[1 - C \ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon_0}}\right) \right] \quad (1)$$

Where τ is the equivalent stress, f_c' is the quasi-static uniaxial compressive strength, D is the compressive damage parameter, p is the actual pressure. A, B, N, and C denote the material parameter, where A is the normalized cohesive strength, B is the normalized pressure hardening coefficient, N is the pressure hardening exponent, and C is the strain rate coefficient. The equivalent stress takes the following form:

$$\tau = \frac{1}{2}\sigma_{eq}\left[1 + \frac{1}{K_s} - \left(1 - \frac{1}{K_s}\right)\left(\frac{r}{\sigma_{eq}}\right)^3\right] \quad (2)$$

The parameter K_s accounts for different responses under tension and compression. It varies within the range of $0.778 \le K_s \le 1.0$ to maintain the convexity of the yield surface. When Ks = 1, the yield surface in the deviatoric plane does not depend on the third deviatoric stress invariant, and as such, the original Drucker–Prager model is recovered. The loading surface given by EQUATION (2) is depicted in Figure 3.

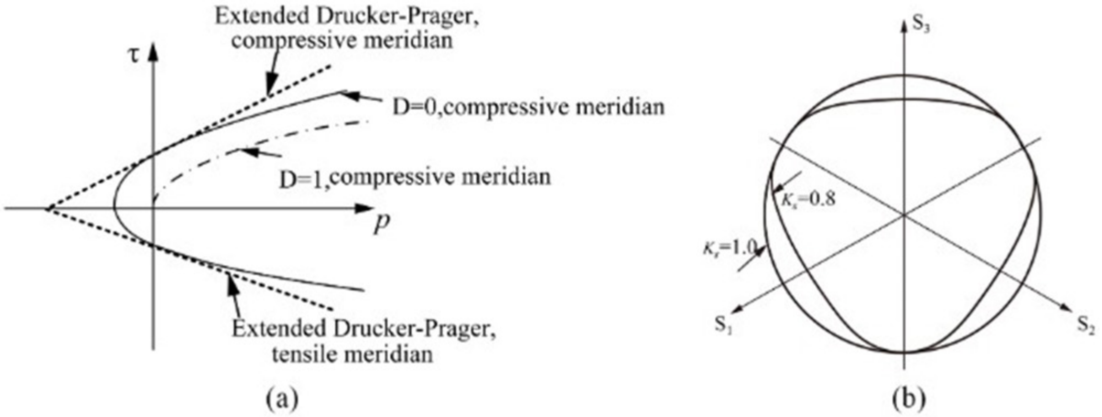

Figure 3. Extended Drucker Prager yield criteria.

Table 1. Parameters of Barre granite.

Material parameters	Unit value	EOS parameters	Unit value
Density (g/cm^3)	2.66	K_1 (GPa)	25.7
Shear Modulus (GPa)	21.9	K_2 (GPa)	-386
Strength parameters		K_3 (GPa)	12800
A	1.248		
B	0.68		
C	0.0051		
N	0.676		
F_c (MPa)	167.1		

4 RESULTS AND DISCUSSIONS

4.1 Determination of optimum spacing between TBM disc cutters

Specific energy is determined using the overall average rolling force acting on the disc cutter and the mass of the rock fragments obtained during the fragmentation process. The first step in the determination of SE is the determination of average rolling force acting on the disc cutter. It is followed by the determination of mass of the rock specimen post fragmentation by disc cutters. SE is then obtained using the volume of rock fragments obtained, length of the rock specimen along the cutting direction and average rolling forced acting on the disc cutter. The average rolling force acting on the CCS disc cutter for penetration of 1.9 and 6.4 mm with 76 mm cut spacing is shown in Figure 4. The rolling force initially remains close to zero. It gradually increases with the accumulation of plastic deformation. Upon satisfaction of the failure criteria, it stabilizes and varies about its average value, which increases with an increase in penetration.

The erosion rule is used to determine the mass of rock debris quantitatively, with elements being removed once the separation criteria is fulfilled. The mass of rock debris (in grams) formed corresponding to different spacing to penetration (*s/p)* ratios is shown in Figure 5. The variation of specific energy for different s/p ratios is shown in Figure 6. When the cuts are too close together, the narrow chips created are subjected to excessive crushing. As the spacing widens, chipping and crushing achieve an ideal balance and as the spacing increases further, cut-to-cut interaction reduces. The results show that, for 76 mm cut spacing, SE reaches a minimum value at a penetration of 5.1 mm. This corresponds to an optimum spacing to penetration ratio of 14.90.

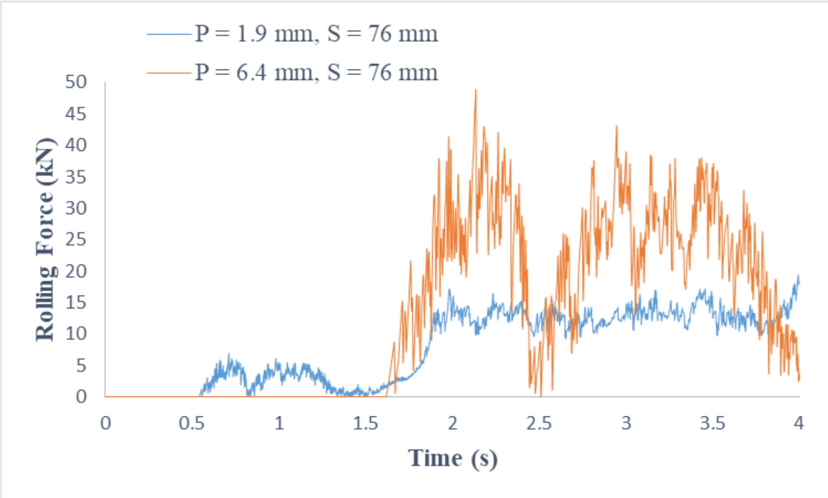

Figure 4. Variation of rolling force with time for 1.9 and 6.4-mm penetration with 76 mm cut spacing.

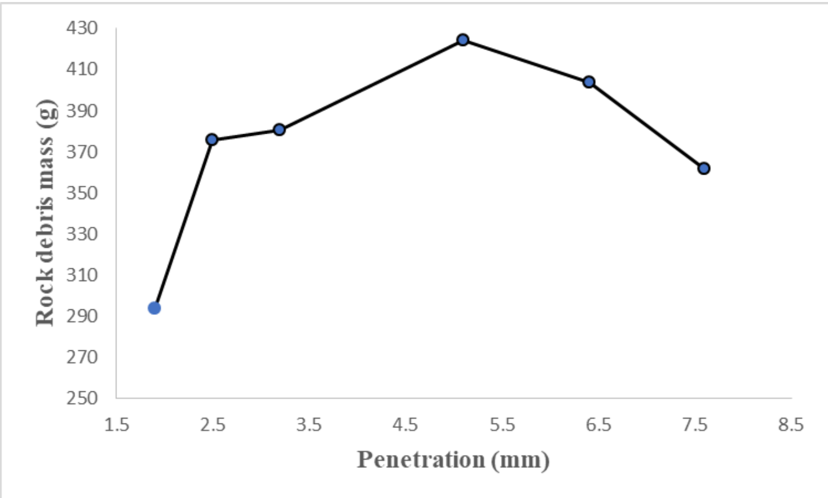

Figure 5. Mass of rock debris (in grams) formed corresponding to different spacing to penetration (*s/p)* ratios.

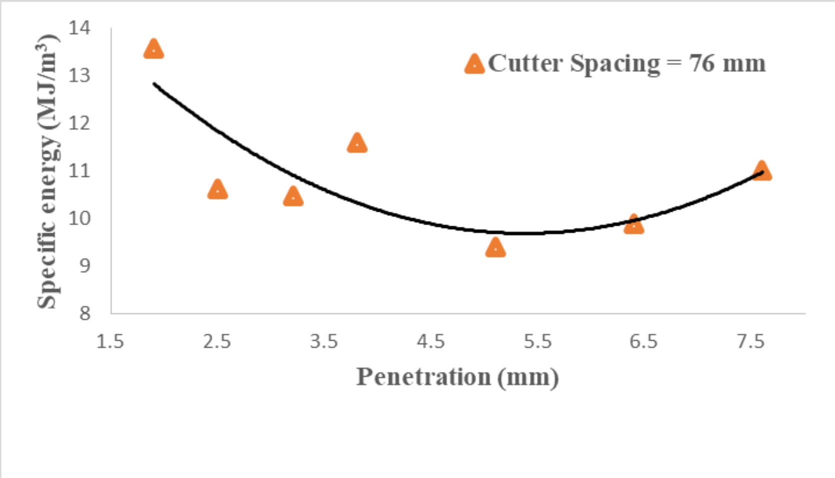

Figure 6. Variation of specific energy for different disc cutter s/p ratios.

5 CONCLUSIONS

We used an explicit finite element approach to determine the specific energy and optimum disc cutter spacing during rock fragmentation by TBM disc cutters. The rolling force acting on the disc cutter is obtained from the numerical tests and the mass of rock debris is determined upon satisfaction of the erosion criteria. The results of the proposed method help in the determination of specific energy during the cutting process. The variation of SE with different *s/p* values helps in determining the optimum spacing of TBM disc cutters on the cutter-head.

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