An Explicit Finite Element Approach to TBM Disc Cutter Induced Rock Fragmentation Simulation

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ABSTRACT: In rock tunnelling, Tunnel Boring Machines (TBMs) are extensively used for Mechanical rock cutting. A good understanding of the rock fragmentation process and subsequently TBM penetration rate could be very useful in the design and operation of TBMs with better scheduling of the project. The important parametersin the design of a TBM cutter head include the cutting forces, rock material characteristics and the cutter configuration. The main tools employed by TBMs for rock fragmentation are disc cutters. The rock cutting process can be characterised by two approaches namely physical testing and numerical modelling. Although physical tests have proved to be reliable, they are uneconomical and time-consuming owing to the intrinsic heterogeneity in the rock material. Moreover, physical tests do not provide a detailed explanation of the initial rock fragmentation process. Numerical modelling, on the other hand, provides a detailed insight into all the phases of the rock fragmentation process. However, the numerical methods are mostly based on some assumptions and do not easily take into account random imperfections in rocks. The finite element approach, among the available numerical methods, can be used to analyse the distribution of temperature, stress, strain, and strain rate in the chip generation zone of the rock cutting process. Using explicit finite element algorithm LS-DYNA, a technique for modelling the fragmentation process during mechanical rock cutting is briefly discussed. FEM algorithm explicitly capturesthe dynamic interactions during TBM rock cutting and the non-linear features of the rock material.

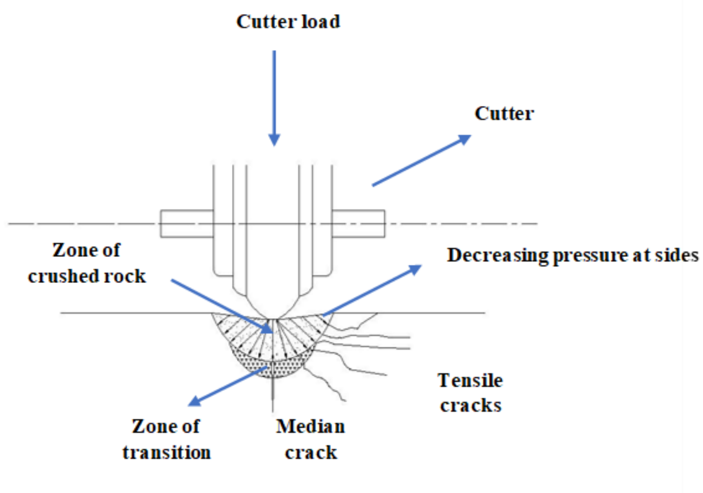
Keywords: *TBM; Disc cutter; Rock fragmentation; Tunnel; Finite element modelling; LS-DYNA*

1 Introduction

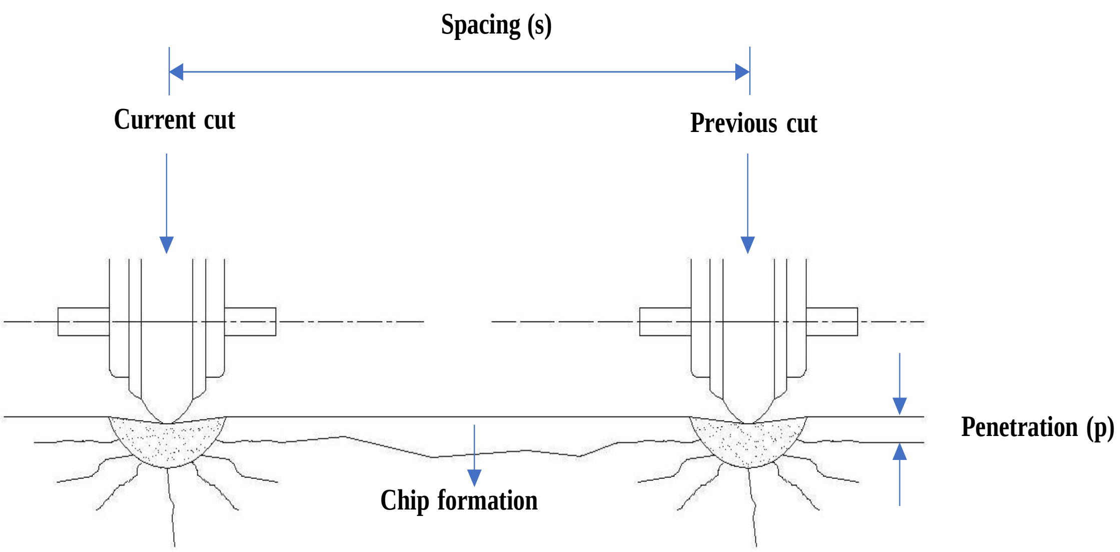
The usage of Tunnel Boring Machines (TBM) in tunnelling is anticipated to increase significantly. The disc cutter is an essential but easily damaged rock cutting instrument in TBM tunnelling. Cutting efficiency is directly related to the disc cutter. In order to enhance the cutting speed and estimate the machine performance, it is necessary to analyze the forces operating on the disc cutter and the failure mechanism. Physical testing and numerical modeling have been used to characterize rock cutting operations. Physical testing in a controlled setting is easy to analyze rock cutting behaviour. The inherent variability of rock material necessitates several studies to establish crucial cutting parameters and fragmentation behavior. Physical testing, as a consequence, is costly and can only provide limited findings [1]. Physical testing has several problems that make it difficult to get an in-depth knowledge of the first stages of breakdown. There are well-known prediction models, such as those from NTNU [2] and CSM [3], that have been proposed to overcome these problems. One may find many theoretical and semi-theoretical equations in the available literature. However, these mathematical models can only provide an approximate approximation of cutting forces. Barton [4] presented a method for predicting TBM performance based on the quality of the rock mass (QTBM). The Q-system and the rock mass rating (RMR) method have also been used to estimate the performance of TBMs. Using neural network analysis, Zhao et al. (2007) created a model for predicting TBM performance in granitic rock masses [5]. Maji VB, Theja GV (2015) proposed a performance prediction model of rock TBMs considering uncertainties in the geotechnical parameters [6]. Fieldwork and previously acquired data are the most common sources of empirical prediction models. The amount of accessible data affects the accuracy of these models. It is not easy to get large volumes of high-quality data. While numerical modeling gives insight into all breakage phases and delivers reliable results for specific cutting circumstances, is a better choice. Several techniques, including the Finite Differential Method (FDM), Displacement Discontinuity Method (DDM), Discrete Element Method (DEM), and Finite Element Method have been employed to simulate the cutting process. Even though both the DEM and the FEM are widely used to illustrate the rock- cutting process, each has its advantages and disadvantages to consider. The continuum damage models in FEM may simulate both ductile and brittle damage modes. A complete description of the chip formation zone includingstresses, strains, and strain rates may also be obtained using the FEM. Other techniques, such as analytical and empirical methods, make it difficult to get this level of detail. The explicit FEM code LS-DYNA can capture dynamic interactions during rock cutting. The FEM technique provides a special method for analysing every facetof the rock cutting process. The ability to study the chip formation mechanism at the micro level is the FEM's most significant characteristic. The distribution of temperature, stresses, strains, and strain rates in the chip forming zone may all be precisely described using the FEM. Other methods, such as analytical methods and experimental/empirical methods, make it difficult to gather this breadth of specific knowledge. The explicit FEMcode LS-DYNA, a computational modelling strategy, can capture dynamic interactions during rock cutting. The development of a FEM method for simulating rock cutting is presented in this paper. This study's objectives are to establish a workable framework for FEM modelling for generic rock cutting analysis.

2 Failure mechanism of breaking rock

Cutting through rock using a TBM cutter is a complicated operation that relies on many factors. It has been observed that strong thrust from the disc cutter generates minimal penetration into the rock face (1 to 15 mm, depending on the rock's strength) Ramezanzadeh et al. [7]. Gong and Zhao [8] studied the processes of rock fragmentation and crack propagation process under TBM rolling cutters to better understand the mechanics of rock fracture. Their research revealed that the process of rock breakage [9] can be separated into two continuous stages (Fig. 1). In the first stage the cutter causes indentation into the rock. It leads to the formation of a highly crushed zone under the cutter. This zone is in a hydrostatic state of stress where tensile cracks are formed as seen in Fig. 1(a). In the second stage, as shown in Fig. 1(b), the fractures between two adjacent cutters coalesce leading to chip formation. Efficient chipping occurs under an optimum spacing-penetration ratio. Bruland [10] and Cigla et al. (2001) found that foliation significantly influences the failure of rock when it comes to fracture propagation [11]. The disc cutter forces are the key design consideration for cutter head throughout the cutting process. Figure 2 depicts the normal, rolling, and side tool forces, which are orthogonal. Normal forces are applied perpendicular to the cutting direction, whereas rolling forces are applied parallel to the cutting direction. During the cutting process, side forces are measured transverse to the cutting path. In comparison to the other forces, they are rather small. Normal forces determine the thrust requirement and rolling forces decide the torque and power requirements of the machine.



(a)



(b)

Fig.1. (a) Rock fragmentation by TBM disc cutter (b) Chip formation between two disc cutters [9].

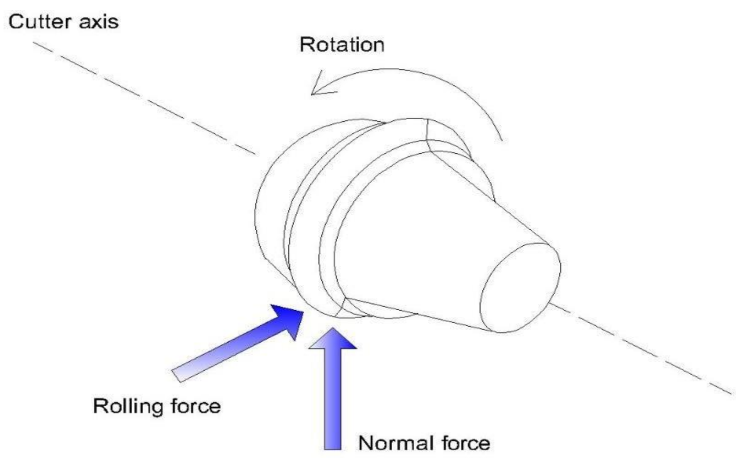


Fig. 2. The forces acting on the disc cutter

3 Rock fragmentation modelling

Cutting rocks involves the disc cutter–rock interaction, the fracture of rocks and the progression of fractures. The modified Lagrange formulation, which alters the geometry at each time step, is used because erosion produces new boundaries. LSDYNA's explicit solution approach prevents the stiffness matrix from becoming singular due to element erosion. Crack propagation problems in rock cutting have long been studied using fracture mechanics-based FEM modelling [12]. However, according to the modelling of fragmentation, the generation of chips and the multiplication of fissures are also part of the fragmentation process. It is difficult to get good results using the fracture mechanics method with defined fissures while modelling rock-cutting fragmentation. This is mostly due to the possibility of intractable fracture development and crack interaction when subjected to long-term, intricate 3-dimensional stress. Furthermore, the classic fracture mechanics-based technique is impractical because of the ambiguity surrounding the influence of the fracture process zone on crack formation and the requirements for acceptable crack development. Fracture and element erosion may be used as an alternative to explicit crack modelling to capture the fracture initiation and growth in a plasticity-based continuum model. Using a damage index, a quasi-brittle material's strain softening may be tracked, and fracture can be pin-pointed. Some of the models in LS-DYNA namely the Continuous Surface Cap model, the RHT model, the Concrete Damage model, and the Johnson Holmquist Concrete model can effectively be used for rock fracturing. Various important aspects of modelling with LS-DYNA are highlighted here.

3.1 Element size

Element size is a critical consideration when trying to achieve realistic fragmentation. Since fractures will likely occur in this area, we utilize the smallest element possible to simulate the rock under consideration. As such there are no major changes in geometry as a consequence of fracturing. It is observed that the kind of element and the discretization approach influences the erosion pattern.

3.2 Contact and detection

The cutter makes contact with the rocks, and the chipped rocks make contact with the parent rock. The model has to describe the link between the rock and disc cutter. The keyword "Eroding Surface to Surface" is used to define the contact between the disc cutter and the rock for this purpose.

3.3 Fracture initiation criteria

Fracture tracking is made possible by element erosion during rock cutting, even when the orientation and trajectory of fractures are not known in advance. Whenever a fracture surface joins to an already existing fracture surface or crosses an edge, chips form.

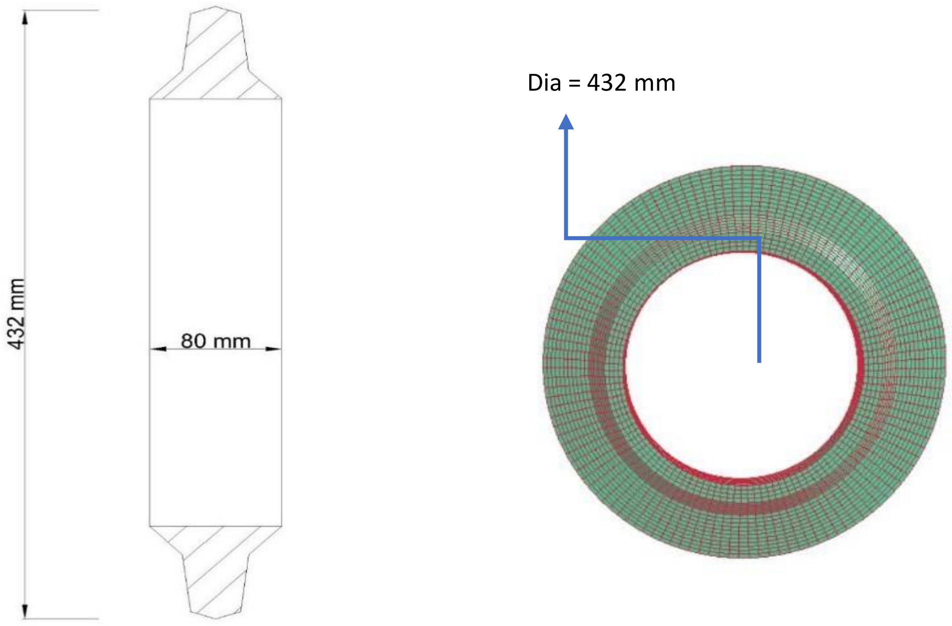
3.4 Disc cutter advancing speed

There is no influence on the specific energy or shear forces until disc cutter velocity reaches the fracture propagation velocity in the rock [13-14]. It is thus reasonable to assume the disc's horizontal and rotational velocities to be greater so that computation time may be reduced.

4 Single disc cutter rock fragmentation process

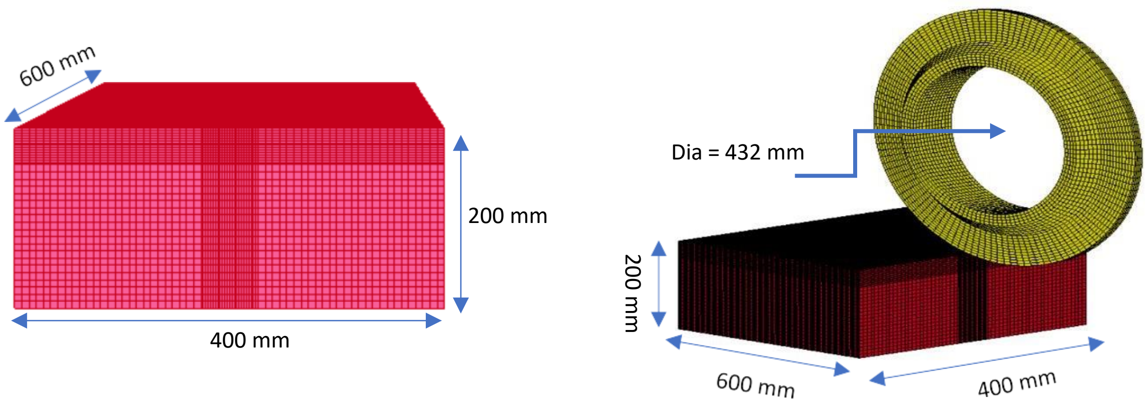
An acceptable solution technique and material model, for numerical modelling of the linear cutting machine (LCM) test, were selected based on experimental test findings from "The Earth Mechanics Institute of the Colorado School of Mines". During the study, researchers used a 17-inch (432 mm) diameter fixed cross-section disc made by Robbins. The disc cross-section is shown in Figure 3(a). The high-strength steel, which has a much greater elastic modulus than rock, is often used to make disc cutters. When utilizing a stiff material model, it is possible to overlook cutter wear or deformation. So, the disc cutter is modelled as a rigid material, shown in figure 3(b). The disc cutter's primary parameters density, Poisson’s ratio and young’s modulus values are 8000 kg/m^3, 0.25 and 210 GPa respectively. The disc cutter was limited in its ability to move linearly along the x-axis and angularly about the y and z-axes.

Figure 4 depicts the finite element model of the rock and disc cutter system employing hexahedron eight-node elements (referred to as solid 164). A ring arrangement was used to represent the whole cutter body to reduce the number of elements required and as a result, the amount of time required for calculation. The Lagrange coordinate system was used in the system. Gertsch et al. (2007) tested the linear cutting machine on a 110 cm long, 80 cm wide, and 60 cm thick rock sample [15]. However, in this study, the length, width, and thickness are taken as 600, 400 and 200 mm respectively in order to speed up the computation process. Rock volume was approximated using fixed nodes and non-reflective boundaries to represent an endless structure on the rock's surrounding surfaces, as seen in this figure 4. The surface-to-surface contact interface erosion algorithm was selected. In this study element erosion is based on strain failure because LS-DYNA requires all loadings to be stated as time functions, the loading conditions on the disc cutter are provided in Table 1. The entire simulation lasted 4 seconds. The disc cutter and rock are assumed to have a coefficient of friction of 0.14 [16].



(a) (b)

Fig. 3. (a) Dimensions of the TBM disc cutter (b) TBM disc cutter modelled using FEM



(a) (b)

Fig. 4. (a) FEM rock model (b) Rock and disc cutter modelled using FEM

Table 1. Variation of loading with time.

Time (sec)	0	2	4
Penetration (mm)	0	-7	-7
Displacement (mm)	0	-210	-420
Angular velocity (rad/sec)	-.5	-.5	-.5

The rock behaviour is described using the Johnson-Holmquist-concrete model to predict its behaviour under the conditions of significant strains, high strain rates, and high pressures [17]. The equivalent strength, calculated using this approach, depends on the pressure, strain rate, and damage. Equation (1) is used to calculate the equivalent strength.

$$\sigma_{eq} = f_c' \left[A(1-D) + B\left(\frac{p}{f_c'}\right)^N\right]\left[1 - C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \tag{1}$$

In equation (1) f_c' is the uniaxial compressive strength, *D* represents damage, and *p* is the pressure. *A*, *B*, *C*, and *N* are input parameters to be defined by the user. $\dot{\varepsilon}_0$ is the reference strain rate.
The JHC material model accumulates damage due to equivalent plastic strain and plastic volumetric strain. it is expressed as:

$$D = \Sigma \frac{\Delta\varepsilon_{eq}^p + \Delta\varepsilon_v^p}{D_1\left(\frac{p}{f_c'} + \frac{T}{f_c'}\right)^{D_2}} \tag{2}$$

In equation (2) *T* represents maximum tensile hydrostatic pressure and D_1 and D_2 are user defined material damage constants.

The pressure-volumetric strain relationship, under the influence of hydrostatic pressure, can be explained in terms of three regions as shown in figure 5. First stage is called the linear elastic stage. In the second stage there is accumulation of plastic volumetric strain upon unloading. As the pressure is increased further a close-grained stage is reached. The relationship is expressed as:

$$p = K_1\bar{\epsilon} + K_1\bar{\epsilon}_v^2 + K_1\bar{\epsilon}_v^3 \tag{3}$$

$\bar{\epsilon}$ is the modified volumetric strain. K_1, K_2, and K_3 are user defined constants corresponding to material with no voids.
Linear rock cutting simulations have largely used this material model (Li and Shi [18] and Li and Du [19]). The parameters of the JHC model are shown in table 2. As a means of finding a solution, the Lagrangian method is used. In this solution strategy, the disc cutter action on the rock deforms the rock elements. Temporal step size decreases to zero, and the solution is terminated because the smallest dimension of the smallest element is perfectly proportional to step size. Consequently, distorted components should be removed from the simulation, as indicated in figure 6, to avoid this. Along with Johnson-Holmquist-Concrete and "MAT ADD Erosion," the

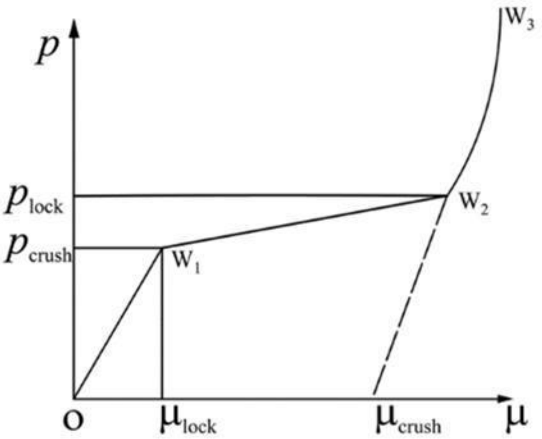


Fig. 5. Pressure-Volume Relationship in Johnson-Holmquist-Concrete material model [17]

simulation uses failure criteria for this purpose. Here, the failure strain (element removal) is as 0.12.

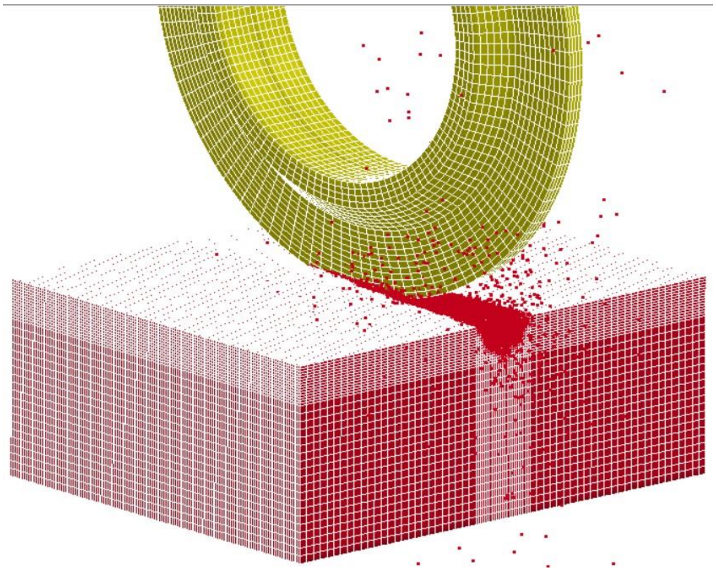


Fig. 6. Deleted nodes from the finite element model of rock

Table 2. Johnson Holmquist concrete parameters for Colorado red granite

Material parameters	Unit value	Damage parameter	Unit value
Density (g/mm^3)	2.665x10^{-3}	D1	0.04
Shear Modulus	17.16x10^3	D2	1
Strength parameters		EOS parameters	
A	0.79	P_{crush} (MPa)	52.67
B	1.60	U_{crush}	10^{-3}
C	0.007	P_{lock} (MPa)	800
N	0.61	U_{lock}	0.11
F_c (MPa)	158	K_1 (MPa)	85x10^3
T (MPa)	9.3	K_2 (MPa)	-171x10^3
SFMAX	7	K_3 (MPa)	208x10^3
EPS0	10^{-3}		

5 Numerical results and discussion

Figure 7 (a) depicts the damage caused to the rock due to the movement of disc cutter, showing the formation of crushed zone, plastic zone and elastic zone. The damage is maximum under the cutter tip due to very high contact stresses under the disc cutter. The development of significant contact stresses under the cutter tip results in a highly crushed zone of rock material. Tensile stresses arise at the limits of this zone because of hydrostatic stress. When the stress level exceeds the rock's tensile strength, cracks appear. Chips are generated when cracks extend far enough to contact adjacent grooves or meet other cracks that have already developed from adjacent cuts Figure 7 (b) and 7(c) depicts the normal force and rolling force acting on the disc cutter respectively. At the first moment of cutter interaction with the rock surface, the normal and rolling forces act differently on the TBM disc cutter. The rock firmly opposes penetration upon initial contact with the cutter, and an immediate high normal force arises. At first, the rolling force is almost zero. This result suggests two essential qualities of TBM performance.

Once the disc cutter makes contact with the rock, thrust force (a function of cutter normal force) increases to a significant degree. However, the initial TBM torque (function of cutter rolling force) is relatively low.

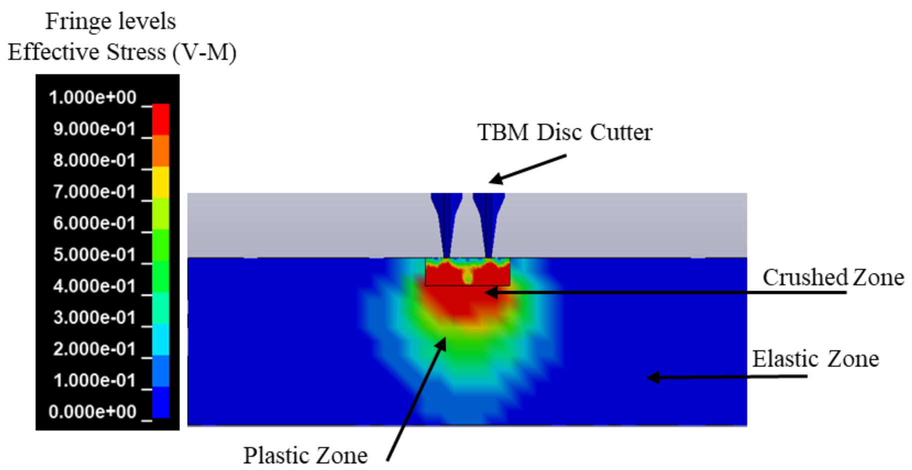
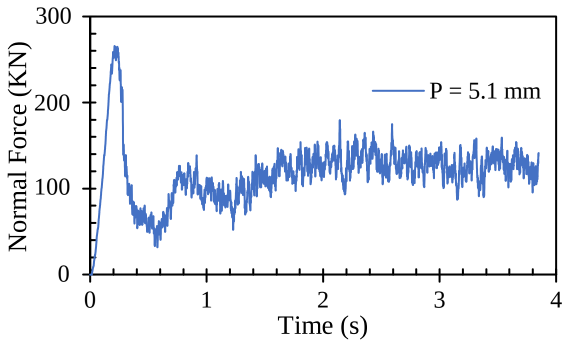
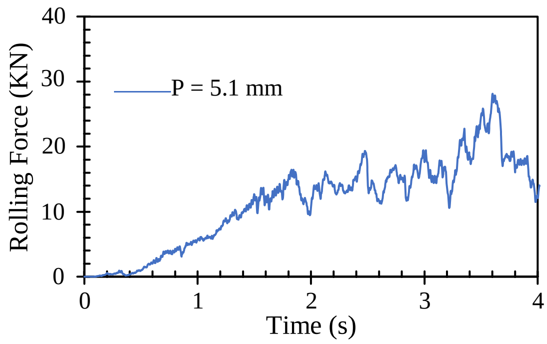


Fig.7 (a). Depicts the damage caused to the rock showing the formation of crushed zone, plastic zone and elastic zone



7(b). Normal force acting on Disc cutter



7(c). Rolling force acting on Disc cutter

6 Summary and Conclusion

A method for modelling typical TBM rock cutting with FEM was described. Using an element erosion scheme in conjunction with continuum plasticity damage mechanics, this study demonstrated a feasible technique. Lagrange's modified formulation, which alters the geometry at each time step, is employed. In order to prevent singularity of the stiffness matrix due to element erosion, the LS-DYNA explicit solution approach is used. The degree of strain softening in a quasi-brittle material is tracked using a damage index, which pinpoints when a fracture occurs. The JHC material model estimates the forces acting on the disc cutter accurately.

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