

Numerical Methods in Civil Engineering



Journal Homepage: https://nmce.kntu.ac.ir/

Evaluation of Disc Cutter Performance in Rock Cutting Process Using 3D Finite Element Method

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ARTICLE INFO

APPLICABLE PAPER

Article history: Received: December 2020. Revised: January 2021. Accepted: February 2021.

Keywords: Tunnel boring machines boreability linear cutting test performance Finite element method

Abstract:

Today, numerical simulation can be used as a suitable tool to measure large quantities that are very expensive and, in some cases, impossible to measure. One of the important issues in predicting rock mass boreability in excavation with full face tunnel boring machines is estimating the disc's forces for rock cutting. For this purpose, the linear cutting test is employed. However, limited access to equipment and the high cost of this test have resulted in a decline in its use. In this research, linear cutting tests have been simulated using numerical methods using ABAQUS 6-14 software, which is based on the finite element method. In this simulation, according to the dynamic analysis, for the explicit solution method and the behavior of the rock, the Johnson–Holmquist-II model (JH-2) is used. Subsequently, after solving the model, the forces acting on a fixed cross-sectional disc are estimated, and then, for validation, the results of numerical modeling are compared with laboratory results and theoretical model. Comparison of the results shows that the cutting forces obtained from the simulation have a deviation of 7% and 11% with normal and rolling forces compared to the mean forces in laboratory work, respectively.

1. Introduction

With the development and progress of industry, the human need to access the depths of the earth to extract minerals and the construction of underground spaces for purposes such as water transfer, transportation, and so on has increased. The scope of the field and the diversity of underground engineering projects in design and implementation have made tremendous progress [1]. The construction of underground spaces in rock is one of the most dangerous and challenging human problems. Over time and with the construction of mechanized boring machines, the problem has been overcome. Mechanized boring underground spaces in rock are based on the creation and expansion of cracks and finally fracture of rock continuously. One method of creating and spreading cracks in rocks is cutting tools, which are used in mechanized and semimechanized boring machines of tunnels, wells, and continuous mining. In fact, cutting tools are the most important part of the machines mentioned above that are directly involved with the rock and are responsible for boring and crushing the rock. One of the most important studies that are widely done today is the research on evaluating the performance of discs in rock cutting. Due to laboratory equipment limitations, special attention is paid to numerical modeling methods using FEM dynamic analysis. Numerical methods can be used to estimate the force required to cut the rock, which can simplify predicting the TBM penetration rate by simulating the rock fracture process. Cook et al. [2] compared the results of wedgeinduced rock crushing by 2D FEM modeling with experimental results. Liu et al., [3] and Kou et al., 2004 modeled rock fracture with a single and dual wedge tool using tool-rock interaction with code R-T2D. Baek and

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Moon [4] used a heterogeneous model using the finite difference method (FDM) to analyze the effect of limiting pressure and distance of the discs on fracture of the rock. Gong and Zhao [5,6] examined the effect of spacing and direction of joints on the disc blades' cutting process. In 2006, they also examined the process of rock fracture with two discs and the optimal distance between them using the 2D discrete element method using UDEC software. Rojek et al. [7] performed a simulation of a rock cutting process using a discrete element method, in which two tools, a stylus, and a fixed-section disc, were modeled in three dimensions. The rock elements were selected from a discrete spherical element type, and the rock model was calibrated using uniaxial compressive strength and the Brazilian test. In this simulation, the estimated cutting forces are compared with the laboratory results [8]. Mabra in 2012 numerically studied the effect of confining stress on rock fracture by tunnel boring machine (TBM) discs by numerical FEA [9]. In this research, in the first step, based on the characteristics of the force-penetration depth curve, the confining stress conditions for tunnel excavation using TBM are divided into three categories based on an index by defining the ratio of confining stress to uniaxial compressive strength. A disc cutter then simulates the rock fracture process with different confining stresses using the RFPA2D code, which is based on finite element analysis. Li and Shi [10] numerically simulated the forces acting on the TBM disc tool considering the confining pressure and damage to the rock using ANSYS and LS-DYNA software. This simulation shows an increase in normal and rolling forces with increasing penetration depth and a greater increase in normal force than the rolling force with increasing Li and Shi pressure. Medel-Morales and Botello-Rionda in 2013 designed and optimized TBMs by simulating the process of cutting rock with a fixed crosssection disc using the discrete element method. Using the constructed model, the interaction between force and rock was measured for TBM design. For this purpose, the linear cutting test (LCT) was simulated, in which a piece of rock (granite) with dimensions of 20×40 cm and a thickness of 5 cm and a 17-inch disc were considered [11]. Mohammedi in 2015 numerically studied the linear cutting test of rock using ABAQUS software. Due to the limitations of linear cutting testing, he used the data of previous studies of Rostami's thesis for validation [12]. Huiyun Li and Erxia Du (2016) [13] simulated a linear cutting test with LS-DYNA (finite element) software and compared the simulation's cutting forces with the experimental results of a linear cutting test. Gong et al. in 2015 numerically simulated the rock fracture process of two TBM disc cutters using the finite element method and examined the effect of disc cutter distance on the penetration rate by simulation using UDEC software on Singapore granite. They stated that the process of fracture with two discs was initially similar to the process

of fracture with one disc and independent of each other. After the crushed zone is formed, the cracks start from this zone, and then the lateral cracks grow in a certain direction due to the interaction of the two discs with each other. As the penetration rate increases, lateral cracks grow between the two discs and merge with each other to form a rock chip. Chip formation largely depends on the distance between the discs and the load applied to them. They also stated that the critical stress for chip formation increases with increasing disc distance [14]. Xia et al. in 2017 published the results of their research on the effect of the distance between the disc cutter and the rock's free surface in rock crushing. For this research, they first created 3D numerical models using the FEM method of crushing rock by a disc and then examined the effect of the distance between the cut and the free surface of the rock mass. Next, linear cutting tests were performed at different distances from the rock's free surface, and finally, the results of the test were compared with the results of numerical modeling. Observations show a decrease in failure of rock blocks and the size of cuttings that have increased with increasing distance [15]. Zhang et al. in 2020 examined the process of rock crushing by TBM disc in mixed soils. They used PFC3D software for this research which indicates that the thrust force and the rotational force of the disc change when moving from hard rock to soft rock [16]. Labra and et al. in 2017 simulated the rock cutting process with discrete and finite element methods. He has compared numerical results with available data from in-situ measurements in a real TBM, in which the results demonstrate good agreement with the theoretical predictions [17].

In this research, using ABAQUS finite element software, linear cutting tests have been simulated to evaluate the disc's performance in rock cutting. In this simulation, to obtain the cutting forces and compare them with the results of the laboratory test of linear cutting of Colorado red granite, many models have been constructed and solved to eliminate all the calculation errors in the model. In the next step, after calibrating the model and using the existing Colorado red granite parameters, the results of solving the model are compared with the results of the linear cutting test performed in the laboratory.

2. Rock Cutting Mechanism with Disc Tool

The mechanism of cutting the rock using the disc tool consists of two continuous steps. In the first step, the disc contacts the rock and penetrates into the rock due to the application of force, which separates small and large particles from the rock. At the same time, cracks will form inside the rock. Cracks from adjacent sections are developed and connected in the second step, and a boring chip is formed [18]. The process of loading the disc on the rock can be divided into four steps, which include the development of the stress field, the formation of the crushed zone, the formation of surface chips, and the formation of subsurface chips. The zone below the edge of the disc that is exposed to extreme contact stresses is called the crushed zone, which is created by the geometry of the disc edge due to the highstress concentration (Figure. 1).



Fig. 1: The steps of rock fracture with disc [19]

Since the amount of stress is sufficiently greater than the rock's tensile strength, cracks that are formed grow into the rock or into the adjacent groove and form a chip. To form a chip, two hypotheses are proposed, that in the first hypothesis, the chip is formed due to the cracks reaching the free surface, and in the second hypothesis, a crack collides with an adjacent crack created by another disc, resulting in the formation of a chip. As mentioned, a crushed zone forms below the edge of the disc, which depends on the amount of pressure applied to the edge of the disc. The exact distribution of pressure in this zone is not known. To make an effective cut, the size of this zone must necessarily be small; otherwise, a large part of the crushing energy will be spent on re-crushing the chips because the formation of micro-cracks in the crushed zone will expand the volume of this zone, which in turn will cause the expansion of tensile stresses and lead to the expansion of cracks to the surface and the formation of rock chips [20]. When a chip is created, the crushed zone's pressure decreases and leads to the force on the disc to fluctuate.

3. Evaluation of Disc Performance in Rock Cutting Process

To evaluate the performance of the disc in the rock cutting process, normal force, rolling force, and side force are used.

Normal force is the mean force that is applied perpendicular to the direction of the cutting surface and causes the disc to penetrate the rock. The normal force determines the boring machine's thrust force, which is shown by Fn [21]. A rolling force is a force that acts parallel to the cutting surface and overcomes the rolling resistance force of the disc. This force determines the power and torque of the boring machine and is also used to calculate specific energy. The rolling force is exhibited by Fr. Side force is caused by asymmetric loading on the disc due to the release of pressure on one side of the disc due to chip formation. This force is also displayed by Fs [22]. Figure 2 illustrates the above forces.



Fig. 2: Relation between the disc cutter and rolling forces in physical view [23]

3.1 Theoretical model

Cutting forces estimation is based on Colorado School of Mines model (CSM). The first version of this model was developed by Ozdemir (1977), and later was updated by Rostami (1997). The CSM model estimates the cutting forces based on a large database of linear cutting machine (LCM) tests [12]. In this model the normal and rolling forces are estimated by assessing the total cutting force. The total cutting force acting on the cutter can be seen in Figure 3 and is calculated according to:

$$F_t = \frac{TRP \circ \phi}{1 + \psi} \tag{1}$$

where F_t is the total forces acting on the disc (kN), T is the cutter tip (mm), R is the cutter radius(mm), P_{\circ} is the base pressure in the crushed zone and ψ is the exponent of the pressure distribution function.



Fig. 3: Scheme of forces acting on a disc cutter [21]

The equations for the normal and rolling forces calculated according to equations (2) and (3) are as follows:

 $F_n = F_t \cos\beta \tag{2}$

 $F_r = F_t \sin\beta \tag{3}$

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Where F_n is normal force (kN), F_r is rolling force (kN) and β is as the middle point of the contact area.

3.2 Linear Cutting Test

The linear cutting test is performed by an LCM that can move a disc in its actual size on the surface of rock block specimens with a certain force and depth of penetration. The linear cutting machine consists of a rigid steel frame on which the disc is installed: a tri-axial force machine (installed between the cutter and the frame) measures and records the forces. The rock sample is fixed in a steel box by concrete so that it does not move during the test, and a hydraulic jack with precise control moves the sample towards the cutter so that the cutter penetrates the rock and cuts the surface of the sample to a predetermined depth along a line. The 3D pressure cell measures the normal, rolling, and side loads applied to the cutter during cutting. After each step, the sample frame is moved to a predetermined distance to take into account the effect of moving the adjacent disc [24] (Figure 4).



Data Acquisition System

Fig. 4: Overview of the linear cutting machine [25]

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The biggest advantage of this linear cutting machine is that it performs real-scale tests with cutting tools. That is, a disc can be moved to its actual size on the rock surface with a controlled thrust force and a specific penetration depth to estimate the cutting forces [26]. The machine allows the complete study of rock crushing with mechanical cutting tools, the interaction between rock and disc, and the effect of different parameters on the cutting forces. The high cost of manufacturing and maintaining the machine has led to increased testing costs and a limited number of machines in some research centers around the world. The machine is currently available at the Colorado School of Mines, Istanbul Technical University, the Australian School of Mechanics and Mining, Seoul National University in Korea, and Beijing University of Technology in China.

4. Numerical Simulation of Linear Cutting

3D code of ABAQUS/CAE software was used to model the linear cutting test to evaluate the performance of the

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disc in rock excavation. This software is based on finite element and is able to simulate the nonlinear dynamic of failure. This software has a very wide set of elements that can model any type of geometry. It also has many behavioral models that make it possible to model various types of properties and behaviors such as metals, polymers, composites, reinforced concrete, as well as geotechnical materials such as soil and rock.

4.1 Model Geometry and Input Parameters

In this research, a sample of Colorado red granite was used to evaluate the disc's performance. Due to the fact that the actual dimensions of the sample in the laboratory for the linear cutting test are 1.1*0.8*0.6 m, the dimensions of the rock block in modeling are also similar to the laboratory, and square elements with dimensions of 1 mm are used for meshing [27]. The number of elements of the whole rock block is 528 million, in which the volume of each element is 1 mm³ (Figure 5).



Fig. 5: Geometry and meshing of the rock block

The rock sample is considered isotropic. The properties of the rock are given in the table.

Table 1: Properties of the Rock Samples Used in the Tests [27]

Properties	Value	
Uniaxial compressive strength	158 Mpa	
Brazilian tensile strength	6.78 Mpa	
Young's ratio	41 Gpa	
Poisson's ratio	0.234	

Another part of the model is the cutting disc. The simulated cutting disc is a fixed cross-section with a diameter of 17 inches (432 mm) and an edge thickness of 13 mm and single. The mechanical properties for the disc include density = 8000 kg/m3, Young's modulus = 210 GPa, Poisson's ratio = 0.25 [13].

4.2 Behavioral Model of Rock

In order to simulate the process of dynamic rock failure by a rock cutting machine, the JH-2 model was used, and the basic equations of rock were defined. The JHC model was first developed to study the behavior of ceramics, followed by high-pressure concrete and high strain rates, as well as rocks. JH-2 model consists of a model of strength of various materials, including intact, damaged, and fractured material. The normalized strength for an intact material is as follows:

$$\sigma_1^* = A(P^* + T^*)^N (1 + CLn\dot{\varepsilon}^*) \tag{4}$$

In the above relation

$$\sigma_I^* = \frac{\sigma_I}{HEL} , P^* = \frac{P}{P_{HEL}}, T^* = \frac{T}{P_{HEL}}$$
(5)

Where σ_I^* is the normalized strength, σ_I is the actual intact strength, HEL is Hugoniot elastic limit of the material, P_{HEL} is the pressure at the Hugoniot elastic limit and $\dot{\varepsilon}^*$ is the normalized strain rate. Also, A, N, and C are also material parameters.

As shown in Figure 6 if the existing sized equivalent stress is greater than the strength of the intact material, the material will deform to its yield surface, and plastic deformation will occur. As the irreversible plastic deformation increases, the damage accumulates inside the material, and its strength gradually decreases from the strength of the intact material (σ_I^*) to σ_D^* . The new yield surface then depends on the damaged surface ($0 \le D \le 1$). If the material is completely damaged (D=1), the new yield surface is reduced to the fractured material level [29].



Fig. 6: Intact, damaged and fractured strength surfaces in JH-2 model

The normalized strength of the fractured material is expressed as follows:

$$\sigma_F^* = B(P^*)^M (1 + CLn\dot{\varepsilon}^*) \tag{6}$$

In the above relation, B and M are the parameters of the fractured material; P*, C, and ε^* are similar to those used in Equation 1. An upper limit (σ^*_{FMax}) is used to control the position of the fractured material strength. The normalized strength of the damaged material is closely related to the damage and can be expressed as follows:

$$\sigma_D^* = \sigma_I^* - D(\sigma_I^* - \sigma_F^*) \tag{7}$$

Damage: Damage is a condition that describes the transition from the strength of a healthy material to the strength of a fractured material as follows:

$$D = \frac{\sum \Delta \varepsilon p}{\varepsilon_P^F} \tag{8}$$

Where $\Delta \varepsilon_P$ represents the increase in equivalent plastic strain during a computational cycle, and $\varepsilon_P^F F$ represents the equivalent plastic strain that must be accumulated during the transition from healthy to fractured material under constant pressure. The equivalent plastic strain is obtained from the following equation:

$$\varepsilon_P^F = D_1 (P^* + T^*)^{D_2} \tag{9}$$

D1 and D2 are material parameters; P* and D* are similar to those used in Equation 1. Because the compressive stress at a point on the rock below the cutting tool tip is much greater than the uniaxial compressive strength of the rock, the use of the JH-2 model is appropriate to describe the dynamic behavior of rock damage in this zone, while in low-stress zones that are far from the tip of the cutting tool, the onset and progression of cracks should be

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controlled using largest main tensile stress [29]. The parameters of the JH2 for read granite are given in Table 2.

	U	•
Parameters	Va	lue
Intact strength constant (A)	0	.3

Table 2:	Constants	of JH2	model fo	r read	granite	[13]	l
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Parameters	value
Intact strength constant (A)	0.3
Intact strength exponent (N)	0.7
Strain rate constant (C)	0.007
Fractured strength constant (B)	2.04
Fractured strength exponent (M)	1.5
Bulk modulus (K1) (GPa)	85
Polynomial EOS constant (K2) (GPa)	-171
Polynomial EOS constant (K3) (GPa)	208
Shear modulus (G) (GPa)	16.61
Damage constant (D1)	0.04
Damage constant (D2)	1

4.3 Rock-Cutter Contact Modeling

Considering that the model is composed of two different parts of rock and cutter disc, modeling the way of contact between these two parts should be defined. In ABAQUS 6-14, there are two ways to define contact between two different objects. The first method is the surface-to-surface contact method and the second method is the general contact method [30]. In this research, due to the movement of the disc on the rock, the general contact method has been selected.

4.4 Boundary conditions

In this study, the basis for applying the boundary conditions is the linear cutting laboratory conditions. The Y-direction disc cutter model is set at 9.3 radians per second with a penetration depth of 1.9, 3.2, and 5.1 mm. Due to the forces during the cutting of the rock by the disc cutter, the disc cutter model is fixed in directions other than its direction of movement (Y direction). Applying the rock model's boundary conditions, similar to the LCT conditions, the rock model on the floor and two parallel side walls for disc movement are limited and free in other directions (Figure 7).



Fig. 7: Boundary conditions of the model

4.5 Selection of the Model Solution Method

ABAQUS has two solvers for solving structural problems. These solvers include standard solvent and explicit solvent. The first difference and the main difference between these two solvents is that the standard solver uses implicit methods to solve problems. In contrast, explicit solvers use explicit methods to solve problems. In the standard solver, the equations of position, velocity, and acceleration of the nodes are calculated simultaneously using the Newton-Raphson method. This solver is mostly used for static and quasi-static stress analysis as well as dynamic analysis. In the implicit solver, the results (including position, velocity, and acceleration of the nodes) at any given time are obtained directly from the results at the previous moment, and no iteration is performed. This solver is mostly used for dynamic analysis in which changes are made at high velocity. In this research, according to the dynamic analysis, the explicit solution method has been used.

4.6 Model Evaluation

To evaluate the model, the normal and rolling forces obtained momentarily in the linear cutting test simulation were compared with the laboratory results presented by Richard Gertsch at the Colorado School of Mines Laboratory. Many models are constructed and solved to eliminate all computational errors in the model to obtain rotational forces. The graph of the changes of two forces on the disc (normal and rolling forces) is obtained by solving the final model. For example, Figure 8 shows the trend of changes in the normal force acting on the surface of the disc blade and the rock at the penetration of 1.9 mm. On the other hand, Figure 9 shows the rotation of the disc on the rock and the crushing.



Fig. 8: Variation of the normal forces acting on the disk cutter with respect to time



Fig. 9: Variation of the rolling forces acting on the disk cutter with respect to time

In the finite element method, elements whose damage factor reaches one, are removed from the model. Therefore, on the surface of the rock, by removing the mentioned elements, a groove is seen in the path of the cutting disc. The behavior of the force-time shape sawtooth graph is highly dependent on the parameters of the rock. In the stronger rock, the variability of this sawtooth graph's amplitude is increased [31]. The graph of changes in the normal force on the disc is in the negative direction, whereas, the normal force on the disc but in the

opposite direction. The side force on the disc also changes in both the positive and negative directions of the time axis. The reason for this change is the formation of chips during rock cutting. In the normal force change graph, it is observed that the range of change is much wider than other forces. The reason for this is the effect of seismicity and collision of the disc when destroying its front elements and re-engaging it with the next elements. The simulation process was also performed for penetration depths of 3.2, and 5.1mm (Figures 10,11).



Fig. 10: Variation of the normal and rolling forces (penetration depths of 3.2mm)



Fig. 11: Variation of the normal and rolling forces (penetration depths of 5.1mm)

The Figures 12, 13 and 14 show the amount of stress in similar time at different penetration depths. As can be seen with increasing penetration depth, the maximum stress also increases. This show that with increasing penetration depth, the amount of crushing of intact rock also increases. In the graphs shown in Figures 15 and 16 the amount of each force is significant for all three values of the penetration rate. In order to be able to estimate the amount

of force on the disc and compare it with the results of the laboratory test of rock line cutting, the amount of each force is averaged. The deviation in the estimation of cutting forces is about 7%. In other results, this deviation is above 10 percent.



Fig. 12: Maximum stress in penetration depth 1.9 mm



Fig. 13: Maximum stress in penetration depth 3.2 mm



Fig. 14: Maximum stress in penetration depth 5.1 mm







Fig. 16: The comparison of the rolling forces obtained from the LCT, CSM and the numerical simulation

5. Conclusion

The performance of full section tunnel boring machines depends on the cutting disc's performance, which is based on the rock-disc interaction, resulting in rock failure and disc penetration. To evaluate the performance of the disc, it is necessary to estimate the thrust forces and torque, which was done in the laboratory with the help of a linear cutting machine. Due to the limited number of linear cutting testers in the world, all researchers cannot test and evaluate disc performance. In this research, an attempt has been made to evaluate the disc's performance using numerical methods using the simulation of this test. After examining the background of the research, the process of linear cutting of rock by fixed cross-section disc based on the finite element method was simulated using ABAQUS software. Model assembly and boundary conditions were performed in accordance with the laboratory conditions of linear cutting, and after solving the numerical model, the mean cutting forces, including rolling and normal forces, were estimated and compared with laboratory results and

theoretical model (CSM) . Comparison of the results showed that the values of cutting forces obtained from the simulation with the cutting forces from laboratory work have a deviation of 7%.

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