Numerical Simulation of Rock-Cutting Mechanism of Tunnel Boring Machine

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Abstract

Accurate estimation of acting forces on the disk cutter is very important in the design of Tunnel Boring Machines (TBM) operations factors such as propulsion (driving) force and torque. To do this, first the forces applied to a single disk cutter, as well as its performance for a particular rock, are determined by performing a linear cutting machine (LCM) test. The results are then generalized for design of TBM on the same rock. In the present numerical study, the linear cutting machine test for a fixed cross-sectional cutter was simulated using LS-DYNA software, and the results of the numerical model were compared with the laboratory results. The results show that the use of the Lagrangian solution method is not appropriate due to the strong dependence of the accuracy of the results on the failure criterion defined to remove the elements, and the use of the SPG solution method will be a more appropriate option instead. Also, using the RHT material model instead of the JHC model will have a much better estimate of the width of the damaged area in the rock. The accuracy of the results shows that in the next step, this solution method can be used to simulate the rotational cutting machine (RCM) test.

1 Introduction

Nowadays, mechanized drilling (Excavation) is a common aspect of underground drilling and its role in the development of underground spaces such as tunnels, wells and other mining applications has become very important. One of the most important issues in the successful use of mechanized drilling is design optimization and performance estimation. Although the subject of predicting the performance of tunnel boring machines (TBMs) may seem large-scale due to its dimensions, it is small-scale in terms of the thin edge interaction of cutting disc with a rock, resulting in rock failure and disc penetration.

In the present numerical research, the linear cutting machine (LCM) test for a 17-inch fixed cross-section cutter is simulated using LS-DYNA software and the results of the numerical simulation have been compared with laboratory results reported by Gertsch et al. (2007). Here, the type of solution method and the intended material model for the behavior of the rock on the amount of forces applied to the disc cutter are investigated.

2 Numerical modeling of linear cutting machine test

In order to select the suitable type of solution method and material model for numerical modeling of the linear cutting machine (LCM) test, experimental test data performed by Gertsch et al. [1] in the center of “The Earth Mechanics Institute of the Colorado School of Mines” were used. In the test, Colorado red granite with a compressive strength of 158 MPa was used to perform a linear cutting machine test and the effects of penetration depth and spacing on the amount of forces applied to the cutter disk was studied.

The disc used in the Gertsch research was a Robbins’ made fixed cross-section disc with a diameter of 17 inches (432 mm) with a thickness of 0.54 inches (13.7 mm) which increases with an angle of 10 degrees from the edge to the center side of the disk cutter. The cross-section of this 17-inch disk with its geometric dimensions is shown in Figure 1. The disc is made of AISI-4340 steel and due to the very high strength of this type of steel, it has been modeled as rigid in the present study.

In the linear cutting machine test performed by Gertsch et al. [1], a rock sample with 110 cm length, 80 cm width and 60 cm thickness was used. But in this study, to reduce the computational time, the length, width and thickness of the rock model are 300, 400 and 200 mm, respectively. However, the chosen dimensions are large enough that the free boundary conditions considered at the edges of the model do not affect the numerical results.

As shown in Figure 2, the contact area between the rock and the cutter disk is locally modeled with smaller elements. In this area, the element size is considered 0.2 mm. In other words, there are at least three elements along the depth of the cutter disk. Also, the penetration depth of the cutter disk in the rock is equal to 6.4 mm (0.25 in.).

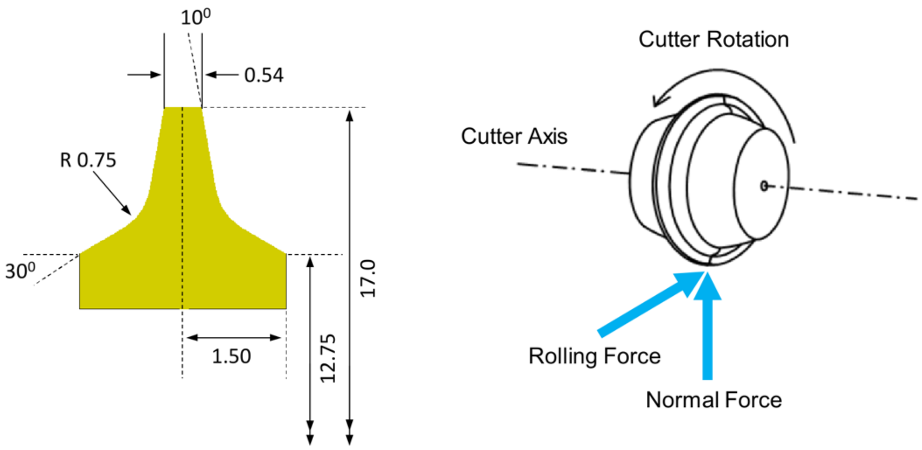

Fig.1: Left: Dimensions of the cutter disc cross section (in inches), right: The forces applied to the disk cutter

Here, only the movement of the nodes of the lower surface of the rock is limited in the vertical direction. The movement of the cutter disc in the horizontal direction (X-axis) is limited to indicate its linear motion. Also, the rotation of the disk as perpendicular to the plane (Z-axis) is limited to indicate its rotational motion.

According to previous studies by Roxborough and Phillips [2], and Cook et al. [3], it was found that the specific energy and shear forces are not affected by the velocity of the cutter disk until the velocity of the cutter disc reaches the crack propagation velocity in the rock. Therefore, to reduce computational time, the horizontal and rotational velocity of the disk can be considered higher. Using this result, Jaime et. al [4], and Cho et al. [5] considered the disk cutter velocity in their numerical model to be 10 and 6 times the actual test velocity, respectively. In the test performed by Gresht et al. [1], the horizontal and rotational velocity of the disk were 0.33 m/s and 1.5 rad/s, respectively.

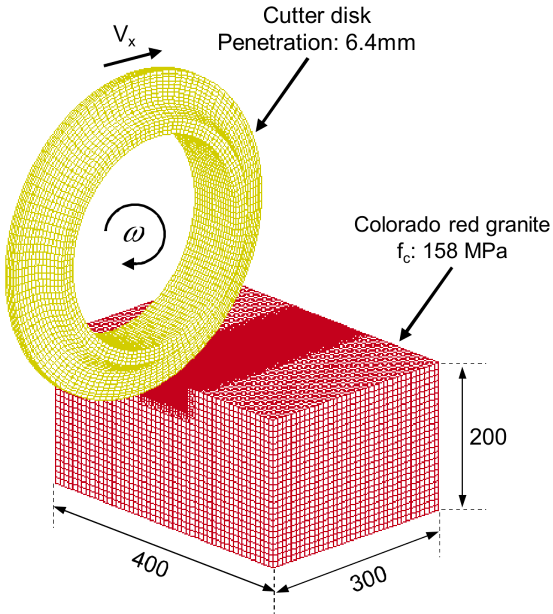

Fig.2: Finite element model (dimensions are in millimeters)

According to this issue, the model is made of two different components of the disk cutter and rock, so the interaction between them must be defined. For this purpose, the contact between the cutter disk and the rock is defined using the keyword “Contact Eroding Surface to Surface.” According to the experimental results obtained by Gaffney [6], the coefficient of friction between the disk cutter and the rock is considered equal to 0.14.

To describe the behavior of the rock, the Johnson-Holmquist-Concrete material model is used. This model was proposed by Holmquist et al [7], to simulate the behavior of brittle materials subjected to large strains, high strain rates and high pressures. In this material model, equivalent strength is expressed as a function of the pressure, strain rate, and damage. The pressure is expressed as a function of the volumetric strain and includes the effect of permanent crushing. The damage is accumulated as a function of the plastic volumetric strain, equivalent plastic strain and pressure. This material model has been widely used to simulate linear rock cutting (Li and Shi [8] and Li and Du [9]). The assumed values for the Johnson-Holmquist model parameters are presented in Table 1.

Material parameters	Unit value	Damage parameters	Unit value
Density (g/mm^3)	2.665E-3	D_1	0.04
Shear modulus (MPa)	17.16E+3	D_2	1.00
Strength parameters		EOS parameters	
A	0.79	P_{crush} (MPa)	52.67
B	1.60	U_{crush}	1E-3
C	0.007	P_{lock} (MPa)	800
N	0.61	U_{lock}	0.11
Fc (MPa)	158	K_1 (MPa)	85E+3
T (MPa)	9.3	K_2 (MPa)	-171E+3
SFMAX	7	K_3 (MPa)	208E+3
EPS0 (1/ms)	1E-3		

Table 1: Johnson Holmquist parameters for Colorado red granite

The Lagrangian method is chosen as a solution method. In this solution method, the movement of the cutter disk on the rock leads to severe distortion of the rock elements. Because the step size is directly proportional to the smallest dimension of the smallest element, the distortion of the elements reduces the temporal step size to zero and the solution stop. So to avoid this, heavily distorted elements should be removed from the simulation. For this purpose, together with the Johnson-Holmquist-Concrete material model, a failure criterion is applied using “MAT ADD Erosion” in the simulation. Here, the value of the principal strain at the failure point (element removal) is assumed to be 0.13 (MXEPS = 0.13).

2.1 Numerical results (Lagrange method and Johnson-Holmquist-Concrete model)

The effect of increasing the cutter velocity by 10 and 100 times of its actual velocity in the experimental test on the rolling and normal force applied to the disk cutter is shown in Figure 3. As seen there, increasing the cutter velocity to 100 times the actual velocity in the experimental test will not significantly change the numerical results. Although these results show that, to reduce computational time, the velocity of the disc cutter can be considered 100 times its actual velocity, but in this study (similar to the work done by Jaime et. al [4]), the velocity of the disk cutter is considered only 10 times its actual velocity. The effect of changes in the value of the MXEPS parameter on the rolling and normal force applied to the disk cutter is shown in Figure 4. As can be seen, by increasing or decreasing the value of failure strain, the amount of force applied to the disk cutter will also change. In other words, these results show that the accuracy of the numerical model results is strongly dependent on the amount of the failure strain defined to remove the Lagrangian elements.

The effect of disc cutter velocity and MXEPS parameter value on the rolling and normal force applied to the disc cutter (results from Figures 3 to 6) is presented in Table 2. These results show that if the value of the MXEPS parameter is considered equal to 0.13, the numerical results can predict the experimental results well.

Figure 5 shows the damage created in the rock due to the movement of the disk cutter. As can be seen, the width of this area is estimated 16 mm, which is much lower than the values observed in the experimental test reported by Gertsch et al. [1]. In other words, although the Johnson-Holmquist-Concrete material model can be used to estimate the rolling and normal forces applied to the disc cutter with great accuracy, this model will not give a good estimate of the width of the damaged area. Correct estimation of the width of the damaged area is very important in determining the effect of spacing on the forces applied to the disc cutter.

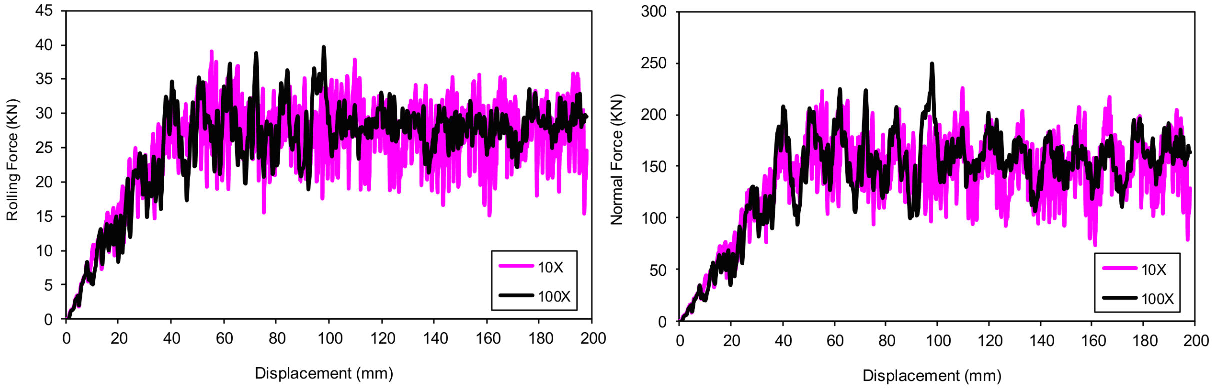

Fig.3: Effect of cutter velocity factor on forces applied to the disc cutter

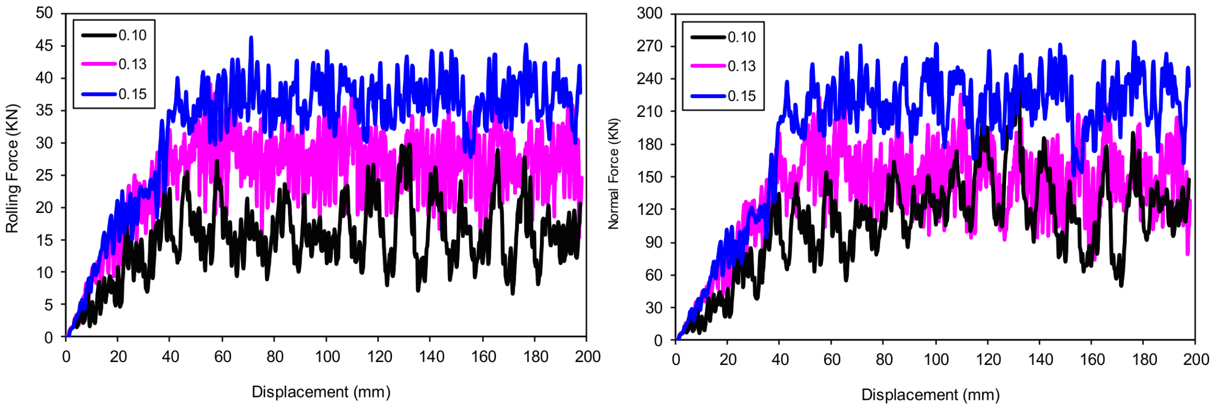

Fig.4: Effect of value of the MXEPS on forces applied to the disc cutter

Cutter Velocity Factor	Erosion (MXEPS)	Rolling Force (KN) Num.	Rolling Force (KN) Exp.	Normal Force (KN) Num.	Normal Force (KN) Exp.
10X	0.13	27.3	19.2	146.2	147.0
100X	0.13	27.9		154.3	
10X	0.10	18.6		120.9	
10X	0.15	38.5		223.8	

Table 2: The effect of cutter velocity and value of the MXEPS on forces applied to the disc cutter

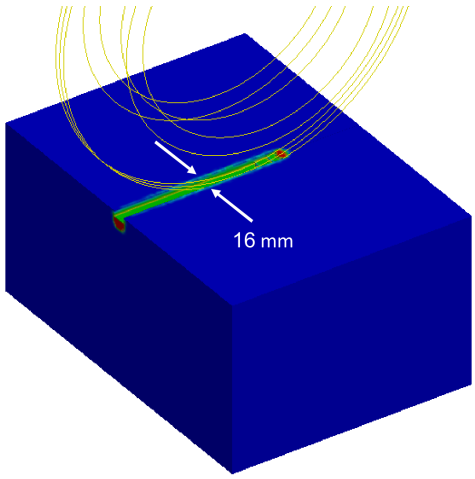

Fig.5: Damage created in the rock due to the movement of the disk cutter (JHC model)

2.2 Numerical results (Lagrange method and RHT model)

The results obtained in the previous section showed that, although Johnson-Holmquist-Concrete model can estimate the rolling and normal forces applied to the disc cutter with acceptable accuracy, the width of the damaged area is significantly less than the results observed in the experimental test reported by Gertsch et al. [1]. Therefore, in this section, the RHT model with default coefficients is used to describe the behavior of Colorado red granite. Here, the value of the MXEPS parameter similar to the previous section is assumed to be 0.13.

Figure 6 shows the rolling and normal force applied to the disc cutter. As can be seen, the rolling force applied to the disc cutter is estimated less than the actual amount. This could be due to the fact that the coefficient of friction in the actual test is higher than the value considered in the numerical simulation. Also, this figure shows that the normal force applied to the disc cutter is predicted to be greater than its actual value. In other words, the value of the MXEPS parameter should be reduced to achieve a better estimate. Similar to the results presented in the previous section, this issue shows that due to the dependence of the accuracy of the results on the value of the failure parameter defined in the numerical model, Lagrangian method may not necessarily be a good option for numerical modeling of rock cutting.

Figure 7 shows the damage created in the rock due to the movement of the disk cutter. As can be seen, the width of this area is estimated to be 44 mm, which is closer to the values reported by Gertsch et al. [1]. In other words, by using the RHT model instead of the Johnson-Holmquist-concrete model, we can have a good estimate of the width of the damaged area.

The effect of material model on the rolling and normal force applied to the disc cutter is presented in Table 3. These results show that, in addition to the dependence of the accuracy of the results of the Lagrangian method on the value of the failure criterion of the elements, by changing the material model of the rock, the value of the failure criterion must also change.

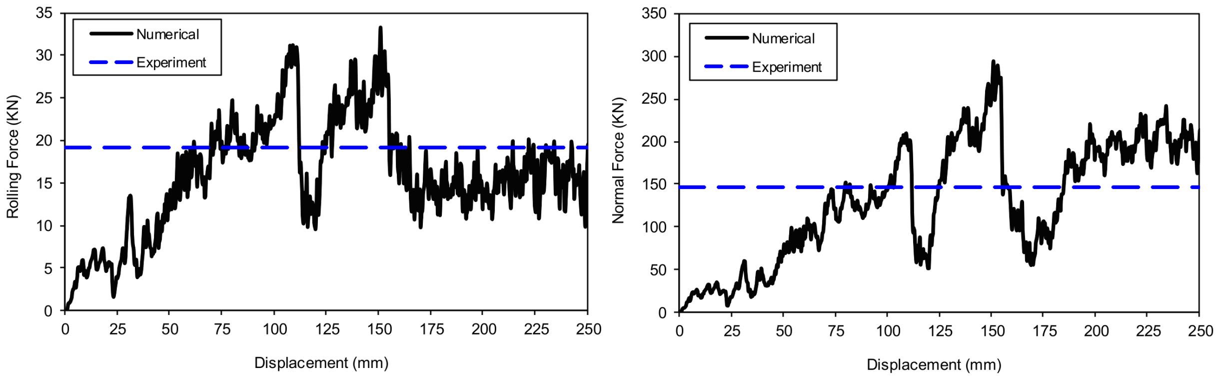

Fig.6: Rolling and normal force applied to the disc cutter

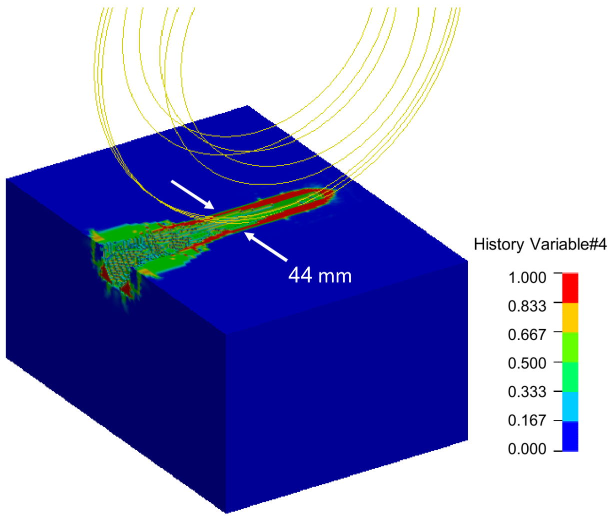

Fig.7: Damage created in the rock due to the movement of the disk cutter (RHT model)

Material Model	Velocity Factor	Erosion (MXEPS)	Rolling Force (KN) Num.	Rolling Force (KN) Exp.	Normal Force (KN) Num.	Normal Force (KN) Exp.
JHC	10X	0.13	27.3	19.2	146.2	147.0
RHT	10X	0.13	15.5		201.1	

Table 3: Effect of material model on forces applied to the disc cutter (solution method: Lagrangian)

2.3 Upgrading Lagrangian method to SPG method

Since in the Lagrangian method the accuracy of numerical results is strongly dependent on the value of the failure criterion defined to remove the elements, the SPG (Smooth Particle Galerkin) method is used to simulate the rock-cutting problem. In this solution method, there is no need to define the failure criterion as in the Lagrangian method, and therefore the accuracy of the material models considered for the behavior of the rock can be estimated better.

Figure 8 shows the model considered in numerical simulation. Here, to reduce the computational time, only the central area of the rock block is modeled with SPG elements. The length, width and depth of this area are 300, 60 and 40 mm, respectively. The dimensions of the rock block are similar to the previous section. Here, the cutter velocity is exactly the same as the experimental test model.

In the SPG method, the Updated Lagrangian kernel is selected as kernel function type. Also, the value of SMSTEP (Interval of time steps to conduct displacement regularization) parameter is considered equal to 30. Using "Contact Nodes to Surface", the interaction between the Lagrangian elements of the disc cutter and the SPG elements of the rock is defined.

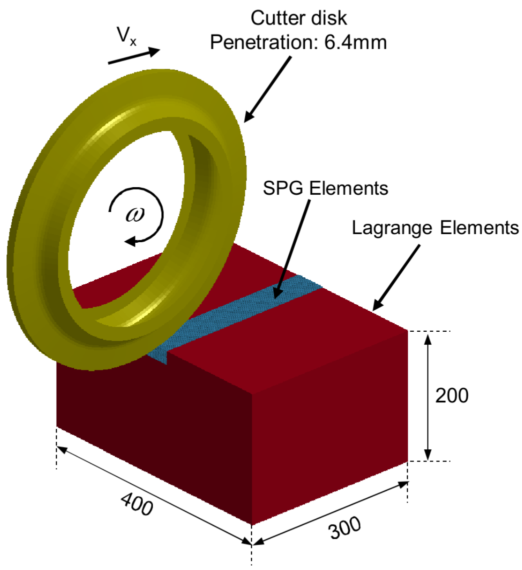

Fig.8: Finite element model (dimensions are in millimeters)

The effect of the material model intended to describe the behavior of the rock on the rolling and normal force applied to the disc cutter is shown in Figure 9. As can be seen, although the rolling and normal forces predicted by the JHC model are about 50% higher than the experimental results, the RHT model was able to predict the rolling and normal forces well. The effect of the material model intended to describe the behavior of the rock on the rolling and normal force applied to the disc cutter (results of Figure 12) is presented in Table 4.

Figure 10 shows the rock damage caused by the movement of the cutter disk at different times. The width of this area is estimated to be 44 mm, which is close to the values reported by Gertsch et al. [1]. According to the presented results, the SPG method along with the RHT material model will be a good choice for simulation rock cutting.

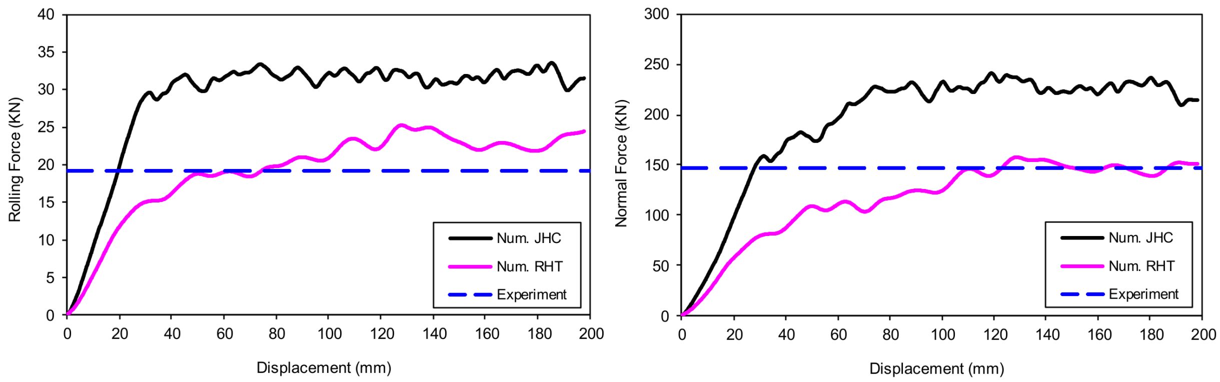

Fig.9: Rolling and normal force applied to the disc cutter

Material model	Rolling Force (KN) Num.	Rolling Force (KN) Exp.	Normal Force (KN) Num.	Normal Force (KN) Exp.
JHC	31.6	19.2	232.0	147.0
RHT	23.4		145.4	

Table 4: The effect of material model on forces applied to the disc cutter (SPG)

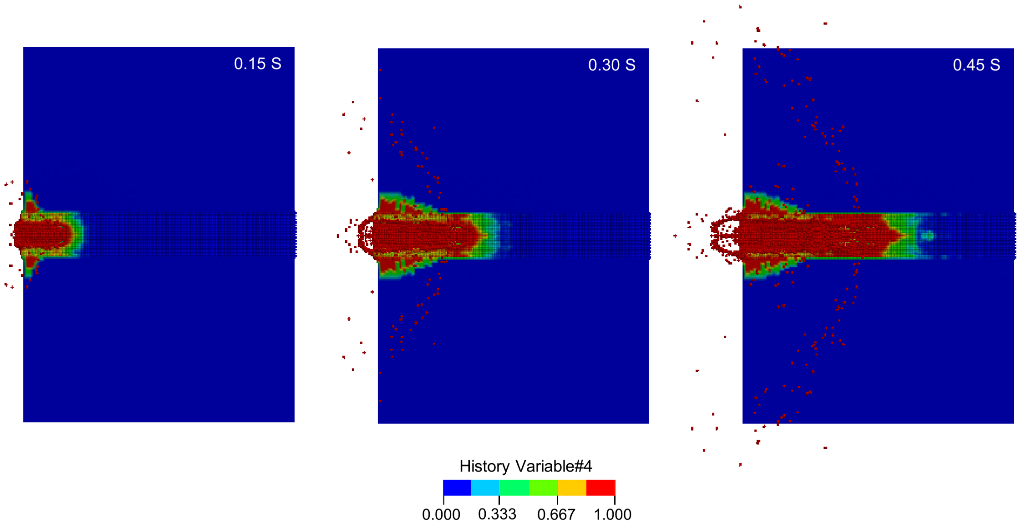

Fig.10: Damage created in the rock due to the movement of the disk cutter

2.4 Spacing

In general, in the process of linear rock cutting, by reducing the distance between the cutting paths, the amount of forces applied to the disk cutter is reduced. In this section, the effect of a spacing is investigated, and the results have been compared with the experimental values reported by Gertsch et al. [1]. Similar to the previous section, the penetration depth of the disk cutter is considered to be 6.4 mm. Here, in order to reduce the computational time, the motion of the three disc cutters is modeled simultaneously, and the forces applied to the middle disc cutter are taken from the software output. Figure 11 shows the finite element model of this problem. The material model, boundary and initial conditions are all selected in a way similar to the previous section. Here, according to the results obtained in the previous section, the RHT material model is used to describe the behavior of the Colorado red granite.

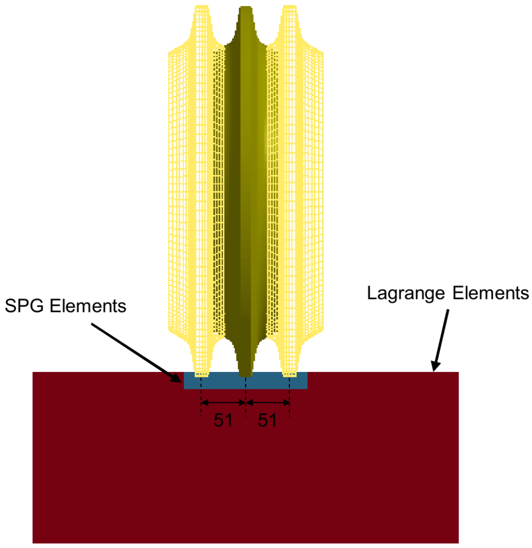

Fig.11: Finite element model (spacing: 51 mm)

The effect of spacing on the rolling and normal force applied to the disc cutter is shown in Figures 12. Although the predicted rolling forces of spacing 76 and 51 mm are about 20% greater than the force measured in the experimental test, the numerical results provide a very good estimation of the normal forces applied to the disc cutter. The effect of spacing on the rolling and normal force applied to the disc cutter (results of Figure 12) is presented in Table 5. Figure 13 shows the damage caused to the rock by the movement of the cutter disc (spacing: 51 mm). Cracks created in the rock due to the movement of the side cutter disc will reduce the strength of the middle area, and thus reduce the forces applied to the middle disc cutter.

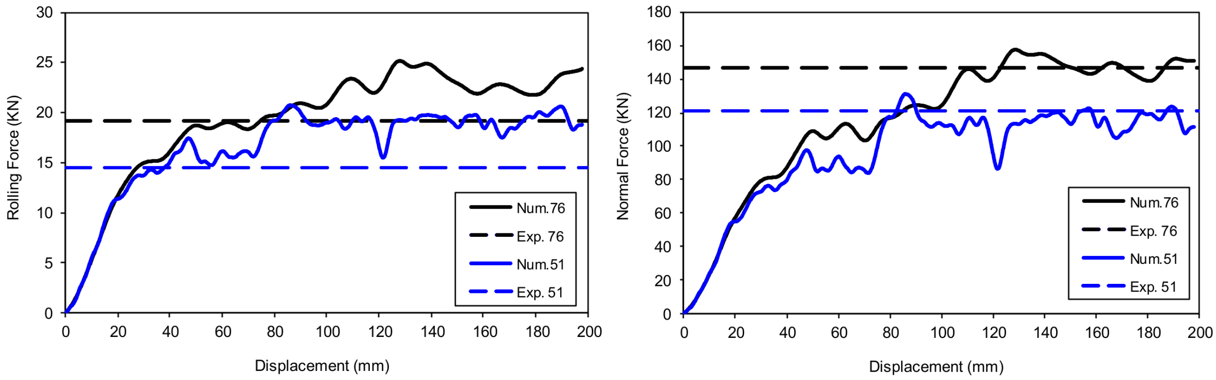

Fig.12: Effect of spacing distance on forces applied to the disc cutter

Material model	Rolling Force (KN)		Normal Force (KN)	
	Num.	Exp.	Num.	Exp.
76	23.4	19.2	145.4	147.0
51	18.65	14.5	114.4	121.0

Table 5: The effect of spacing distance on the forces applied to the disc

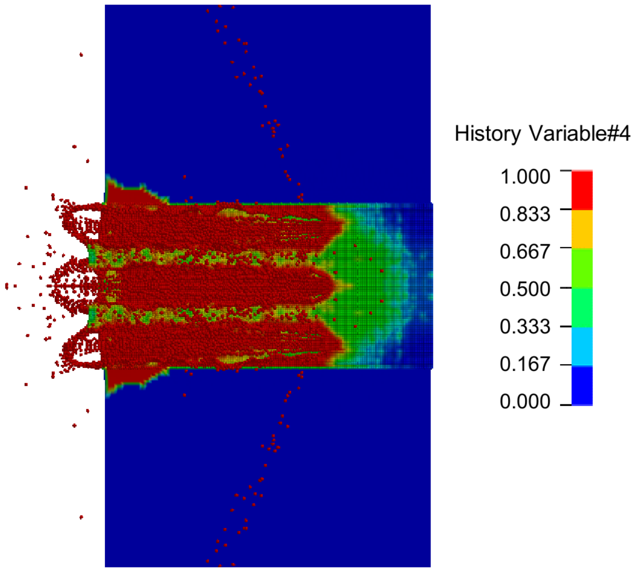

Fig.13: Damage caused to the rock by the movement of the cutter disc (spacing: 51 mm)

3 Summary

In the present numerical study, the linear cutting machine (LCM) test for a fixed cross-sectional cutter was simulated using LS-DYNA software, and the results of the numerical model were compared with the laboratory results. The results showed that the use of Lagrangian method is not appropriate due to the strong dependence of the accuracy of the results on the failure criterion defined to remove the elements, and the use of the SPG solution method will be a more appropriate option instead. Also, using the RHT material model instead of the JHC model will give a much better estimate of the width of the damaged area in the rock. The accuracy of the results showed that in the next step, this method can be used to simulate the rock rotational machine (RCM) test.

However, it seems that a major step in simulating rock cutting has not been considered. This preliminary step is the calibration of the material models parameters used to describe the behavior of the rock using laboratory tests. In the next step, the calibration of these material models parameters will be investigated using laboratory tests and the selection of a more accurate material model to describe the behavior of the rock in the linear cutting machine test.

4 Literature

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