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Efficiency Evaluation of Rock Cutting by TBM Disc Cutter in Closely Jointed Rock Mass

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Abstract

In this research, the effect of geometric parameters of closely joints on rock cutting efficiency by TBM disc cutter is studied using PFC3D software. A validated numerical model of linear cutting machine test is developed and the efficiency of disc cutter is investigated on rock mass specimens with different joint configurations (possible combination of dip angles of 30, 60, 90 degrees with joint spacings of 3, 5, 10, 15, 20 cm). Numerical modeling results reveal that in general, the joint spacing has a greater effect on rock cutting efficiency than joint orientation. If the joint spacing is less than 10 cm, the role of the joint angle is reduced and the distances between the joints control the efficiency. When the joints are close together and have a spacing of less than 10 cm, particularly 3 to 5 cm, the best cutting efficiency can be achieved for a joint angle of 90 degrees. The cutting coefficient is decreased by increasing the joint spacing and the maximum CC occurs at a joint spacing of 5 cm. For joint spacing more than 10 cm, the joints with a 90 degrees dip angle have the greatest impact on the specific energy and reduce cutting efficiency. The best disc cutter efficiency and the minimum required normal force is achieved when joint spacing is more than 10 cm and the angle between the joints and advance direction of the disc cutter is 60 degrees. In the tunnel excavation process, with increasing joint spacing, the TBM machine thrust is more important than its torque. The findings of this research provide a basis for predicting TBM efficiency through joint characteristics.

1. Introduction

In mechanized tunneling by tunnel boring machines (TBMs), the excavation process in hard rock is done by rock cutting. The rock cutting process is defined as fragmentation of rock beneath the disc cutter and penetration of the disc in the rock. Due to the importance of the time and high cost of TBM projects, it is so important to study the rock cutting process in order to predict the efficiency of the machine. It is also noteworthy that the presence of discontinuities in the rock is one of the most important factors affecting the rock cutting. Considering the problems in the investigation of discontinuities, this factor has received less attention and the focus of the most of the researches in the field of predicting the performance of a disc cutter is on intact rock characterization. Nevertheless, in recent years, various researches have been conducted to modify traditional prediction models with the aim of applying discontinuities, as in NTNU model [1, 2] and CSM model [3-5]. In addition, some models have been presented to predict the TBM performance based on rock classification systems including Q [6], RMR [7-10], RSR [11] RMi [12], and GSI [13] [14]. It should be noted that these models mainly consider the effect of joints on TBM performance based on empirical studies on various case studies; therefore, it can be concluded that the use of these models is limited to very specific circumstances and they usually have a lot of errors in unknown grounds and conditions. In addition to the empirical studies in this regard, some researchers have tried to study discontinuities by performing laboratory tests [15, 16]. In these studies, due to the problems and high costs involved in the preparation of a large-scale jointed rock sample, it is very difficult to make a large number of samples and study different factors.

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The existence of all these restrictions on the one hand, and the development of computer science on the other, have led the researchers to make more use of numerical analysis. Therefore, in the last two decades, many researchers have put numerical simulations into use in order to better understand the process of rock cutting by a disc cutter and the effect of discontinuities on it. Gong et al. investigated the orientation [17] and spacing [18] effects of the joints on the cutting process of hard rock using distinct element method by UDEC software. Bejari et al. also studied the effects of orientation and spacing simultaneously on the rock cutting with disc cutters [19] and then with two disc cutters [20]. Zhai et al. [21] inquired the effect of geometrical parameters of joints on cutting performance using GPD-General Particle Dynamics method. Choi and Lee [22] simulated the cutting process using PFC2D and measured the applied forces to the disc cutter by considering the effect of the spacing and orientation of the joints. These numerical studies are mainly carried out in two-dimensional (2D) form which simplifies the actual three-dimensional rock mass concept. In 2D numerical studies, the tip width, the crack propagation, the spatial distribution of the discontinuities of rocks, and the chip formation on both sides of the disc cutter are usually neglected in order to simplify the process; whilst it is completely different in reality. In addition, the 2D models cannot provide rolling force and subsequently the specific energy and cutting coefficient (rolling force divided by normal force). Moreover, the 2D models cannot deal with complex profile such as the cutters with inserted teeth. On the other hand, previous researchers have mostly focused on crack propagation, and the relationship between joint parameters and cutting efficiency has been less studied.

Of the few three-dimensional studies conducted in this field, Lui et al. [23] studied the influence of discontinuities on the cutting process using double disc cutter by using the 3DEC software. In this research, the effect of the disc cutter on a stress-induced rock block was simulated, but the rolling effect and penetration depth of the disc cutter were omitted. In addition, depending on the type of modeling, the rock cutting process is limited to both the type of mesh and the mesh size. One of the researches in this field, which is closer to our article, is the 3D numerical simulation of rock fragmentation by a TBM disc-cutter considering the effects of joints that is conducted by the 3D MatDEM software [24]. In this research, the influence of different joint parameters (orientation and spacing) on rock fragmentation volume and specific energy (SE) and finally on rock-cutting efficiency was examined. However, they did not consider normal force and penetration depth to calculate jointed rock-cutting efficiency. Also, the cutting coefficient (CC) parameter as an important parameters in the field of the TBM cutting efficiency was not studied. Other research similar to this article is the investigation of the effects of joint shear strength, orientation and spacing on the rock breakage mechanism through numerical simulations using a two-dimensional particle flow code, PFC2D [25]. Numerical simulation results reveal that the increase in the joint shear strength changes the internal block breakage mode to cross-joint breakage mode for rock masses with joint orientations of 45° and 60° and with a moderate joint spacing. In this research, the numerical study was performed in two dimensions, which, as mentioned, has its own problems. Also, the effect of joint spacing and orientation on CC and SE was not investigated. Sabri et al. [26] examined the effect of disc cutter wear on TBM operational parameters such as thrust force, net penetration rate, and specific energy. They proposed a new equation to predict normal and rolling cutting forces. The results revealed that replacing worn disc cutters enhances penetration rate while reducing thrust force, resulting in an increase in specific penetration. As one of the latest works on the effects of crack on rock crushing under a cutter of TBM, Gao et al. [27] presented a numerical investigation into the fragmentation behavior of pressure-dependent rock with a pre-existing crack under a TBM cutter. It is found that the depth, length and position of the pre-existing crack, as well as the confining pressure, have a significant effect on the response and fragmentation of rock, including the new cracks pattern, the fragmentation area, and the contact force from the TBM cutter.

In recent years, some studies have been conducted on the performance of disk cutting and wear of cutting tools. Dehghani and Mikhak Beiranvand [28] investigated the effects of rock mass properties on the penetration rate and obtained a mathematical equation to calculate the TBM penetration rates. They used the Monte-Carlo (MC) simulation method to model the TBM performance. Farrokh [29] investigated the different components of hard rock TBM tunneling downtime on the basis of the information about several TBM tunneling projects from around the world. The TBM performance and daily advance rate depend on the duration of these downtimes. He [30] also discussed the parameters impacting Learning Phase Period (LPP), and introduced an algorithm for estimation of the approximate extent of LPP. The practical application of the proposed models is in the performance prediction of a TBM for a new project. Nickjouye Tabrizi et al. [31] after introducing a new TBM tunneling simulator, investigated the effect of the density of two types of soil with different granulation and moisture on the wear of cutting tools under different conditions. Also, Mousapour et al. [32] using this machine studied the cutting tool wear using granulation prepared from Tabriz metro line 2, as well as operating parameters of mechanized excavation machines, such as penetration rate and cutter head rotation speed. In another similar study, Ansari et al. [33] investigated the effect of various soil grading parameters such as D10, D30, and D60, coefficient of gradation, uniformity coefficient, sorting coefficient and effective size on the cutting tools wear. Chakeri et al. [34] designed and built a new laboratory device with which the amount of wear of cutting tools in excavation machines can be obtained against rough rock samples. In this research, the laboratory wear results obtained from this device were compared with those obtained from the numerical modelling of the same device in PFC3D discrete element software, both for the cutting blades and the sample itself. The results showed that numerical modelling of this research can estimate the amount of wear of the cutting tools and the crushing of the samples, and the results obtained from it are in relatively good agreement with the experimental results. Zahiri et al. [35] introduced a comprehensive numerical method for estimation of disc cutter wear. The results obtained from the numerical method indicated that by passing the critical wear, the disk cutters lose their optimal performance. Their method also showed that confining pressure will increase the wear of the disc cutter. They claimed that by the proposed formulation, the cutter consumption rate can be predicted with a high accuracy. Maleki et al. [36] investigated the impact of rock mechanical properties on the cutting tool wear using a newly developed small-scale Linear Cutting Machine (LCM). In this study, while constructing a small-scale LCM linear cutting device, the impact of tool wear on rock cutting efficiency was investigated, and a comparison was made with V-shaped cutting discs. Chakeri et al. [37] investigated the performance of cutting tools using a novel small-scale Linear Cutting Machine (LCM). The cutting components, including specific energy (SE), cutting coefficient (CC), and disk wear, were analyzed in linear cutting tests. Also, laboratory tests were numerically modeled using the finite element method. Results indicated that Basalt, due to its high porosity, required the highest specific energy, and also, the cutting coefficient increased with penetration depth. Karami et al. [38] simulated the dynamic process of the TBM boring in the jointed rocks using a real-scale numerical analysis based on the rock fracturing factor using the discrete element method (DEM). The numerical results indicated that a higher penetration rate as well as more lifetime for disc cutters can be achieved in highly fractured rocks. Also, the volume of the plastic zone and the actual penetration depth in the highly fracturing rocks measured also about 40% and 42% higher than in the slightly fractured rocks under applying the same TBM parameters, respectively.

In the present study, the three-dimensional particle flow code (PFC3D) is used to simulate the rock cutting process by the disc cutter in three-dimensional form in order to investigate the effect of geometrical parameters of joints on the rock cutting efficiency. For this purpose, first, a reference numerical model is developed and validated by simulation of a linear cutting laboratory test on intact red granite. Then, by adding joints to the validated model, fifteen models were developed including different combination of dip angles of 30°, 60°, 90° with joint spacings of 3, 5, 10, 15, 20 cm. The normal and rolling forces applied to disc cutters and also, the specific energy and cutting coefficient are considered to evaluate the cutting efficiency and the performance of the machine. In this way, more reliable results of rock cutting process efficiency by TBM disc cutter will be obtained. Finally, by using results of this research, it is possible to estimate the performance of the TBM based on the geometric parameters of the joints, which is usually available at low cost in tunnel projects.

In this research, PFC3D software is used because the particle flow code is the best and most suitable method for analyzing the processes that are performed by fragmentation and chipping of the material. It is able to model a brittle solid, by bonding every particle to its neighbor; the resulting assembly can be considered as a “solid” that has elastic properties and is capable of “fracturing” when bonds break in a progressive manner. Moreover, the PFC software is able to model the collapsing impressed by stress changes, simulate the limited joints and model the breakable blocks during the analysis of discontinuous medium. In addition, there is essentially no limitation to the magnitude of displacement that can be modeled. These advantages lead to more realistic results of the rock cutting process by the TBM disc cutter. Also in the present study, the phenomenon of rock cutting in three dimensions has been investigated and therefore does not have the disadvantages mentioned for two-dimensional studies. Also, in this study, considering constant penetration depth, the analysis of the effects of joints on the rolling force and SE (which are the indexes of required torque for excavation by TBM) and normal force and CC (which are the indexes of required thrust for TBM), has distinguished this research from previous one in the field of numerical modeling of cutting process. However, there are some researches which studied the SE and CC and their relationship with cutting efficiency in form of 3D-numerical simulation [39, 40, 41], but the effect of joints on these two factors has usually been neglected.

2. Numerical Modeling of LCM test

In this study, a reference numerical model of linear cutting machine (LCM) test had first to be made. To provide a reference numerical model and its validation, it is necessary to simulate a laboratory test and match numerical modelling with laboratory test results. In this section, a linear cutting test on intact rock was simulated as the reference model. This laboratory LCM test was performed on intact red granite with a disc cutter with 43.2 cm in diameter at the Colorado school of mines [42]. In the next section, using this validated model and joints added to it, the effect of the joint geometrical parameters on the rock cutting process was investigated.

2.1. Calibration of rock properties

When the rock behavior is modeled using particle flow code (PFC), it is necessary to determine the micro properties in order to achieve the laboratory properties of the rock sample. In the particle flow models, there is a significant difference between the mechanical behavior of single particles and a group of particles. The characteristics of red granite are presented in Table 1. The parallel bond model was selected as the contact model in this study. The applied calibration tests including uniaxial and triaxial compression strength tests and Brazilian test are shown in Figure 1. The calibrated micro parameters for particles and parallel contacts, as well as achieved macro properties of rock, are presented in Table 2. The comparison of the stress-strain curve obtained by the PFC numerical simulation and laboratory test, is shown in Figure 2.

2.2. Simulation of rock block

The calculation time in a numerical analysis using PFC strongly depends on the size of the model and the number of constitutive particles of the model. Therefore, the correct choices of dimension and particle radius in the model are of great importance. In this research, block dimensions are selected in a way that the model's particles disturbance in parts far from the cutting position are minimized. In addition, in order to reduce the computation time, the radius of particles is selected in the range of 2 to 6.45 mm. As shown in Figure 3, the trend of increasing the radius of particles (includes 33889 balls) is from top to bottom, so that the disc cutter operates on the location with the smallest particles. The radius of the particles that are in direct contact with the blade is 2~3 mm.

2.3. Simulation of joints

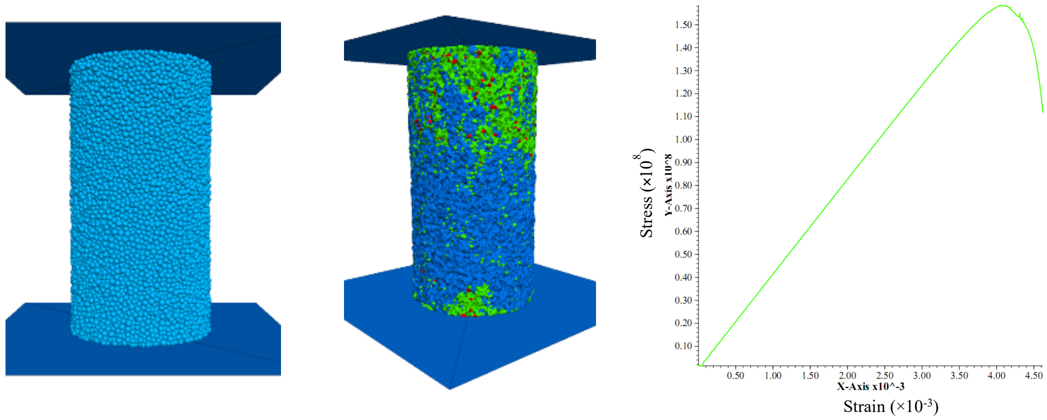
In this study a smooth joint model is used for joints modeling in PFC. The Calibrated micro parameters and achieved macro properties of the joint are presented in Table 3. Calibration of joint properties is performed by simulation of direct shear tests based on trial and error process (Figure 4).

Table 1. Red Granite properties [42]

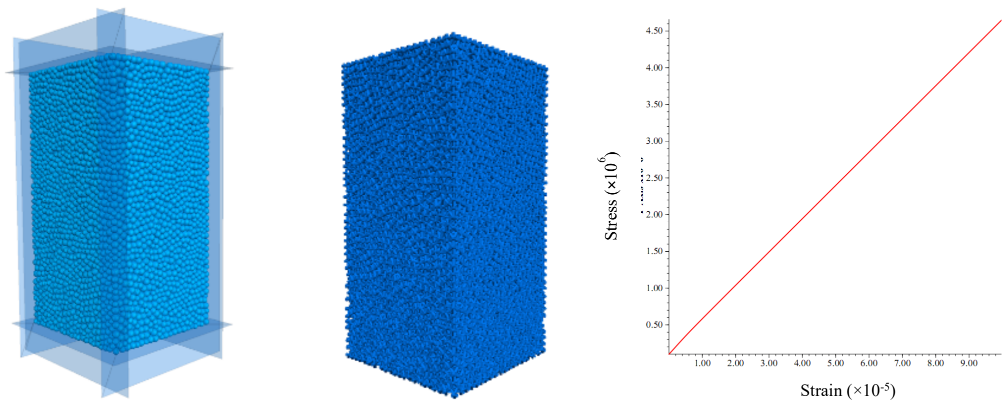
Properties	UCS (MPa)	BTS (MPa)	Young's modulus (GPa)	Poisson ratio	Density (kg/m3)	Porosity (%)
Values	158	6.75	41	0.23	4	

Table 2. Calibrated micro properties and simulated macro properties of rock

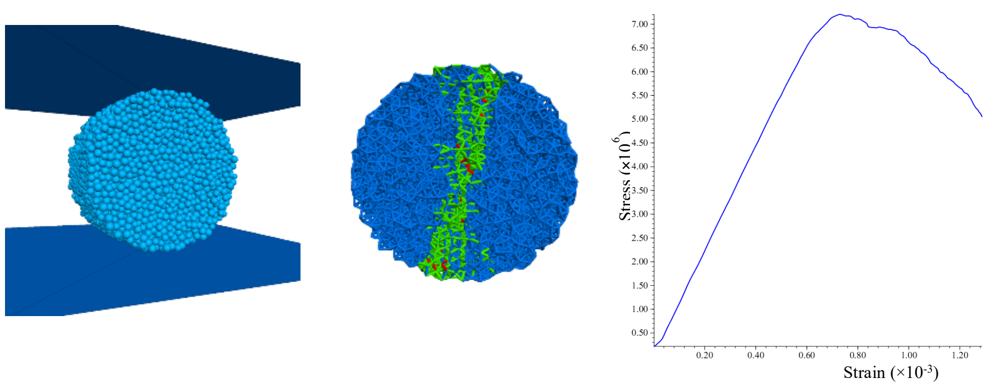
Calibrated micro properties	Notations	Values
Lower bound of particle radius (mm)	R_{min}	2
Ratio of upper bound of particle radius to lower bound of particle radius	R_{max}/R_{min}	1.5
Particle density (kg/m3)	γ	2700
Young's modulus of the particle (GPa)	E_c	30
Ratio of normal stiffness to shear stiffness of the particle	k_n/k_s	7
Friction coefficient of particle	μ	0.58
Young's modulus of the parallel bond (GPa)	$\bar{E}_c$	17
Ratio of normal stiffness to shear stiffness of the parallel bond	$\bar{k}_n/\bar{k}_s$	7
Tensile strength of the parallel bond (MPa)	$\bar{\sigma}_c$	37.5
Cohesion of the parallel bond (MPa)	$\bar{c}$	30
Friction angle of the parallel bond (^{0})	φ	29
Simulated macro properties		
Uniaxial compressive strength (MPa)	σ_c	159
Brazilian tensile strength (MPa)	σ_t	7.2
Young's modulus (GPa)	E	41.4
Poisson ratio	ϑ	0.23



(a) Uniaxial compression strength test



(b) Triaxial compression strength test



(c) Brazilian test

Figure 1. The calibration tests

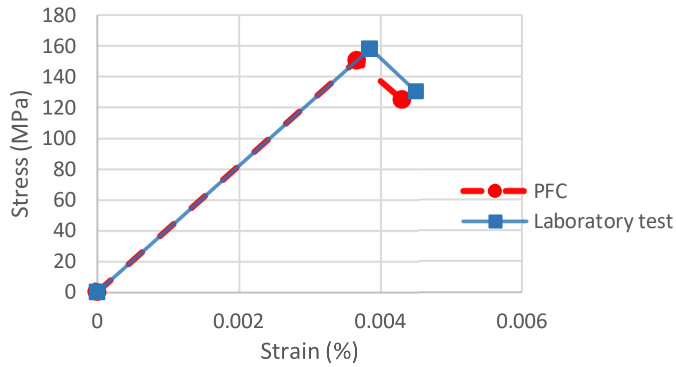


Figure 2. The comparison of the stress-strain curves

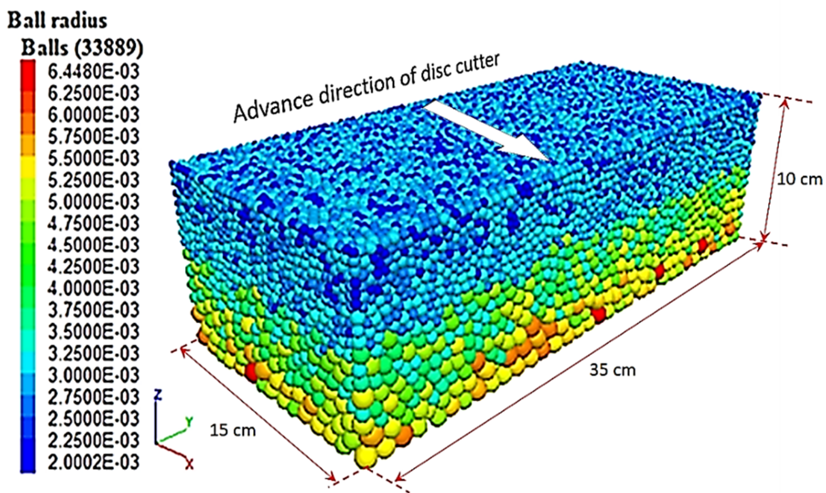


Figure 3. Simulated intact rock block

Table 3. Calibrated micro properties and simulated macro properties of joints

Calibrated micro properties	Notations	Values
Normal stiffness (GPa/m)	k_n	10
Shear stiffness (GPa/m)	k_s	10
Friction coefficient	Fric	0.6
Cohesion (Pa)	c	0
Large		1
Simulated macro properties		
Normal stiffens (GPa/m)	k_n	22.13
Shear stiffness (Ga/m)	k_s	1.61

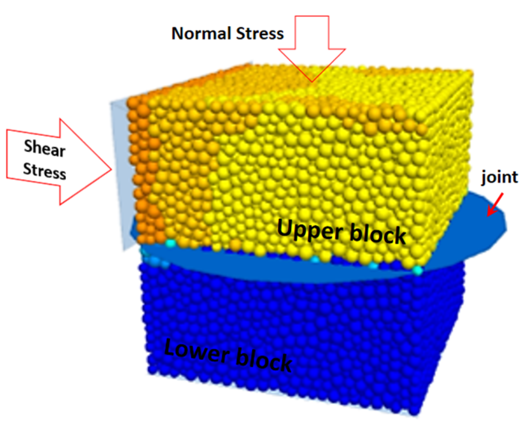


Figure 4. A view of direct shear test modeling

2.4. Simulation of the Disc Cutter

The simulated disc cutter is a constant cross section with 43.2 cm in diameter and 13 mm in the tip width (Figure 5a). In order to simulate the disc cutter, the rigid wall element is used in PFC model, so that the deformation of the cutting tool in this research is neglected. Since not all parts of a disc cutter affect the results, only the ring of the disc (shown in Figure 5b with the red box) were simulated as the disc cutter in order to decrease the model complexity and increase the computational speed. The dimensions of disc cutter are derived from Gertsch et al. (2007).

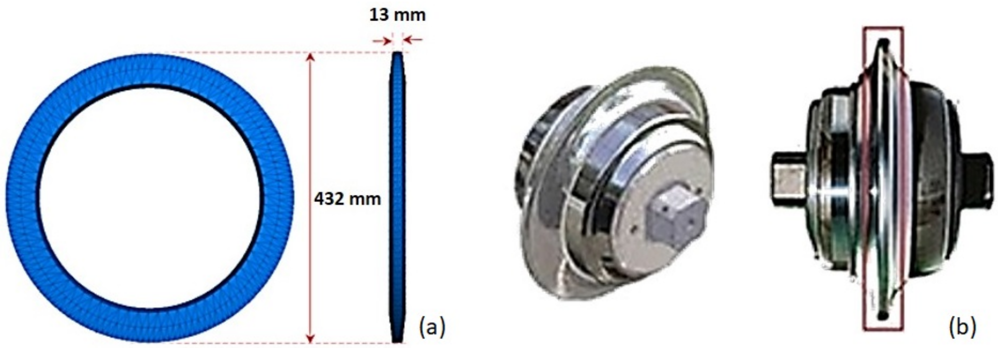


Figure 5. A view of direct shear test modeling

2.5. Validation

In this article, four primary cuts with depths of 5, 6, 7 and 8 mm and eight secondary cuts with the same depth and with 51 and 76 mm spacing relative to the first cutting were created by a disc cutter on the rock sample for validation and in accordance with laboratory tests [42]. For this purpose, the first disc cutter had to make the first cut with a defined penetration depth and then the adjacent one was to be created by the second disc cutter with the same penetration depth and a spacing defined from the first cut. Normal force and rolling force created on the disc in the second cut were considered as the comparative parameters in this study. In the numerical model, the created normal and rolling forces on discs were the produced forces in contacts between particles and discs. The normal force and the rolling force are the results of contact forces in vertical direction and contact forces in horizontal direction, respectively. The first and the second cuts and the direction of the applied normal and rolling forces to the disc are shown in Figure 6. In this figure, blue part is the intact part of the rock after the cutting process (bonded contacts) and red part shows the contacts that are disconnected after passing the disc cutter (unbonded contacts). In this modeling, the overcoming of the tensile force on tensile strength in contacts leads to failure. The rock block is completely fixed from the surrounding and the floor. Also, the disc movement modeling is such that the disc cutter spins with a rotational speed of 1 radians per second around its axis and moves on the rock with a linear speed of 0.02 meter per second in the positive direction of the x-axis.

In Table 4, the mean values of the created forces on the disc cutter and the cutting coefficient (CC) and specific energy in second cuts are presented. These values are related to different penetration depths and spacings in the both states of numerical modeling and linear cutting experimental test. These results are fully illustrated in Figure 7 and Figure 8.

According to these results, there is a good agreement between the numerical modeling and the linear cutting test results, especially in the increasing trend of graphs with increasing penetration depth. However, they are not exactly the same; this difference can be attributed to the simplifications which were made; such as the rigidity of the disc cutter, large radius of the particle and small dimensions of the numerical model compared to the real model. It should be noted that these assumptions are considered concerning time duration and computation considerations. In addition, the natural weakness in the real sample and the absence of such weakness in the numerical model could be another reason for this difference.

Table 4. Results of 2nd Cuts

Penetration depth (mm)	Space between discs (mm)	Numerical Modelling Mean Values				LCT Mean Values [42]			
		Normal Force (KN)	Rolling Force (KN)	CC	SE (MJ/m^3)	Normal Force (KN)	Rolling Force (KN)	CC	SE (MJ/m^3)
5	51	87.7	6.5	0.074	5.21	106.4	11. 4	0.107	6.25
6	51	106.2	7.1	0.065		118	13.4	0.114	
7	51	124.1	8.2	0.066		130	15.7	0.121	
8	51	133.4	9.6	0.072		141	18	0.128	
5	76	109.3	8.4	0.077	5.13	130.6	14.4	0.110	5.78
6	76	128.8	9	0.070		142	17.5	0.123	
7	76	147.4	11.5	0.078		153	20.6	0.135	
8	76	151	12.7	0.084		164	23.8	0.145	

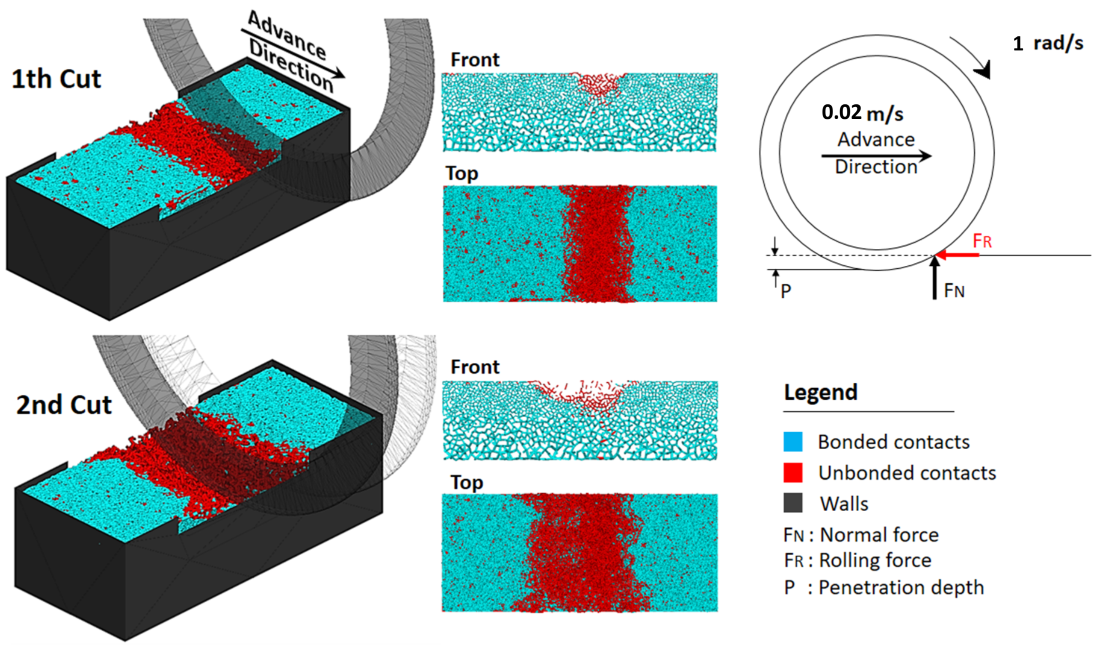
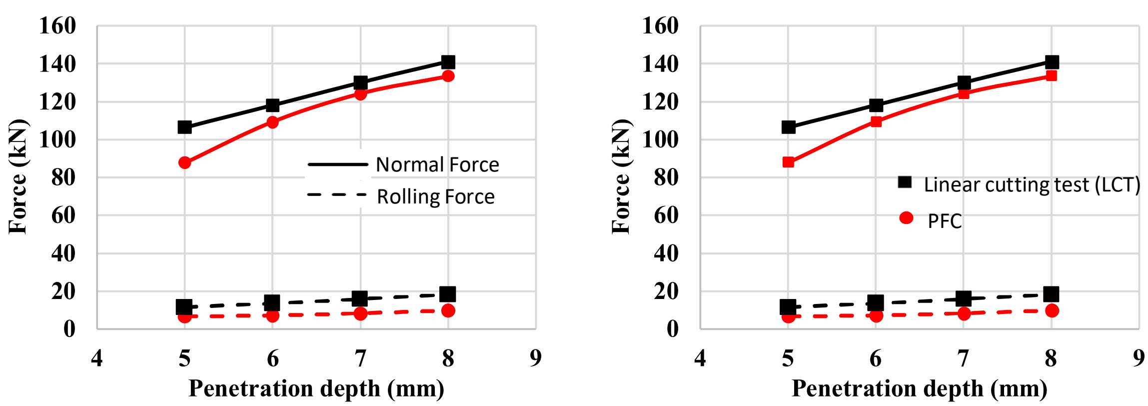


Figure 6. Modeling of the Rock Cutting by disc cutter (1st and 2nd cuts)



(a) Spacing 51 mm **(b) Spacing 76 mm**

Figure 7. Force plots in different penetration depths

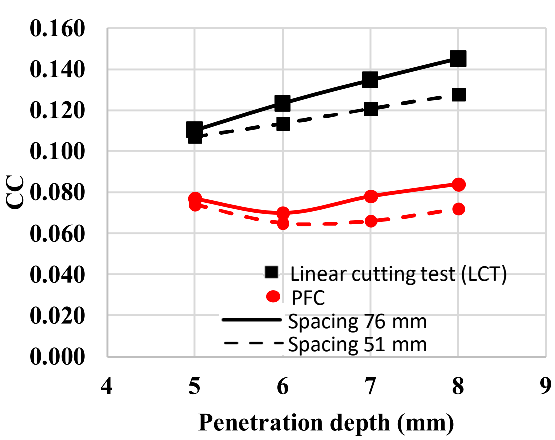


Figure 8. The CC plots in different penetration depths

3. Numerical investigation of the effect of closely joints on cutting efficiency

In regard to the research objectives, as shown in Fig. 9, the footprint dimensions of the simulated rock block increased, but the height did not change. The advance direction of the disc cutter was also considered in the direction of the larger side in order to investigate the effect of joint sets on cutting process. Finally, the rock block for analysis of joints was made with 56742 particles (balls). The boundary conditions including fixed walls are also shown in Fig. 9. The micro properties of the simulated block are as in Table 2. In the following, the effect of joints on cutting efficiency is evaluated from three aspects: Cutter Forces, Specific energy, and Cutting coefficient.

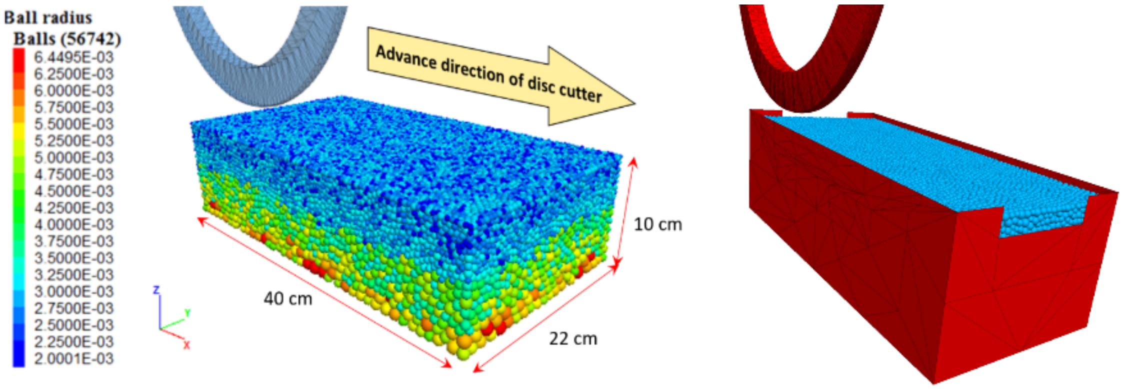


Figure 9. Simulated intact rock block to investigate the effect of joints

3.1. Cutter Forces

In order to compare the rock cutting efficiency in intact and jointed rock modes, before applying joints into simulated intact rock block, a single cut is created on the intact rock sample. According to the results of this single cut, the mean normal and rolling forces values are 128 and 15.2 KN, respectively. The mean normal and rolling forces in each cut with a length of 40 cm are the ratio of the total applied forces to the disc during the cutting process to their number. The plot of the force-displacement for both normal and rolling forces in the intact rock block cutting are presented in Figure 10.

In this research, fifteen models were developed in order to investigate the effects of geometric parameters of the joints, including joint dip and spacing on the cutting process by the disc cutter. In these models, three dip angles of 30°, 60° and 90° with five joint spacing of 3, 5, 10, 15 and 20 cm were modeled and the penetration depth was considered 5 mm for all models. The various geometrical states of the joints for each model are shown in Figure 11. In this figure, in order to observe the condition of the joints, the walls around the block are invisible. As Also, the corresponding force-displacement plots obtained by the cutting process is illustrated in Figure 12. The mean value of the normal and rolling force of each model are given in Table 5. As shown in Figure 12 and Table 5, the forces created on the disc cutter in out-crop of joints are significantly reduced due to the direct impact of the joints on fragmentation and thus, consequently on the cutting tool efficiency.

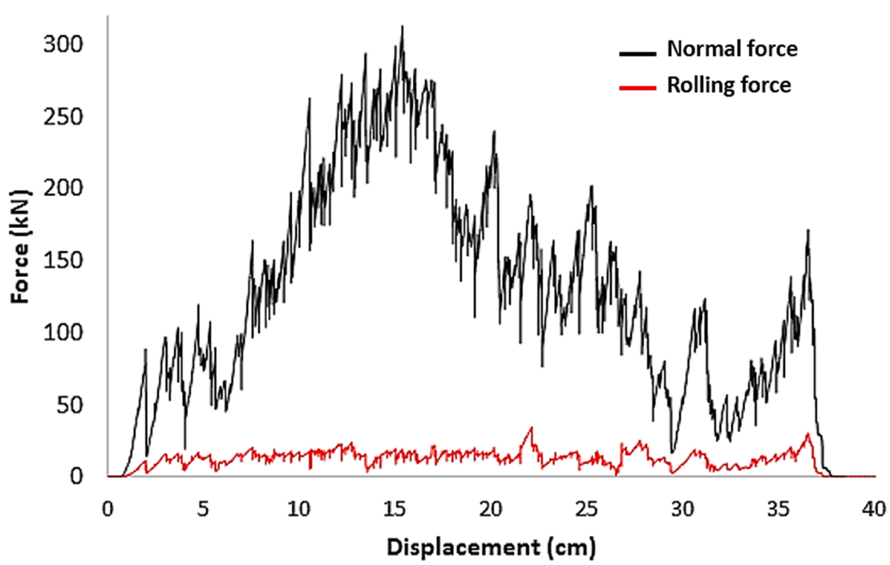


Figure 10. The force-displacement plot of intact rock block cutting

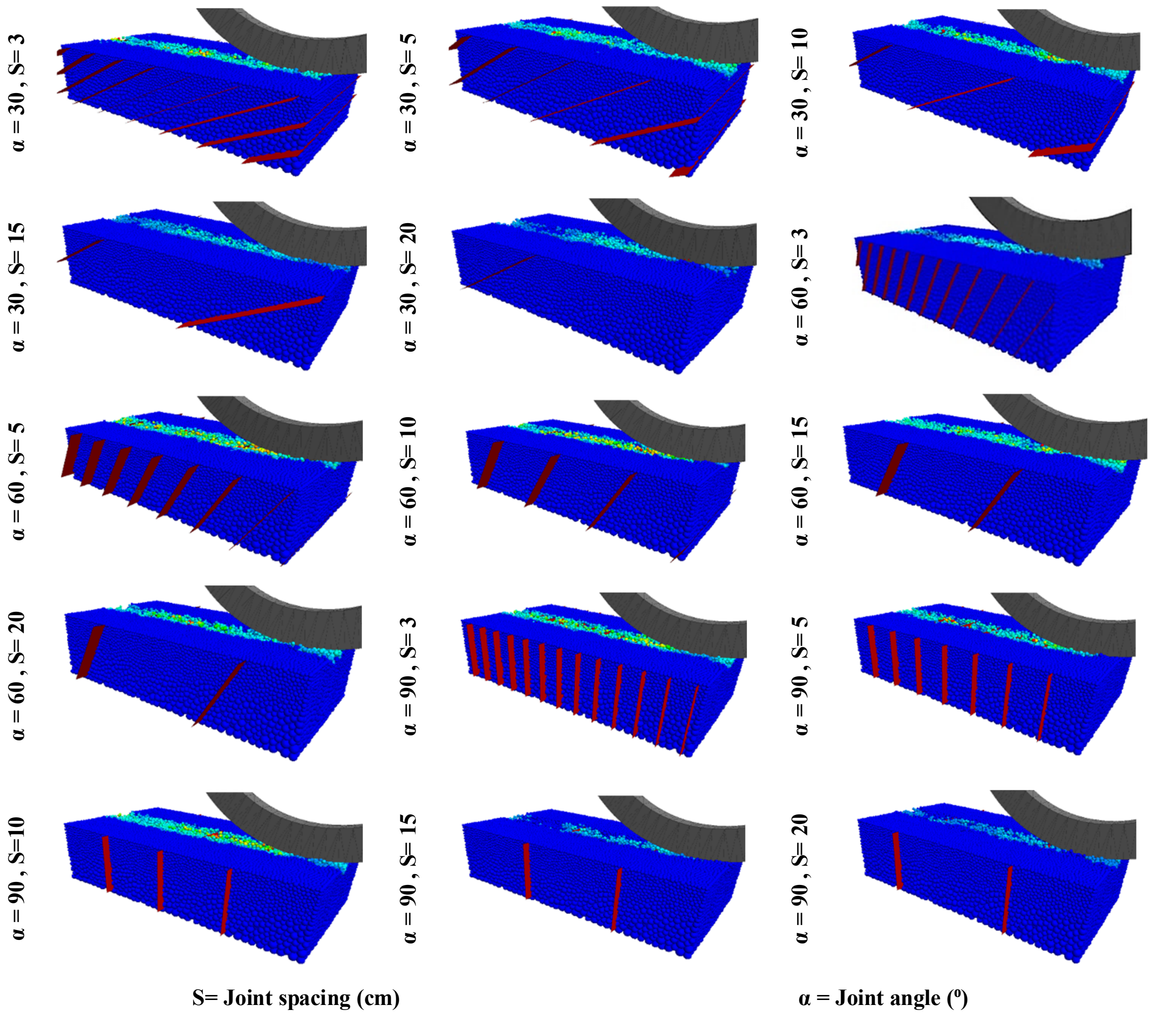


Figure 11. Applied joint in intact rock block with different spacing and angle

Table 5. Results of numerical modelling in different states

α (degree)	S (cm)	Mean Normal Force (KN)	Mean Rolling Force (KN)	Specific Energy (MJ/m3)	cutting coefficient
30	3	61	8.3	6.77	0.136
30	5	62.7	9.5	6.9	0.151
30	10	81	10	7.28	0.123
30	15	100	11.6	8.56	0.116
30	20	110.1	11.6	8.89	0.105
60	3	55.4	6.8	5.99	0.122
60	5	59.8	9	6.97	0.150
60	10	71.8	10.2	7.59	0.142
60	15	76.2	10.4	8.53	0.136
60	20	98.8	12.3	8.6	0.124
90	3	43.3	7	5.89	0.161
90	5	56.3	8.8	6.57	0.156
90	10	89.6	11.3	8.63	0.126
90	15	101.7	12.6	10.13	0.123
90	20	117.4	13.5	10.65	0.114
Intact rock		128	15.2	11.86	0.118

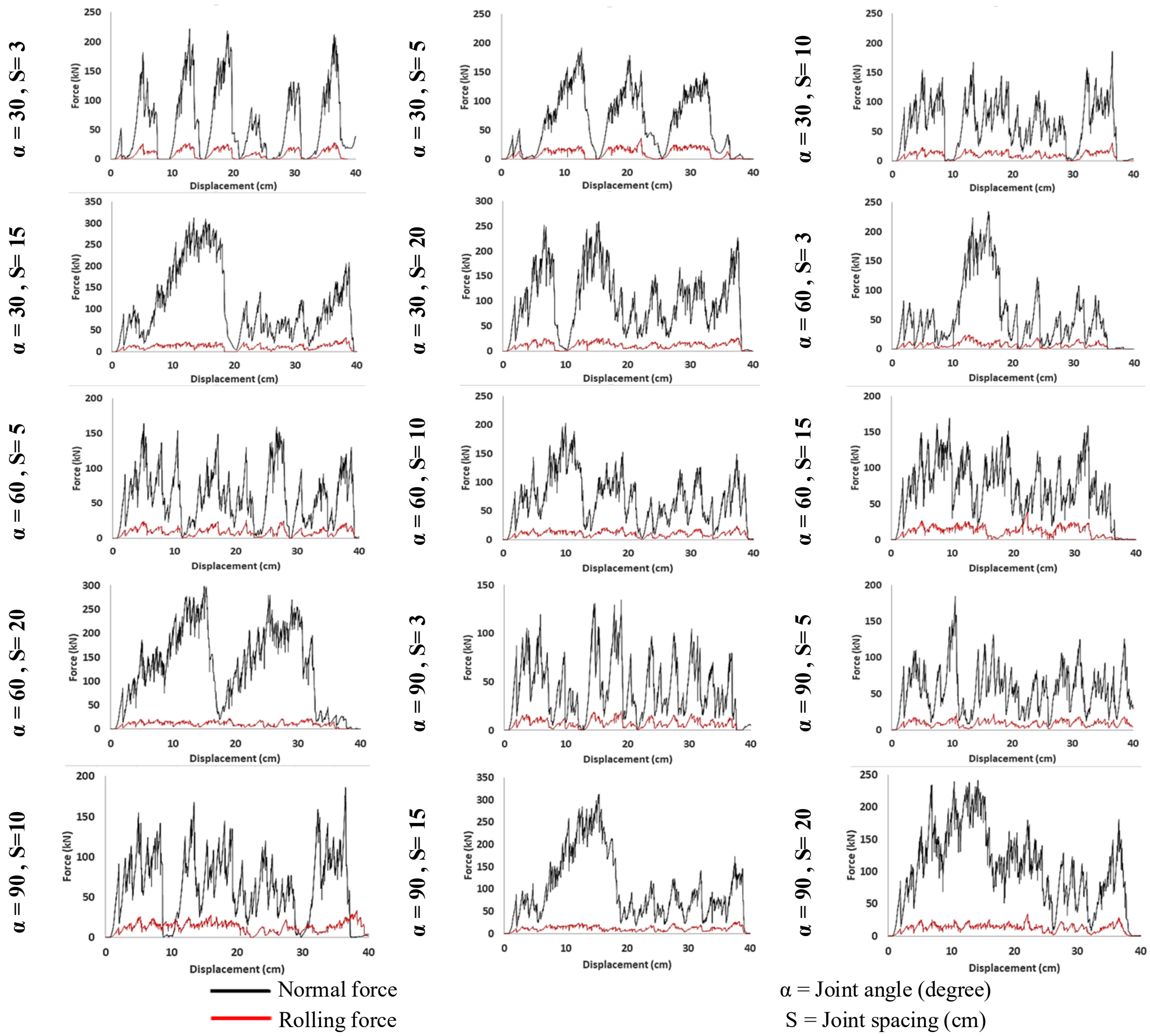


Figure 12. The force- displacement plots of cutting for different states of joint spacing and dip angles

The trend of force changes relative to the variations of joint dip angle and spacing is shown in Figure 13. As shown in this figure, in the spacing values of 3 and 5 cm, the normal force increases with reduction of the joint dip angle and it cannot be seen as a significant change in the rolling force. However, by comparing the force values at different spacing, it can be seen that with increasing the joint spacing values to more than 10 cm, the minimum force is created at the joint dip angle of 60°. Also, at different joint angle, the range of changes of normal force versus joint spacing is longer than rolling force. This means that the normal force parameter must also be considered in estimating the cutting efficiency.

In addition to the created force on the disc cutter, two important parameters were also studied in the field of the cutting efficiency which are named specific energy and cutting coefficient.

3.2. Specific energy (SE)

Specific energy is defined as the amount of energy needed to collapse a certain amount of rock by cutting tools. This parameter is a function of the created rolling force on the disc cutter, which is calculated using equation 1 [43, 44]:

$$SE = \frac{F_r . D}{V} \tag{1}$$

Where are:

SE – specific energy

F_r – rolling force

D – cutting length

V – cutting volume

In the present study, the cutting volume is actually the total volume of particles (balls) that are disconnected from other particles and separated from the rock block during cutting process. For calculating the cutting volume, the volume of one disconnected particle is multiplied to the number of separated particles. The particle is separated when the contact bond assigned between particles reaches zero. The rolling force also is the mean rolling force of each model due to the cutting process. As an example, the calculation of SE for mean rolling force of 8.3 kN has been presented below.

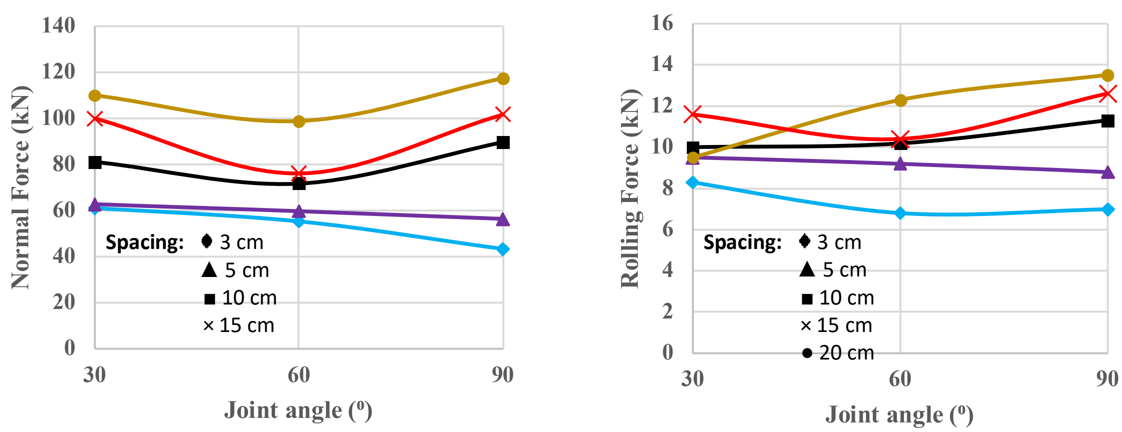
$F_r = 8.3\ kN\ ,\qquad D = 40\ cm\ ,\qquad V = n \times (4\,\pi\, r^3)/3\ ,$

r = mean radius of disconnected particles: 2.5 mm

n = the number of separated particles

$$SE = \frac{8.3*0.4}{7488\times(4\,\pi\,0.0025^3)/3} = 6774 \text{ KJ/m3} = 6.77 \text{ MJ/m3}$$

Specific energy values for different models are presented in Table 5 and the correlation of this parameter with different joint states can be seen in Figure 14. According to this figure, the specific energy for cutting the rock block is increased by increasing the joint spacing. This relationship applies for all the three angles of 30°, 60° and 90°. It should be noted that the slope of variations for the joint dip angle of 90° is much more than the two other dip angles, so that in the spacing of 20 cm, the value of the specific energy is very close to the value of specific energy in intact rock cutting (11.86 MJ / m^3). Accordingly, it can be stated that joints with a vertical dip angle have the greatest impact on the rolling forces applied to the disc and specific energy, resulting in a decrease in the cutting efficiency.



(a) Normal force (b) Rolling force

Figure 13. Relation of the created forces with different joint dip angles and spacing

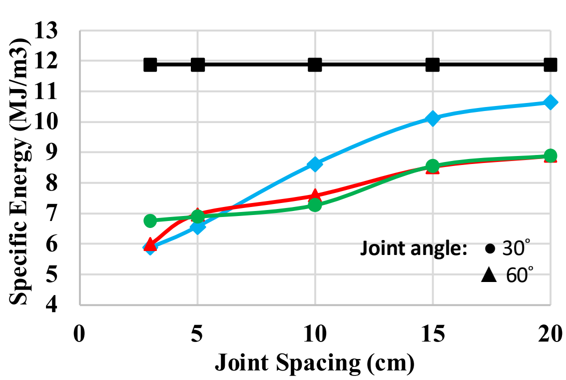


Figure 14. Correlation of the specific energy with different joint spacing and dip angle

3.3. Cutting coefficient (CC)

Cutting coefficient is the ratio of rolling to normal forces. It is used to determine the torque requirements for mechanical excavation [45]. The change of CC with different joint states are presented in Table 5 and Figure 15. As it can be seen from the figure, there is a nonlinear relationship between CC and joint spacing with different joint angles. According to this figure, for joint spacing higher than 5 cm, the cutting coefficient is decreased by increasing the joint spacing and for lower than 5 cm, it is the vice versa. In addition, at close joint spacing, the values of the cutting coefficient are higher than those of intact rock, and with increasing distance between the joints, the cutting coefficient values approach the value of the cutting coefficient of intact rock. At open joint spacing (higher than 20 cm), the values of the CC are lower than those of intact rock. Also, in the spacing range higher than 5 cm, the maximum CC is for 60° joint angle. For joint spacing of more than 5 cm, since the role of normal force on CC changes is greater (Due to more changes in normal force than rolling force as shown in Figure 13), it can be said that the maximum CC at a joint angle of 60 degrees is due to the rate of further reduction of required normal force for fragmentation. As shown in Figure 15, at angles of 30 and 60 degrees, the CC is first increased and then decreased by the increasing of the joint spacing. This is because, by increasing the joint spacing from 3 to 5 cm, the amount of rolling force increase is more than normal force. In other words, for joint angles of 30 and 60 degrees, at joint spacing less than 5 cm, with increasing joint spacing, the rate of increasing of the rolling force is higher than the normal force. Conversely, at joint spacing of more than 5 cm, with increasing joint spacing, the rate of increasing of the normal force is higher than the rolling force. At a 90° joint angle, with increasing joint spacing, the rate of increase of the normal force is higher than the rolling force.

4. Discussion

By comparing the effect of spacing and joint dip angle on the cutting efficiency, it is revealed that the joint spacing has a greater effect on the normal and rolling force. It is evident that increasing the spacing between the joints led to raise the normal and rolling force which means the more joint spacing increases, the higher amounts of torque and thrust is required for excavation practically. This matter was also reported by many researchers such as field studies [1, 3-6, 46] and numerical simulation of cutting process in jointed rock [18, 20, 44, 47]. Moreover, when the spacing is lower than 10 cm, the optimum joint angle for efficient cutting is 90° while for the spacing higher than 10, the best joint angle is 60°. This claim is in parallel with previous studies that had a detailed analysis on joint orientation [17, 20, 47]. Furthermore, due to the large variation of the forces at the joint angle of 90°, it can be concluded that the joint spacing at this joint dip angle is especially important.

It should be noted that when the rolling force parameter is examined alone, the effect of different jointing scenarios on this parameter is not noticeable, while by examining the specific energy, this change is quite obvious. According to the SE diagram, at a joint spacing of more than 10 cm, the maximum torque required for drilling is when the joint angle is 90 degrees. Also, according to the CC changes in different joint spacing, it can be said that in the tunnel excavation process, with increasing joint spacing, the TBM machine thrust is more important than its torque.

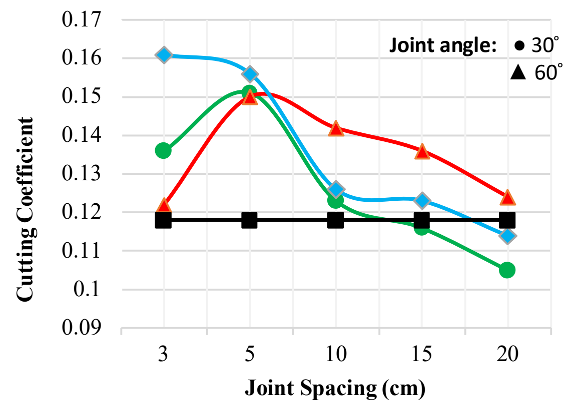


Figure 15. Correlation of the cutting coefficient with different joint spacing and dip angle

At low joint spacing, the role of the joint angle is reduced and the distances between the joints control the efficiency. As the joint spacing increases, the maximum CC and the minimum required force (or maximum efficiency) occur at the 60° joint angle. From these two results, it can be seen that the greater part of the force reduction (consequently, increasing efficiency) in the 60° joint angle is related to the normal force.

Maximum efficiency at 60° joint angle can be considered due to the role of joints in promoting the initiation and propagation of cracks in the granitic rock. This can depend on the mechanical properties of the rock, including strength, modulus and type of rock. Other types of rocks with different mechanical properties need to be examined in order to arrive at a general rule.

5. Conclusions

In this study, the effect of joint dip angle and spacing on rock cutting was investigated using numerical modeling in three dimensions by PFC software. For this purpose, joints with dip angles of 30°, 60° and 90° and spacing of 3, 5, 10, 15 and 20 cm were investigated. The rolling force and SE (which are the indexes of required torque for excavation by TBM) and normal force and CC (which are the indexes of required thrust for TBM), in combination with penetration depth are considered as criteria to evaluate the cutting efficiency of the machine. The numerical model has been validated by results of the laboratory test that was performed on intact red granite at the Colorado school of mines. Results show that the joint spacing has a greater effect on rock cutting efficiency than joint orientation. Also, by increasing the spacing between the joints, the rolling and normal forces applied to the disc cutter increase. This indicates a reduction in the cutting efficiency by increasing the joint spacing. The best disc cutter efficiency and the minimum required normal force is achieved when joint spacing is more than 10 cm and the angle between the joints and advance direction of the disc cutter is 60 degrees. This result is consistent with previous studies. The normal force plays a major role in the increase in efficiency at the 60 degrees joint angle. When the joints are close together and have a spacing of less than 10 cm, particularly 3 to 5 cm, the best cutting efficiency can be achieved for a joint angle of 90 degrees. The cutting coefficient is decreased by increasing the joint spacing and the maximum CC occurs at a joint spacing of 5 cm. By increasing the joint spacing, for all joint angles, the specific energy required for cutting the rock block is increased. For joint spacing more than 10 cm, the joints with a 90 degrees dip angle have the greatest impact on the specific energy and reduce cutting efficiency. According to the cutting coefficient study, the values of the cutting coefficient are higher than those of intact rock when the joint spacing is less than 15 cm. Also, at joint spacing less than 5 cm, the rolling force plays the main role in the cutting process, and at joint spacing of more than 5 cm, the normal force plays the main role. Consequently, it can be concluded that in the tunnel excavation process, with increasing joint spacing, the TBM machine thrust is more important than its torque. These findings provide a better understanding of the effect of joints on TBM performance and provide basis for improving the TBM cutting efficiency through jointed rock masses. This study focuses on granitic rock. To accurately understand the role of joints on the efficiency of disc cutter and its relationship with the mechanical properties of the rock, future research should investigate other rock types with different mechanical properties. This can be achieved through both numerical simulations and laboratory experiments.

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ارزیابی کارایی برش سنگ توسط دیسک‌های برش‌دهنده TBM در توده سنگ‌هایی با درزه‌های نزدیک به هم

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کلمات کلیدی

مدل‌سازی عددی
دیسک برش‌دهنده TBM
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چکیده

در این تحقیق، تاثیر پارامترهای هندسی درزه‌های نزدیک به هم بر راندمان برش سنگ توسط دیسک‌های برش‌دهنده TBM با استفاده از نرم‌افزار PFC3D بررسی شده است. یک مدل عددی اعتبارسنجی شده از آزمایش دستگاه برش خطی (LCM)، توسعه داده شده و راندمان دیسک‌های برش‌دهنده بر روی نمونه‌های توده سنگ با پیکربندی‌های مختلف درزه (ترکیب احتمالی زوایای شیب ۳۰، ۶۰، ۹۰ درجه با فاصله‌داری درزه ۳، ۵، ۱۰، ۱۵، ۲۰ سانتی‌متر) بررسی شده است. نتایج مدل‌سازی عددی نشان می‌دهد که به طور کلی، فاصله درزه‌ها تاثیر بیشتری بر راندمان برش سنگ نسبت به جهت درزه‌ها دارد. اگر فاصله درزه‌ها کمتر از ۱۰ سانتی‌متر باشد، نقش زاویه درزه کاهش می‌یابد و فواصل بین درزه‌ها، راندمان را کنترل می‌کنند. هنگامی که درزه‌ها نزدیک به هم هستند و فاصله‌ای کمتر از ۱۰ سانتی‌متر (به ویژه ۳ تا ۵ سانتی‌متر) دارند، بهترین راندمان برش را می‌توان برای زاویه درزه ۹۰ درجه به دست آورد. ضریب برش با افزایش فاصله درزه‌ها کاهش می‌یابد و حداکثر CC در فاصله درزه ۵ سانتی‌متر رخ می‌دهد. برای فاصله‌داری درزه بیش از ۱۰ سانتی‌متر، درزه‌های با زاویه شیب ۹۰ درجه بیشترین تاثیر را بر انرژی ویژه دارند و راندمان برش را کاهش می‌دهند. بهترین راندمان دیسک برش‌دهنده و حداقل نیروی عمودی مورد نیاز زمانی حاصل می‌شود که فاصله درزه‌ها بیش از ۱۰ سانتی‌متر و زاویه بین درزه‌ها و جهت پیشروی دیسک ۶۰ درجه باشد. در فرآیند حفاری تونل، با افزایش فاصله درزه‌ها، نیروی رانش دستگاه TBM از گشتاور آن مهم‌تر است. یافته‌های این تحقیق مبنایی برای پیش‌بینی راندمان TBM از طریق ویژگی‌های درزه‌ها فراهم می‌کند.

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