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Real-Scale Numerical Analyzing Dynamic Process of TBM Boring in Jointed Rock; a Case Study: Kerman Water Conveyance Tunnel in Iran

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Abstract

One of the important cost items in mechanized tunneling is the cost of repairing or replacing the disc cutters that have suffered from normal wear during the boring of the hard abrasive rocks. For inspecting the health of the disc cutters, the boring operation shall be stopped, and after checking, the worn disc cutters may be replaced. In this work, the dynamic process of the TBM boring in the jointed rocks is simulated using a real-scale numerical analysis based on the rock fracturing factor using the discrete element method (DEM). The stress distributions induced within the disc cutters as well as the development of the plastic zones in the rock are investigated and compared with the actual results recorded in the Kerman water conveyance tunnel (KWCT). The numerical results indicate that the increase in the rock fracturing causes a decrease in the induced stresses and an increase in the size of the plastic zone. In other words, a higher penetration rate as well as more lifetime for disc cutters can be achieved in highly fractured rocks. Moreover, the average von Misses stress in the disc cutters in the highly fractured rocks is predicted about 16-23% less than stress induced in the slightly fractured rocks. Due to the TBM tunneling, the volume of the plastic zone as well as the actual penetration depth in the highly fracturing rocks are also about 40% and 42% higher than in the slightly fractured rocks under applying the same TBM parameters, respectively.

1. Introduction

Mechanized tunneling using a hard rock TBM is one of the fastest and safest methods for excavating long tunnels across medium- to high-strength rocks. This method can be successful if the TBM type and specifications are selected based on the project's geology and hydrogeology. The machine's cutter-head is a component of the TBM that transmits the thrust and torque from the machine's power system to the tunnel face, while the disc cutters are the parts that contact the face for crushing the rock. The process of transmitting TBM power to the rock is impacted by the wear of disc cutters, which is controlled by continuous and dynamic contact between the disc cutters and the tunnel, as well as the abrasive properties of the rocks [1, 2].

Disc cutters wear out during the excavation of the tunnel and their diameter decreases, while by increasing in the tip width of the disc cutter (i.e. bluntness), the stress applied by the TBM to the rock will be reduced due to increasing the contact area. Therefore, the required energy for crushing the specified volume of the rock (i.e. specific energy) will be increased and the machine efficiency drops. In addition, the additional wear of the cutter-head and the structural damage to the TBM cutter-head can occur by not replacing the worn disc cutters on time and simultaneously use of the new, partially worn, and completely worn disc cutters on the TBM cutter-head [3]. This problem may cause serious damage to the cutter-head, and in critical conditions, even may lead to the project's long-term delay due to repairing the cutter-head's hard facing and support structures. According to the recent studies, the cost of the disc cutter replacement can be as high as 10% of the total cost of the TBM tunneling. Moreover, the disc cutters' repairs and replacements can take

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approximately 30-40% of the total time of the tunnel construction in certain projects where extremely hard and abrasive rocks are encountered [4].

During the TBM tunneling, the disc cutters will reach the replacement's threshold due to two main reasons: normal and abnormal wear. In mechanized hard rock tunneling, the disc cutter is the main cutting tool that is subjected to normal wear (or abrasion) as the most common type of tool wear. This type of wear includes the highest percentage of the total wear or replacement of the disc cutters [5]. For example, by studying the data of 871 disc cutters during 1592 meters of tunneling in 2020, Su *et al*. have found out that approximately 87% of the disc cutters are replaced due to normal wear, and the others have are due to abnormal wear [6]. Therefore, it is important to identify the conditions affecting the wear of the disc cutters, and to determine and apply the proper machine parameters including thrust force, torque, penetration rate, RPM, and so on to minimize the normal wear of the disc cutters. In addition, regular and frequent inspections of the cutter-head at the right times, continuous recording of the wear status of the disc cutters along the tunnel route, and in-time replacement of the worn disc cutters can prevent the drop in the boring efficiency. The abnormal wear category is somewhat random, and it has to do with the quality of disc cutters, condition and quality of bearings, maintenance and proper upkeep of the disc bearings, and in some cases, the geology, especially in very hard and strong rocks where highest thrust levels are used.

In this work, the available data in the Kerman water conveyance tunnel (KWCT) project in Iran is used to examine the effects of rock mass fracturing on the wear of the TBM disc cutters. The study includes the numerical analysis using the discrete element method to analyze the impact of the geological conditions on normal wear of the disc cutters through examination of the induced stresses in the disc cutter. In particular, the study evaluates the impact of rock mass fracturing and specifically the spacing of the joint sets and their orientation relative to the TBM advancing direction on the wear process. Furthermore, two assumptions used in this study include; the wear of TBM disc cutters is related to their induced von Mises stresses, and the fragmentation of the rock mass is proportional to the volume of the plastic zone developed in the tunnel face during the cutting process as determined by the numerical analysis.

The main innovation in this work is the application of the numerical method to simulate the TBM boring in the jointed rocks dynamically. The rotation, revolution as well as penetration of the disc cutters, and cutter-head have been considered in this modelling. Moreover, the phenomenon of the disc cutter's wear has innovatively related to the von misses stress. According to the numerical results as well as comparison with the actual data, the von Misses stresses are the proper representative for studying the disc cutters' wear. Furthermore, the rock mass fracturing factor, for the first time, has been considered in the numerical simulations.

2. Effective properties of rock mass on wear of disc Cutter

Cracks, fractures, joints, and faults are considered as the main discontinuities in rock mass that decrease the strength of intact rock. The discontinuities may change the behavior of the rock under the stress field and static and dynamic forces. The characteristics of the joints in the rock mass affect the TBM performance directly and the life (or wear) of disc cutters indirectly. In the highly jointed rocks, the penetration rate is higher than in the intact rocks by applying a constant load, and the disc cutters are able to crush a larger volume of the rock under a certain thrust and torque. Therefore, one of the important factors that shall be considered for determining the life of the disc cutter is the joint properties in the rock mass [7]. Figure 1 briefly describes the characteristics of the discontinuities within the rock mass [8].

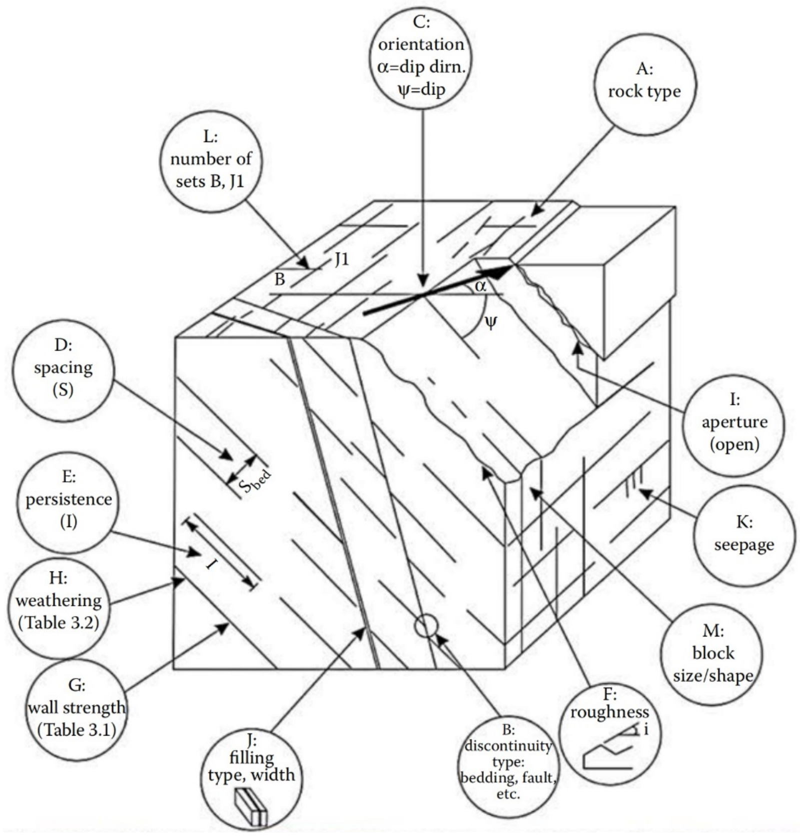


Figure 1. Characteristics of discontinuities within rock mass [8].

In this work, the concept of rock fracturing has been used to investigate the effect of the joints on the disc cutter's wear as well as on the rock's excavation during the TBM tunneling. In 1998, Bruland introduced the factor k_s to define rock fracturing based on the spacing of the discontinuity (i.e. joints or fissures) as well as the orientation of the discontinuity relative to the tunnel axis [9], which was recently modified by Macias *et al*. [10]. In order to calculate the value of k_s, the fracture class shall be firstly determined based on the average spacing of the joints or cracks from Table 1. Then the strike angle of the plane of weakness (α_s), the dip angle of the plane of weakness (α_f), and the azimuth of the tunnel axis (α_t) are used to calculate the alpha angle (α) based on Eq. (1). Using α and fracture class, the k_s can be estimated according to the chart presented in Figure 2. Finally, for all joint sets in a rock mass, $k_{s\text{-}tot}$ can be calculated as a total factor using Eq. (2) and k_s values of each joint set.

The main advantage of using the $k_{s\text{-}tot}$ is that the qualitative classification of rock mass fracturing changes to a quantitative classification based on tunneling direction. the factor $k_{s\text{-}tot}$ is currently used by many researchers and engineers as a parameter to represent the fracturing degree of the rock mass.

$$\alpha = \left|\arcsin(\sin\alpha_f \,.\sin(\alpha_t - \alpha_s))\right| \quad (1)$$

$$k_{s-tot} = \left(\sum_{i=1}^{n} k_{si}\right) - (n-1)\times 0.36 \quad (2)$$

where,

α_s: the strike angle of the plane of weakness,

α_f: the dip angle of the plane of weakness,

α_t: the azimuth of the tunnel axis

n: the number of the joint sets

k_{si}: the rock fracturing factor for i^{th} joint set

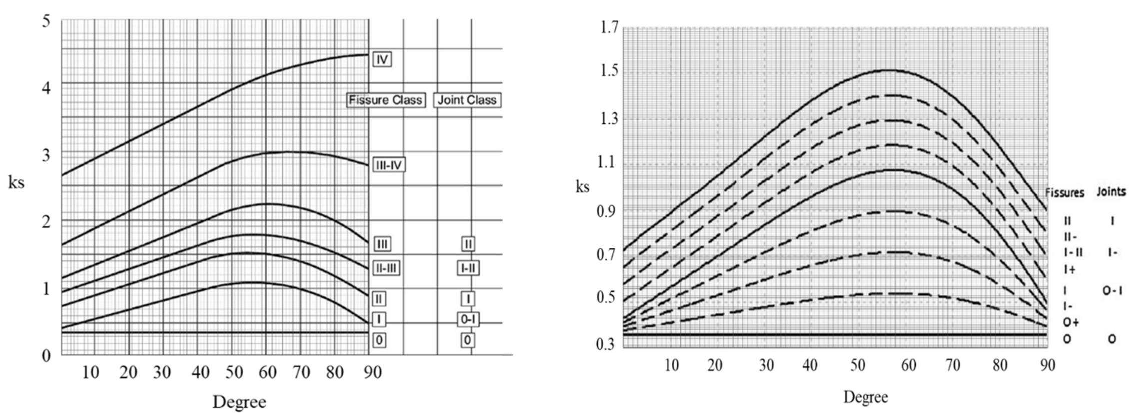
$k_{s\text{-}tot}$: Total rock fracturing for rock mass

The main advantage of using the $k_{s\text{-}tot}$ is that the qualitative classification of rock mass fracturing changes to a quantitative classification based on the tunneling direction. The factor $k_{s\text{-}tot}$ is currently used by many researchers and engineers as a parameter to represent the fracturing degree of the rock mass.

Many researchers have studied the effect of the rock mass properties on the wear phenomenon of the TBM disc cutters [11-18]. Briefly, strength properties, rock abrasivity, tensile strength as well as rock competency have a negative effect on disc cutter life. On the other hand, some weakness structures like joints can decrease the wear of the disc cutters during the tunnel boring. As a recent research work, Karami *et al*. (2021) have used the actual data from hard rock TBM tunneling, and presented an empirical model for predicting the life of TBM disc cutters in jointed rocks. The offered relationship includes the fracturing parameter due to the joint sets, Cerchar abrasivity index, and uniaxial compressive strength of rock, which is an acceptable prediction model in the jointed rocks [7]. It shall be mentioned that the influence of rock fracturing was considered as an input parameter in the wear prediction model of the TBM disc cutters by the authors [7], while such a parameter had not been included in the previous models. In the current study, the authors attempt to show the influence of this important factor on the wear of the disc cutters as well as on the boring mechanism.

Table 1. Fracture class as defined by spacing between planes of weakness [7].

Fracture class (joints/fissures)	Average spacing between planes of weakness a_f (cm)	Range of spacing (cm)	Discription
0 0+	∞ 190	240-∞ 160-240	Massive rock interval with few joints or fissures. Seldom found in complexly deformed terranes except for granoblastic metamorphic rocks and equiangular, cross-cutting igneous rocks. Fracture spacing must be greater than 160 cm.
0-I	140	110-160	Massive rock interval with fracture spacing of 110-160 cm
I-	90	60-110	Relatively massive rock interval with fracture spacing of 60-110 cm
I I+ I-II II-	40 35 30 25	37.5-60 32.5-37.5 27.5-32.5 22.5-27.5	Fractured rock
II	20	17.5-22.5	Well-fractured rock mass
II-III	15	12.5-17.5	
III	10	8.75-12.5	Highly fractured rock mass
III-IV	7.5	6.25-8.75	
IV	5	4-6.25	Highly brecciated with closely spaced anastomosing fractures completelt associated with zones of stress relief, fault breccia, and fault gouge.

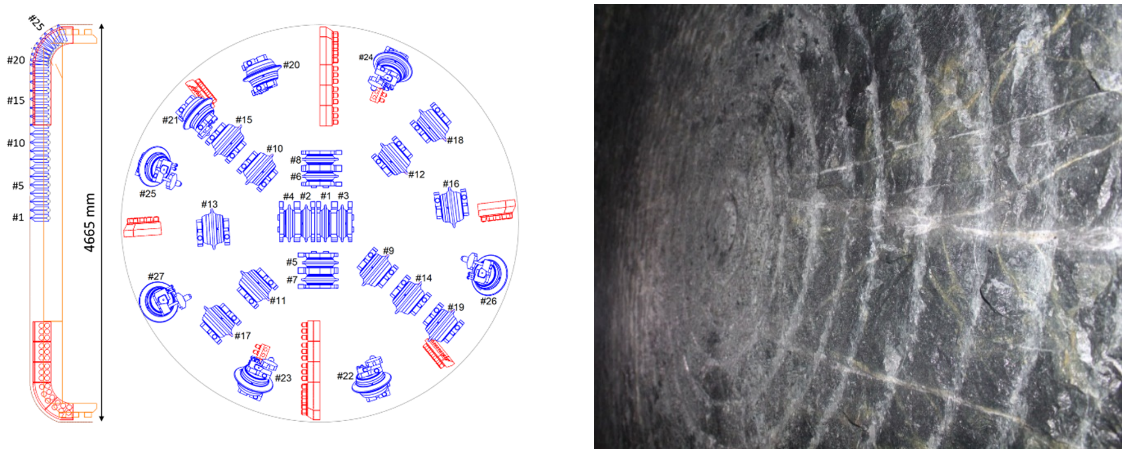


(a) (b)

Figure 2. (a) Calculation of fracturing factor (k_s) based on angle between tunnel axis and plane of weakness and fracture class [9]; (b) Interpolated curves for low fracture classes (i.e. joints: 0-I, and fissures: 0-II) [10].

3. Kerman water conveyance tunnel (KWCT) project

The KWCT project is 38-km-long, and extends from Safa Dam to the city of Kerman. The tunnel is divided into two equal northern and southern lots. The finished diameter of the tunnel is 4.5 m. The vertical alignment of the tunnel in the southern lot shows a +0.06% grade. The northern lot is 3.9 m in finished diameter, and has a length of about 18.8 km and a gradient of -0.135%. The main application of the tunnel is to convey the water to the city of Kerman. These two lots are under construction using two double shields (DS) TBMs made by Herrenknecht. Figure 3 shows the schematic drawing of the TBM cutter-head used for boring the northern lot as well as the tunnel jointed face. The main specifications of the TBM used in the KWCT project are presented in Table 2. So far, about 11 km of the northern lot has been bored, and 10 different stratigraphic units have been identified. The geological profile of the north tunnel is shown in Figure 4. Also a brief description of rock formations along the tunnel and their geotechnical properties are presented in Table 3 [7].



(a) (b)

Figure 3. (a) Schematic drawing of TBM cutter-head used for boring northern lot of KWCT project; (b) Disc trajectories on tunnel face in KWCT project [7].

Table 2. Main specifications of DS TBM used in northern lot of KWCT project [7].

Parameter	Value
Cutter-head diameter	4665 mm
Number of cutters	27
Total thrust of cutter-head	16913 kN
Thrust cylinder stroke	1500 mm
Normal torque of cutter-head	1,030 kNm (at 11.01 rpm)
Maximum cutter-head rotation speed	11 rpm
Discs No./diameter	
Center	1 to 8/432 mm
Face	9 to 19/483 mm
Pre-Gage	20 to 25/483 mm
Gage	26 & 27/483 mm

Table 3. Description of rock units along initial 11 km of KWCT project [7].

Engineering Geology Units	Dominant lithology	Length (m)	Max. Overburden (m)	Average Percent of Minerals				UCS (MPa)	CAI (10^{-1} mm)
				Qz	Fd	Cal. & Sec. Min.	Others		
RT1	Andesite	1700	290	30	20	0	50	160	3.5-4.5
RT2	Basalt	560	200	25	50	5	20	130	3-4
RT3	Andesitic basalt	2785	250	10	80	5	5	180	3.5-5
RT4	Diabase	940	395	15	25	5	45	90	1.5-2
RT5	Dacite	70	300	5	70	0	25	180	3.5-4
RT6	Flysch	2540	400	10	0	85	5	130	<1.5
RT7	Sandstone	1365	315	45	10	25	0	70	1.5
RT8	Sandstone/Andesite	560	360	30	30	20	15	155	2.5
RT9	Limestone	470	350	0	0	100	0	150	1.5

Qz: Quartz, Fd: Feldspar, Others: Other abrasive minerals (with a hardness of more than 4 mohs), Cal. & Sec. Min.: Calcite and secondary minerals, CAI: Cerchar abrasivity index.

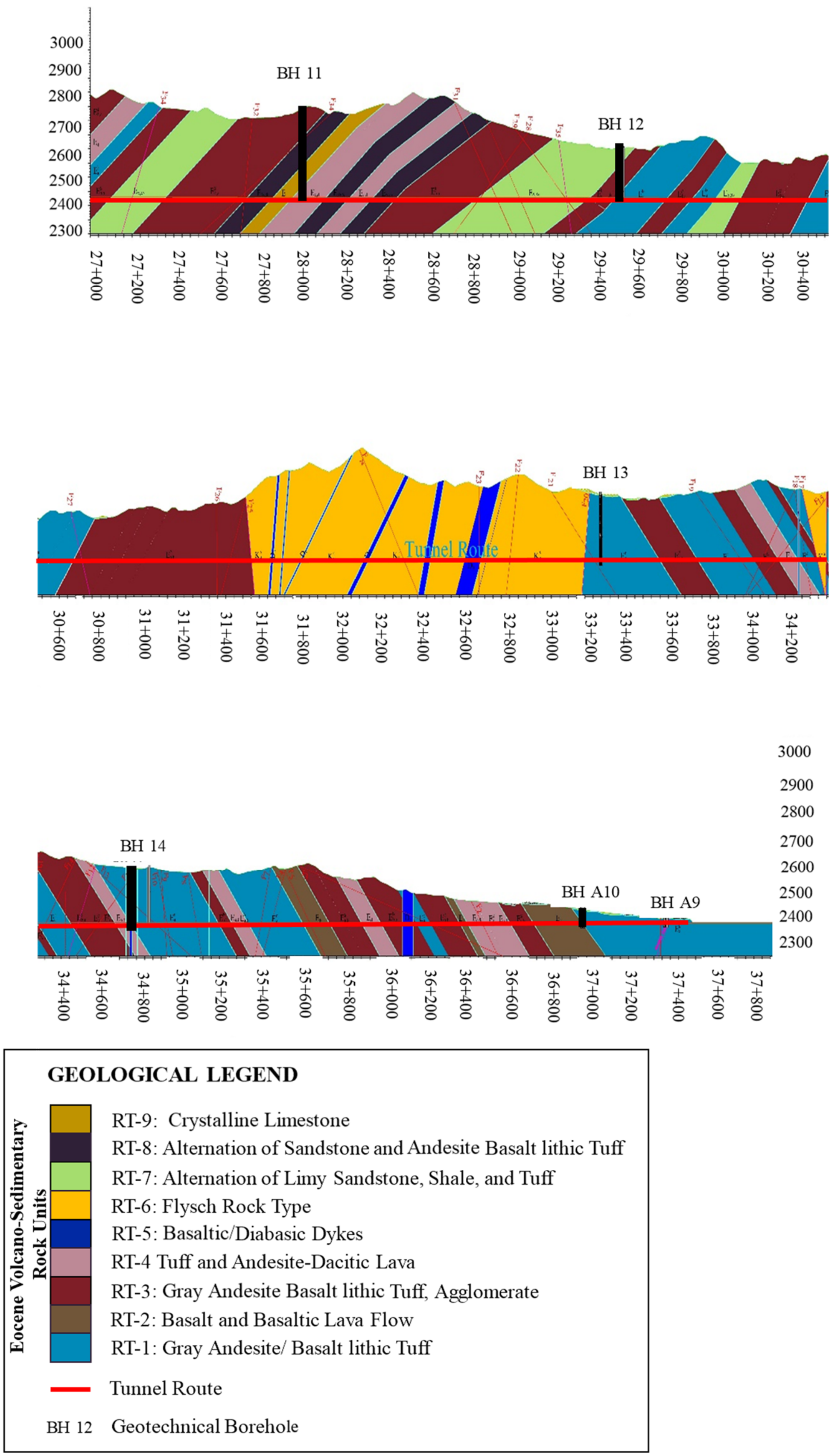


Figure 4. Geo-technical profile of completed part of north lot in KWCT project [7].

4. Numerical analysis of disc wear and rock cutting

The numerical models have been widely used to find and evaluate the most important parameters affecting disc cutter wear and rock fragmentation. The following studies include numerical investigations on the parameters that have affected the wear of the disc cutter during the rock cutting.

In 1998, Tan *et al*. used the displacement discontinuity method (DDM) to simulate the crack propagation caused by the disc cutter force [19]. In 2005 and 2006, Gong *et al*. studied the effect of the joints' spacing and orientation on rock fragmentation by TBM disc cutters using the UDEC software [20, 21]. Park *et al*. have developed a heterogeneous 2D model using the FLAC software to evaluate the lateral pressure and spacing between the TBM disc cutters on the rock fragmentation [22]. Rojek and Rojek *et al*. have used the discrete element method to simulate the rock cutting process [23, 24]. Cho *et al*. have simulated the rock breaking process on the linear cutting machine (LCM) test using the finite element method and the AUTODYN-3D software. They also determined the effect of the disc cutters spacing on the cutting forces [25]. Ma *et al*. have investigated the effect of the lateral confining stress on the disc cutters' function using a finite element code (RFPA2D) based on the statistical theory and the damage mechanics [26]. Bejari and Khademi Hamidi used the UDEC software to analyze the effects of the joints' spacing and orientation on the rock fragmentation and chip formation process [27]. In 2013, Rizo used PFC3D to estimate the forces for cutting the rock by disc cutters [28]. In 2014, Zhao *et al*. numerically simulated and analyzed the interaction between the TBM components and the rock mass properties [29].

Liu *et al*. have studied the process of rock cutting by disc cutters in mixed grounds using the manifold numerical method (NNM) [30]. Sun *et al*. have used numerical methods for the optimal arrangement of the disc cutters on the TBM cutter-head [31]. Li and Du have used the LS-DYNA commercial code based on the finite element method to simulate the dynamic process of the rock cutting and the analysis of the plastic zone under the disc cutter [32]. Li *et al*. have investigated the mechanism of rock crushing with different geometries of wedge disc cutter with the bonded particle model (BPM) [33]. Zhai *et al*. have developed a novel mesh-free numerical method known as general particle dynamics (GPD) to study the effects of the joints on the performance of the TBM disc cutters [34, 35]. Mohammadnejad *et al*. have studied the cutting process of the rock by combining the finite and discrete element methods [36]. Labra et al. presented several numerical models to simulate the laboratory test of the rock cutting by a single TBM disc cutter. The model was based on the combined discrete element/finite element method (DEM /FEM), and while comparing the numerical, theoretical and actual results, they performed a sensitivity analysis on the geometric parameters of the disc cutter, cutting velocity, penetration rate and the spacing between the disc cutters [37].

Zhang *et al*. have investigated the crushing of the various rock types using PFC2D and physical tests. They also studied the crack initiation and propagation to form rock chips by disc cutters in mixed grounds [38]. Guiju and Caiyuan have studied the dynamic and mechanical simulation of the cutting process by disc cutter using the ABAQUS software [39]. Zhai *et al*. have used the general particle dynamics (GPD3D) to simulate the rock fragmentation by TBM disc cutter under various lateral stresses. They found that as lateral stress increased, the forces required to initiate cracks increased and the maximum angle of cracks decreased [40]. In 2019, Afrasiabi *et al*. studied the TBM performance on a real scale by simulating the cutter-head with the PFC3D software and considering the spacing and orientation of the joint sets [41]. Liu *et al*. have used the discrete element method to numerically study the laboratory tests of the TBM cutting under high confinement stresses [42]. In order to investigate the disc cutter wear, Zhao *et al*. have simulated the rolling boring tests with the ANSYS software considering the orientation and spacing of the joints [43]. Using the ABAQUS software, Gue *et al*. have analyzed the effect of the penetration rate and cutting speed on the cutting force during the coal cutting process. The results showed that the average cutting force increased linearly with the penetration rate and cutting speed [44].

This brief review shows that the numerical modelling of the disc cutters has been successful but none of the previous numerical models has combined the analysis of forces, the volume of excavated materials, and the induced stresses in the disc cutter ring for the assessment of wear.

4.1. Numerical modeling of rock cutting by a single disc cutter

In this study, 3DEC$^{©}$ by ITASCA has been used to evaluate the effect of the fracturing on the rock fragmentation and disc cutter wear. This software is a 3D numerical simulation program based on the discrete element method for the analysis of the discontinuum problems such as jointed rocks under static and dynamic loadings. In this software, the individual blocks can behave as a rigid or flexible material, and it is possible to analyze the large displacements on the joints as well as the rotation of the blocks. The blocks can be divided into finite difference elements by meshing, and each element behaves according to a predefined linear or non-linear stress-strain law. Therefore, this software is well-able to simulate the dynamic rotation of the cutter disc and cutter-head on the jointed rock mass. In addition, it is possible to study the distribution of stress, displacement and strains in rock and disc cutter.

The numerical modelling of the rock cutting by TBM disc cutters includes generating the model geometry (i.e. TBM disc cutters as well as rock mass), mesh generation, applying the motion equations to the disc cutters, assigning the constitute models to the disc cutters and jointed rock and their related properties, and applying the boundary conditions. In this paper, it is assumed that the distributed stress on the disc cutters caused by the cutting forces is proportional to the wear of the disc cutter. This is a logical assumption because, in reality, a disc cutter that is subjected to high induced stresses is more likely to incur normal wear conditions.

Since the purpose of this study is to numerically investigate the effect of the rock joints on the wear of TBM disc cutters, therefore, it is necessary to calibrate the output of the numerical model with the theoretical or laboratory results for a specific case. Once the calibration results were acceptable, the numerical modelling on a larger scale can also be trusted. This means that various conditions can be simulated and mechanisms of the phenomena resulting from rock cutting in the actual projects can be investigated, and the possible behavior of the system under different circumstances can be predicted. For this purpose, according to the rotational, revolution, and penetrating motion of the disc cutter, as well as Newton's second law, the reactions of these motions are applied to the disc cutter from the rock (i.e. the normal, rolling, and side forces).

In order to validate the numerical model, the analysis was performed for intact rock conditions (without joints), and then based on the input data presented in Table 4, its results were compared with the theoretical CSM model [45, 46]. The CSM model is one of the theoretical models for estimation of the cutting forces acting on a disc cutter which include normal, rolling, and side forces (Figure 5) [47]. Using Eqs. (3) and (4), this model is able to calculate the cutting forces applied to the disc cutter including the normal and rolling forces.

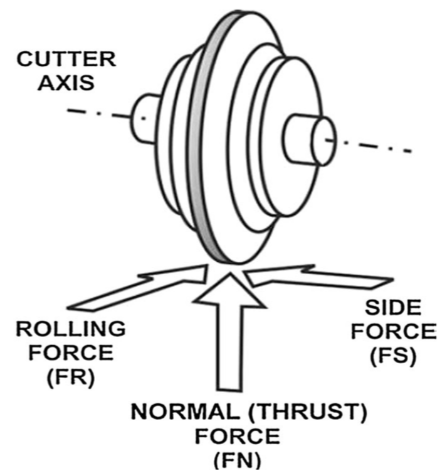


Figure 5. Forces acting on a disc cutter [47].

$$F_n = CTR\varphi\sqrt{\frac{\sigma_c^2\sigma_t s}{\varphi\sqrt{RT}}}\cos(\frac{\varphi}{2}) \tag{3}$$

$$F_r = CTR\varphi\sqrt{\frac{\sigma_c^2\sigma_t s}{\varphi\sqrt{RT}}}\sin(\frac{\varphi}{2}) \tag{4}$$

In Eqs. (3) and (4), C is a constant factor (=2.12), T is the width of the disc cutter tip, R is the radius of the disc cutter, σ_c is the uniaxial compressive strength of the rock, σ_t is the tensile strength of the rock, and s is the spacing between the adjacent disc cutters. φ is the angle of the contact area calculated as $cos^{-1}\left(\frac{R-p}{R}\right)$, where p is the penetration per revolution. The unit of length is in millimeters or inches, unit of stress is in MPa or psi, and all angles are measured in radians.

In general, the cutting motion of the TBM disc cutters on the rock includes the three basic velocities: rotation of the disc cutters around their own axis (rotation, V_d), rotation of the disc cutters around the tunnel axis (revolution, V_c), and finally, linear penetration into the rock (penetration, V_z). For the numerical modelling in this study, the velocities applied to the disc cutters correspond to these three basic movements (i.e. Eqs. (5) to (7)). Accordingly, the rotation radius is equal to the radius of the disc cutter (R_d), and the revolution radius is equal to the installation radius of the disc cutter (R_i) (Figure 6). The rotation and revolution velocities of the disc cutter are a function of time (t), while the penetration velocity is constant and time-independent. It should be noted that the rotation angular velocity (ω_d) of the disc cutters should be proportional to the velocity of their revolution angular velocity (ω_c) according to Eq. (8); otherwise, the disc cutters will slip on the rock or rotate in place.

In the validation process and after 0.3 m of rock cutting, the normal forces calculated in the numerical method and the CSM model are 339 kN and 355 kN, respectively, and the relative difference is less than 5% (Figure 7). Also the rolling forces calculated in the numerical method and the CSM model are 47.5 kN and 51.6 kN, respectively, and the relative difference is about 9% (Figure 8). Therefore, the results of the numerical can be considered valid and within the range of results from an empirical model such as the CSM model. This shows the validity of the selected parameters, and indicates the ability of the model to simulate the rock mass conditions by introducing the discontinuities in the geometrical model.

It should be noted that due to the revolution of the disc cutter on a circular path in the numerical model, the disc cutter is under the side force (Figure 9). In the CSM model, assuming a linear cutting path for the disc cutter (i.e. the radius of the revolution is infinite), the side force is assumed to be neutral (ideally average around zero). According to the disc cutter position that depends on time, the cutting forces calculated numerically are variable, which is contrary to the CSM model that predicts a constant average value that is based solely on the geometric parameters of the disc cutter and rock strength. Compared to the theoretical and laboratory methods, the numerical analysis can incorporate the effect of the geological complexities, geometric parameters of the disc cutter, and other special conditions into the calculation of the cutting forces.

According to the Mohr-Coulomb (MC) that has been assigned for describing the 3D mechanical behavior of the rocks, the plastic zones developed in the rock include two failure modes: shear and tensile failures. The status of the plasticity is checked in each element by the 3DEC software, and each plastic zone may include one of the failure modes or have both modes at the same time. At a specific time, the suffix -p (past) and –n (now) are used to represent the plastic zones, which have already failed and are just failed, respectively. Figure 10 shows the plastic zones due to the rotation, revolution, and penetration of the disc cutter over the rock without joints. Figure 10a shows the failure modes of the plastic zones.

Induced stresses in the TBM disc cutter rings are due to the cutting forces (normal, rolling, and side-forces) that are applied to the TBM disc cutters. In the numerical analysis, the von Mises failure criterion can represent the behavior of the disc cutter as a ductile (non-brittle) material in a stress field. According to this criterion, the yielding of a ductile material occurs when the second invariant of the deviatoric stress (J2) reaches a critical value. In materials science, the von Mises yield criterion can be formulated based on the relation of the equivalent stress (σ_v) to the principal stresses according to Eq. (9). Since the von Mises yield criterion is independent of the first stress invariant, it is used to analyze the plastic deformation of the ductile materials such as metals or any materials in which the yield depends on the components of the stress tensors. In 3DEC, it is possible to assign the von Mises criterion and display its stress contours for the steel disc cutter zones. If the value of this stress is higher than the strength of the disc cutter, then it can be said that some of the disc cutter zones have yielded, and practically, the disc cutter has undergone deformation. However, the level of the induced stresses can also indicate the wear rate of the cutter ring. In other words, the higher induced stresses correspond to a higher rate of wear.

$$V_d = R_d \omega_d \sin \omega_d t \tag{5}$$

$$V_c = R_i \omega_c \sin \omega_c t \tag{6}$$

$$V_z = -P \tag{7}$$

$$\omega_d = \frac{R_i \omega_c}{R_d} \tag{8}$$

$$\sigma_v = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]} \tag{9}$$

Table 4. Properties of disc cutter and rock in comparative analysis between CSM and numerical models.

Material	Parameter	Value	Unit
Disc cutter	Constitutive models	von Mises	-
	Elastic modulus	210	GPa
	Tensile strength	600	MPa
	Cohesive strength	600	MPa
	Poisson's ratio	0.3	-
	Density	8000	Kg/m^3
	Revolution velocity (RPM)	2	RPM
	Rotation velocity	4.14	RPM
	Penetration velocity	10	mm/rev
	Cutter tip	24	mm
	Cutter radius	241.5	mm
	Spacing between cutters	70	mm
	Penetration depth	10	mm
Rock	Constitutive models	Mohr-Coulomb	-
	Elastic modulus	15	GPa
	Poisson's ratio	0.2	MPa
	Cohesion	1	MPa
	Friction	35	Degree
	Density	2700	Kg/m^3
	Rock compressive strength	180	MPa
	Rock tensile strength	10	MPa
	Rock friction angle	40	Degree
	Rock cohesion	1e6	MPa

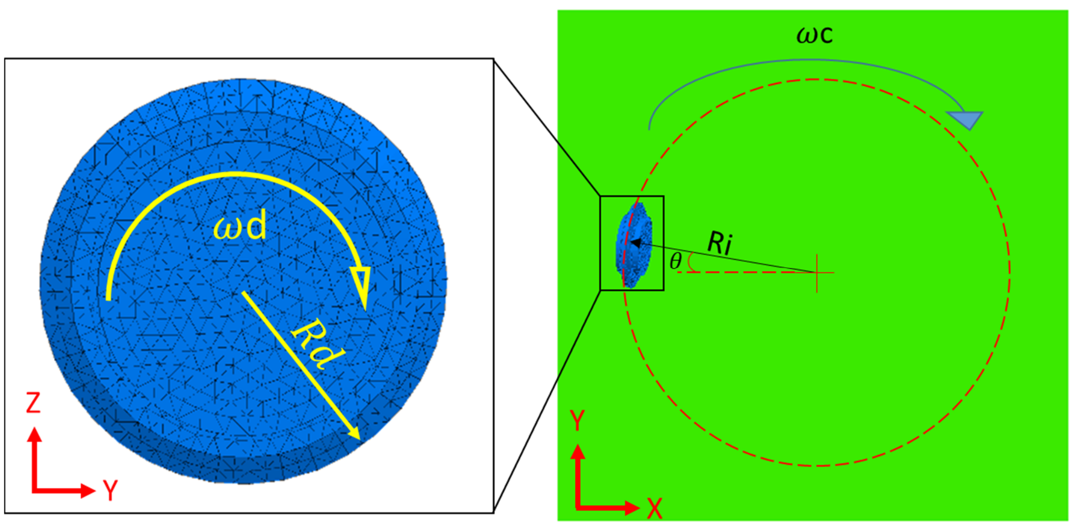


Figure 6. Radius of rotation (R_d) and revolution (R_i) of disc cutter with corresponding angular velocities (ω_d) and (ω_c).

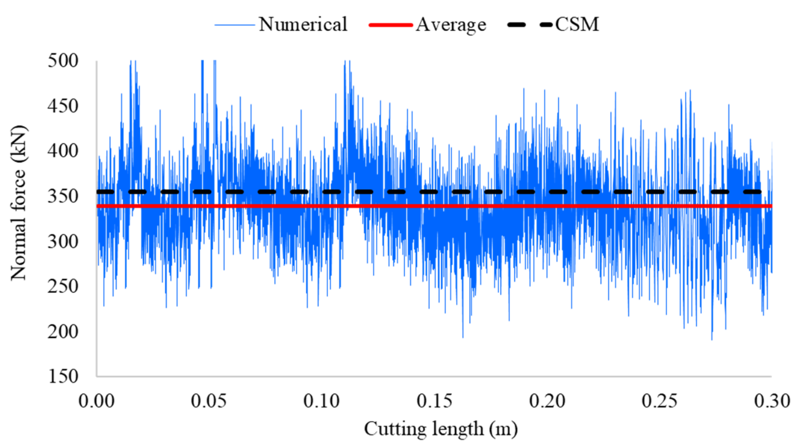


Figure 7. Variation of normal force on disc cutter calculated using 3DEC and CSM.

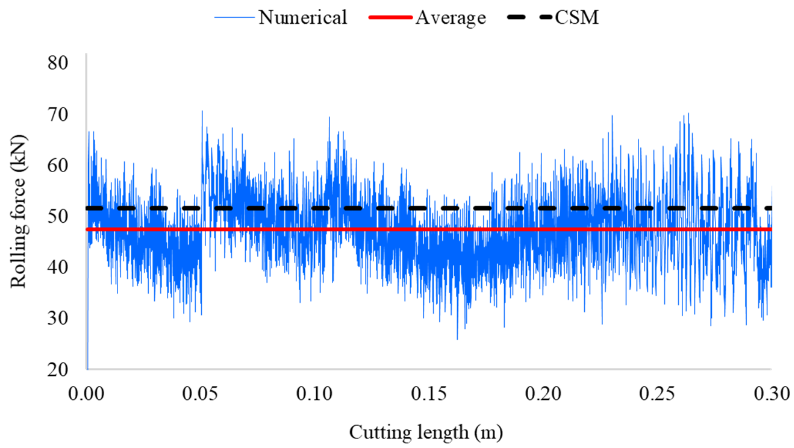


Figure 8. Variation of rolling force of disc cutter calculated using 3DEC and CSM.

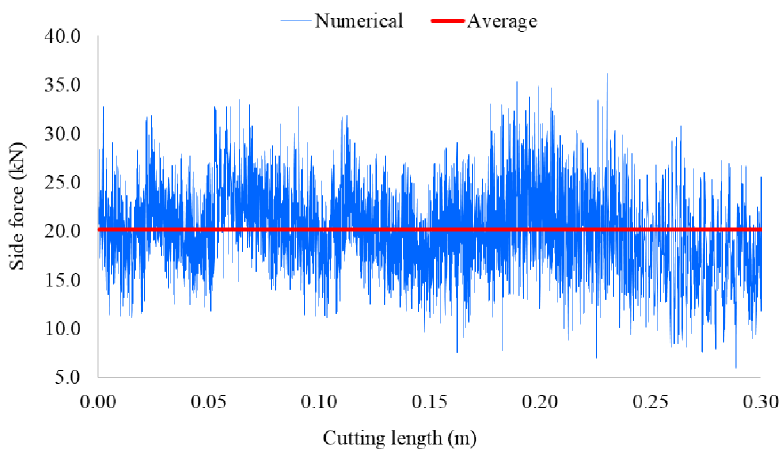


Figure 9. Estimated variation of side-force of disc cutter calculated using 3DEC.

4.2. Numerical modeling of jointed rock crushing by TBM disc cutters

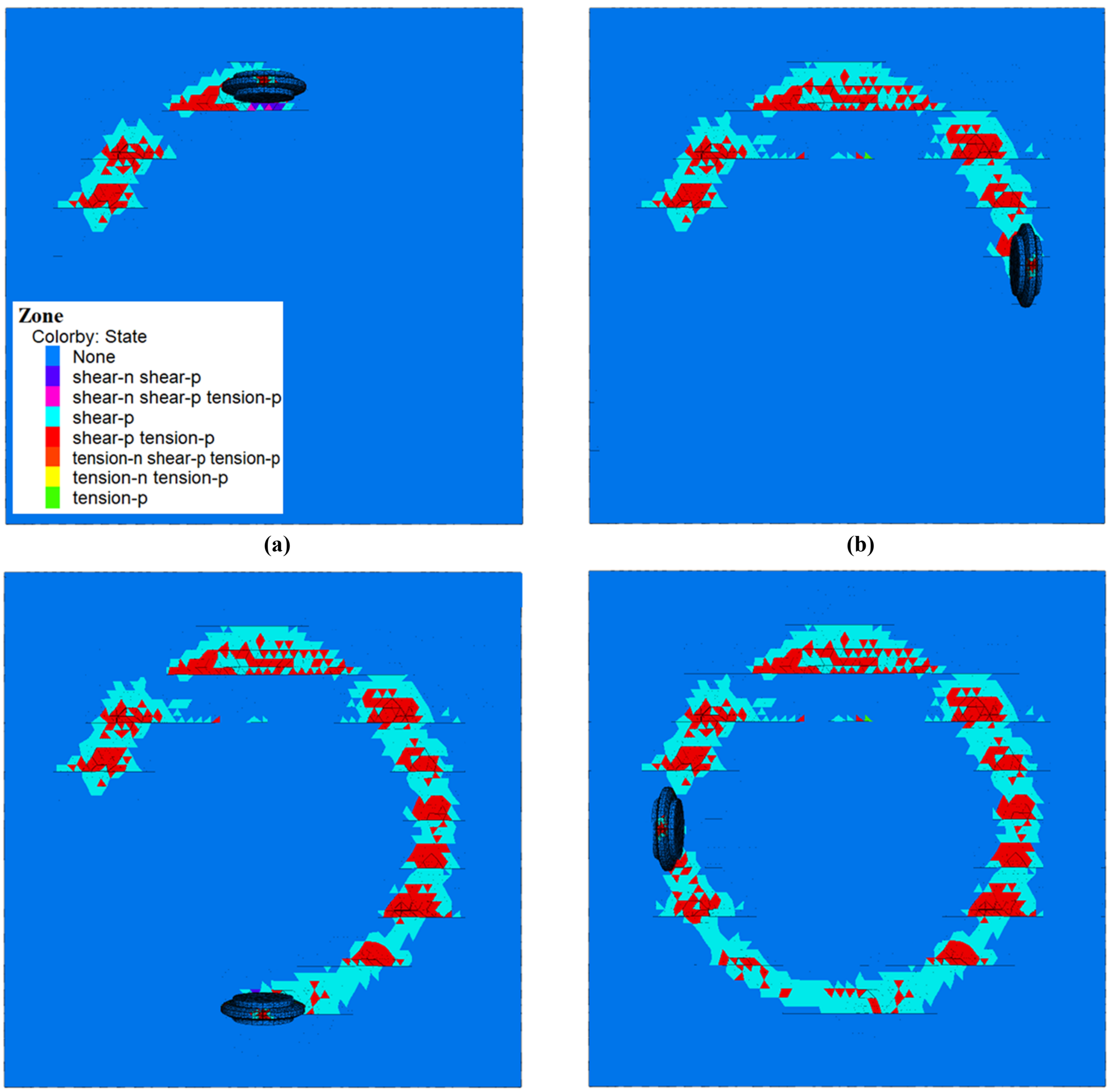
To analyze the effects of the joint sets on the rock crushing process and disc cutter wear, the actual recorded data related to two selected rock units (i.e. RT-1 and RT-4) of the KWCT project have been compared with the numerical results of the real-scale modelling using the 3DEC software. These two rock units are shown in Figure 4. Also the properties of the units are presented in Table 5. The units have been selected based on the rock fracturing according to the k_{s-tot} and availability to the data of the disc cutters' life. The lithology and geology of these units are almost similar but the TBM disc cutters have experienced different wear rates during boring these units. Since the implementation of the numerical model with large dimensions and fine meshes is very time-consuming, the results obtained from the dynamic analysis during only one complete rotation of the cutter-head were used to evaluate the effects of the joint conditions on the cutting process as well as on the disc cutters' wear.

Table 5 presents the spatial characteristics of the joints, including orientation and spacing, as well as the joint class and the rock fracturing parameter (k_{s-tot}) for the geological units RT-1 and RT-4. Figure 11 shows the model geometry and dimension, which is generated by 3DEC for the numerical analysis of the rock mass cutting by the TBM cutter-head. This figure includes the layout of the TBM disc cutters for the KWCT project based on Figure 3a. For both units RT-1 and RT-4, the properties considered for the joints are assumed to be the same and are entered as input parameters in the numerical model according to the Table 6.

The modelling process is as follows: after applying the boundary conditions and assigning strength and behavioral properties, the disc cutters roll over the rock in a circular path proportional to the installation radius of the disc cutters (revolution radius) at a certain penetration rate.

The boundary condition includes two important items: displacement and velocity. The model boundaries shall be fixed based on the related axes (Figure 12). This condition will cause the model geometry not to be moved during the calculations. Also these fixed conditions around the model boundaries as known values help the numerical calculations to reach the converged solutions. Furthermore, the disc cutters shall be rolled over the tunnel face and penetrated into the rock mass. Therefore, the boundary condition for the disc cutters should coincide with Figure 6 and Equations (5) to (7). It should be noted that the tunnel circular face shall be completely free to be displaced during the numerical analysis. for achieving this requirement, the tunnel face has been generated about 0.5 m behind the forward plane, which is absolutely distinguished in Figure 11. In Figure 13, the joint planes are numerically shown for geological units RT-1 and RT-4 according to Table 5. As shown in Table 5, the $k_{s\text{-}tot}$ for unit RT-4 is higher than unit RT1, which can be seen visually in Figure 13.

As a result of the disc cutters' action on the tunnel face, the plastic crushed zones are developed in the rock and von Mises stresses are induced in the disc cutters, which are directly related to the wear rate of the disc cutters. In other words, due to the higher induced stresses, the disc cutters will experience a higher wear.



(a) (b) (c) (d)

Figure 10. Extent of excavated material caused by motion of disc cutter on jointed rock mass and resulting plastic zones at different angular positions: (a) 90 degrees; (b) 180 degrees; (c) 270 degrees; (d) 360 degrees.

Table 5. Determination of $k_{s\text{-}tot}$ for geology units of KWCT [7].

Geology units	Max. overburden (m)	Orientation (dip/dip direction)			Spacing (cm)			Fracture class			ks-tot	UCS_{rm} (MPa)	CAI	H_f (m^3/cutter)
		J1	J2	J3	J1	J2	J3	J1	J2	J3				
RT-1	290	73/105	76/353	64/015	120	170	120	0-I	0+	0-I	1.43	22	3.50	631.9
RT-4	395	67/217	82/090	78/135	130	140	100	0-I	0-I	I-	2.06	10	1.75	802.74

J1, J2, and J3: Three dominant joint sets

Table 6. Properties of disc cutter and jointed rock in the comparative analysis between CSM and numerical models.

Parameter	Value	Unit
Cutter-head Rotation velocity (RPM)	6	RPM
Penetration per rev or velocity	10	mm/rev
Elastic modulus	15	GPa
Poisson's ratio	0.22	-
Cohesion	1	MPa
Friction	35	Degree
Density	2700	Kg/m^3
Uniaxial compressive strength	180	MPa
Rock tensile strength	10	MPa
Rock friction angle	35	Degree
Rock cohesion	1	MPa
Constitutive models	Coulomb slip failure	-
Joint normal stiffness	10	GPa/m
Joint shear stiffness	1	GPa/m
Joint friction	25	Degree

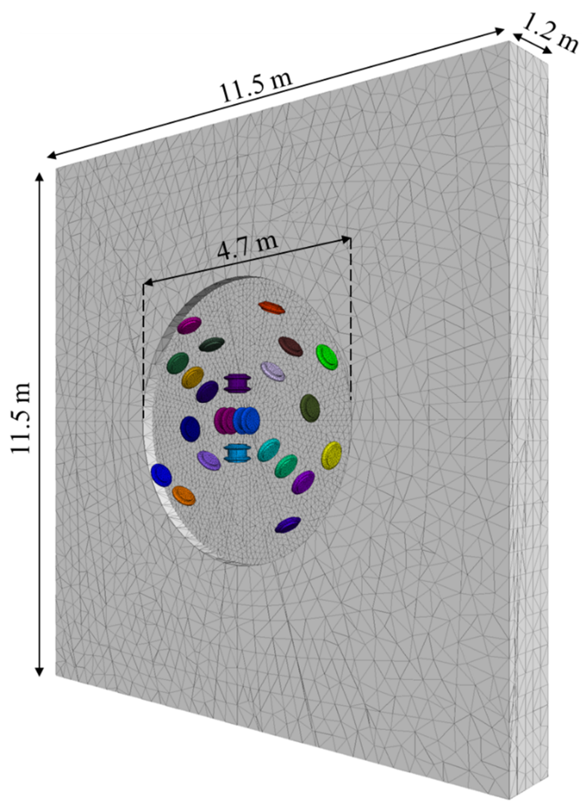


Figure 11. Model geometry generated by 3DEC for numerical analysis of rock mass cutting by TBM cutter-head.

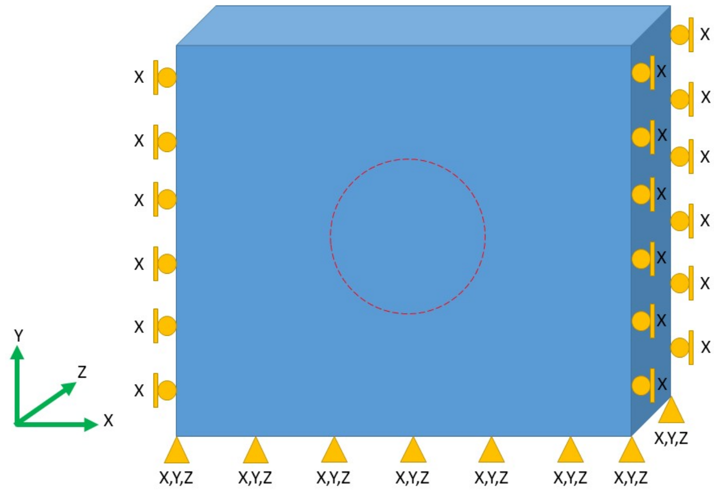
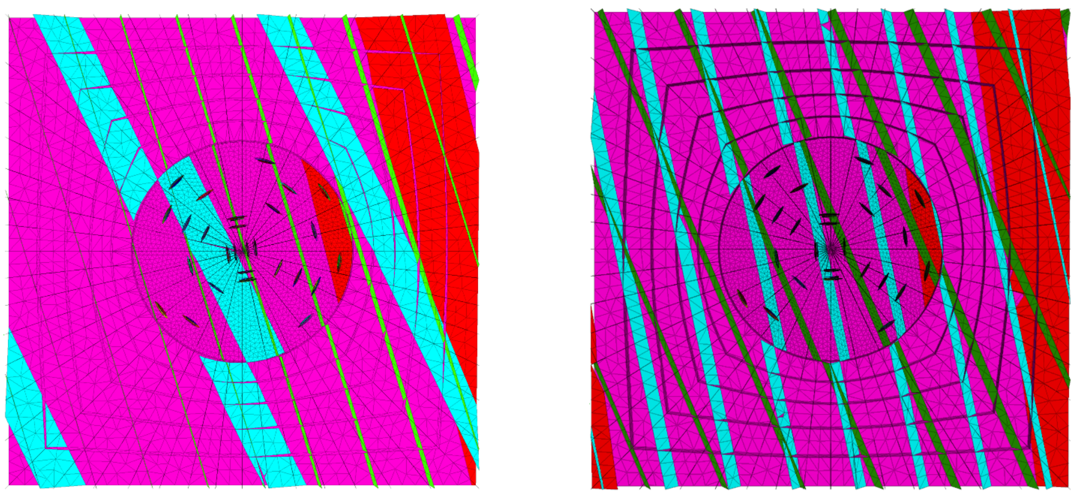


Figure 12. Boundary conditions applied to model in X, Y, Z directions.



(a) **(b)**

Figure 13. Joint sets for geological units: (a) RT-1; (b) RT-4.

Figures 14 and 15 show the estimated extent of the plastic zone due to a single revolution of the cutter-head (set of disc cutters) for the geology units RT-1 and RT-4 calculated by the numerical model, respectively. At the beginning of the cutter-head rotation, the plastic zones are created by shear stresses, and as rotation (i.e. boring) progresses, the tensile and shear-tensile failure are developed. The volume of the plastic zones in unit RT-4 is higher than in unit RT-1. The volume of the plastic zones developed in the rock due to the application of the rotation, revolution, and penetration velocities of the disc cutters in units RT-1 and RT-4 of the KWCT project are shown in Figure 14. The plastic volumes are the sum of the zones' volume that have reached the yield limit of the shear or tensile strength or both and are known as boring affected zones. According to Figure 16a, the volume of the plastic zones in units RT-1 and RT-4 are 0.23 and 0.32 m^3, respectively. This means that the amount of crushed rock in unit RT-4 is about 40% higher than unit RT-1. This is due to the joints' spatial characteristics in the rock which has provided favorable conditions for crushing. In Figure 16b, the average penetration depth is determined from the volume of the crushed rock mass divided by the tunnel area. Since the penetration rate of disc cutters in dynamic analysis is applied as an input parameter of 10 mm/revolution, it can be seen that due to the presence of joints in the rock, the penetration depth is higher than the nominal penetration rate of disc cutters during analysis's time. The penetration depth of the disc cutters in unit RT-1 and unit RT-4 is 12 mm and 17 mm, respectively. On the other hand, the fracturing of unit RT-4 due to the orientation and spacing of the joint sets has a great impact on the penetration depth. In other words, more fracturing in the rock causes the TBM cutter-head to penetrate deeper and easier. Consequently, the boring efficiency and the life of the disc cutters increase. By comparison, it can be said that the penetration depth in unit RT-4 is about 40% higher than in unit RT-1 under the same cutter-head thrust.

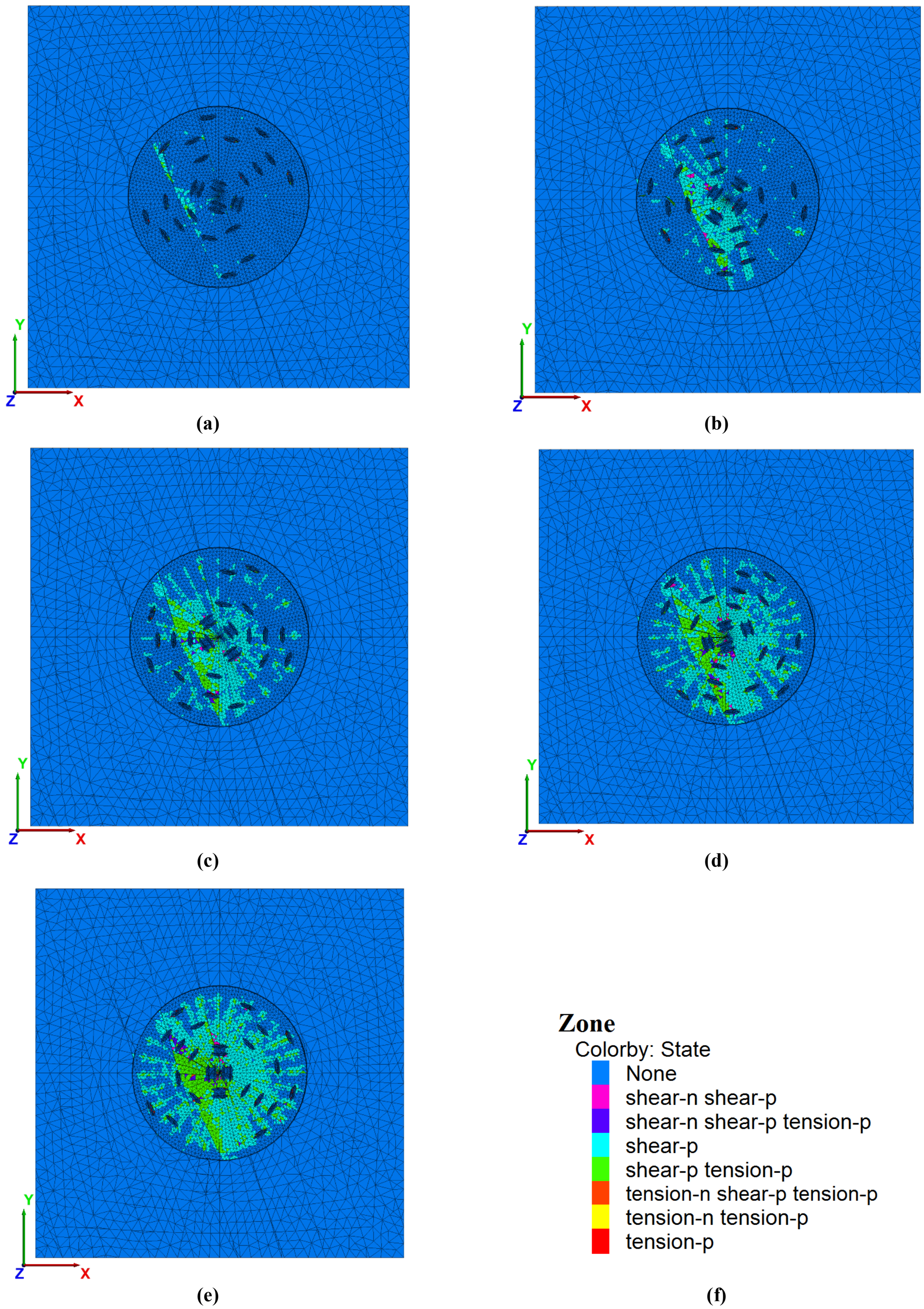


Figure 14. Development of plastic zones in unit RT-1 due to TBM boring during 10 s dynamic time: (a) 1st s.; (b) 2nd s.; (c) 4th s.; (d) 6th s.; (e) 8th s.; (f) 10th s.

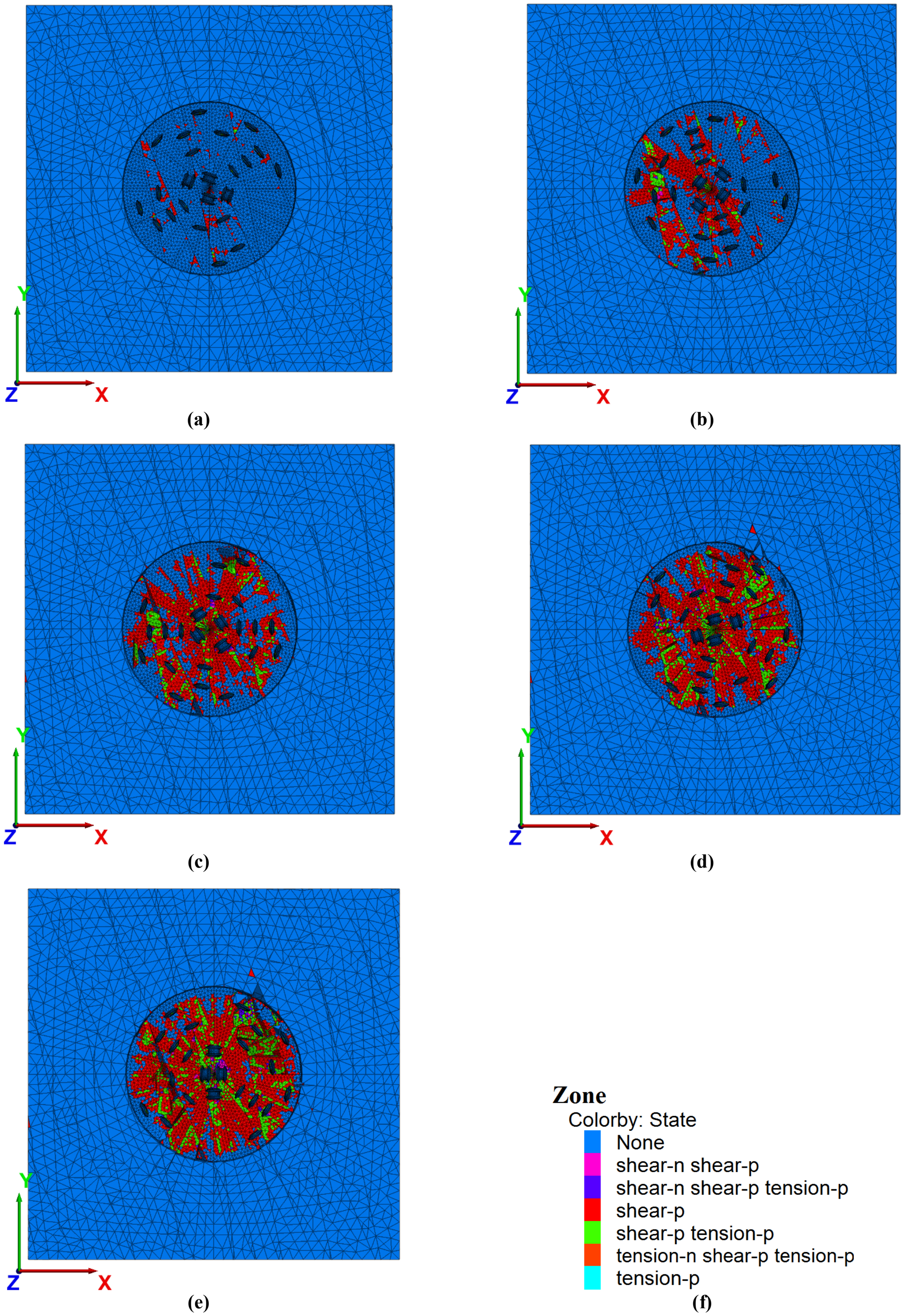
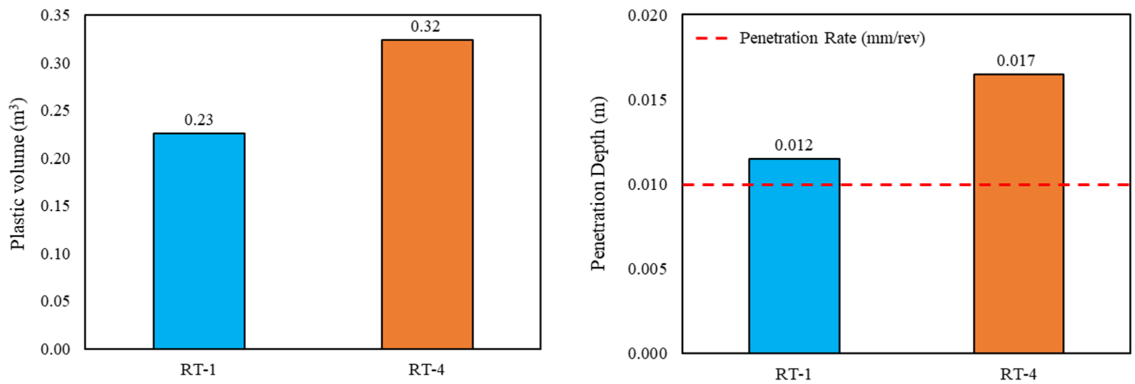


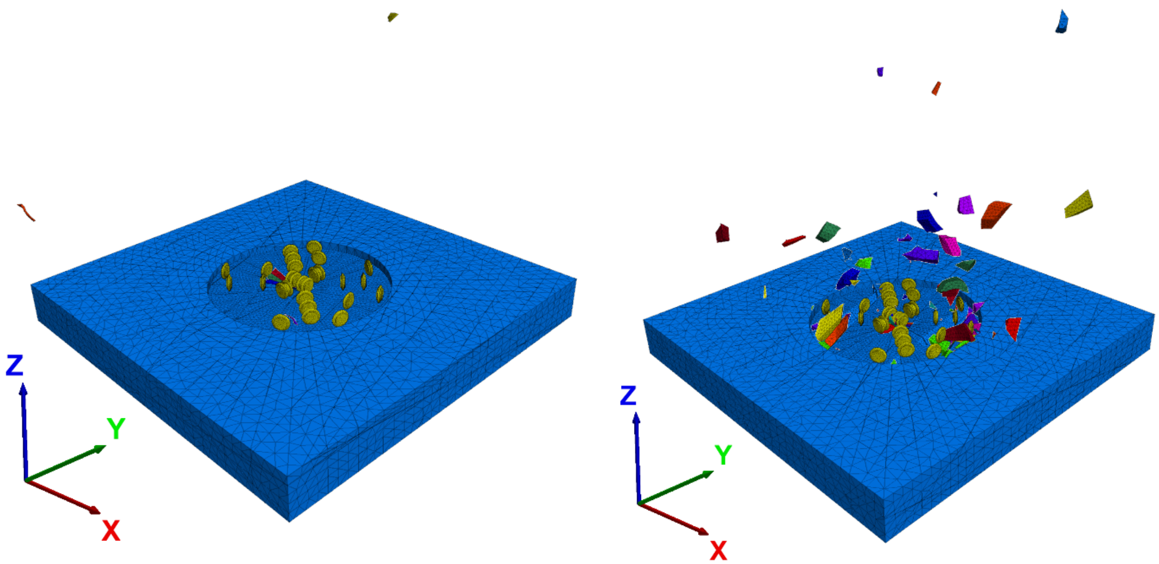
Figure 15. Development of plastic zones in unit RT-4 due to TBM boring during 10 second dynamic time: (a) 1st s.; (b) 2nd s.; (c) 4th s.; (d) 6th s.; (e) 8th s.; (f) 10th s.

Figure 17 shows the separation of the blocks from the tunnel face for unit RT-1 and RT-4. These rock blocks, which are made by the intersection of the joint planes, have been separated due to the force applied by the disc cutters. The spatial displacements of the separated blocks are affected by the normal and shear stiffness of the joints. In unit RT-1, only two small blocks are separated from the tunnel face, and the others have a displacement of about less than 10 cm. In unit RT-4, the number of blocks with a displacement of more than 10 cm is much higher than in unit RT-1. This phenomenon is due to the fracturing of the rock mass, which is represented by the fracturing factor ($k_{s\text{-}tot}$).



(a) (b)

Figure 16. Numerical results: (a) Volume of plastic zone in numerical model for two selected geological units; (b) Penetration depth affected by plastic zones and nominal penetration rate.



(a) b

Figure 17. Separated rock blocks from surface of tunnel face due to cutter-head (disc cutters set) advancing in numerical model for geological units: (a) RT-1; (b) RT-4.

Figures 18 and 19 show the induced von Mises stresses that are induced in the disc cutters in the center, face, pre-gage, and gage group for geological units RT-1 and RT-4, respectively. The graphs plotted for the selected disc cutters oscillated due to the dynamic motion of the disc cutters, but over time, an average value can be assigned to each graph. In Figure 20, the average values of the von Mises stresses are shown for the different groups of the disc cutters in units RT-1 and RT4 of the KWCT project. According to Figure 20, it can be seen that the average von Mises stresses are increasing from the center disc cutters toward the gage cutters. The only exception is the face disc cutters, which do not follow this trend. In addition, the average von Mises stress in unit RT-1 is about 16 to 23% higher than unit RT-4.

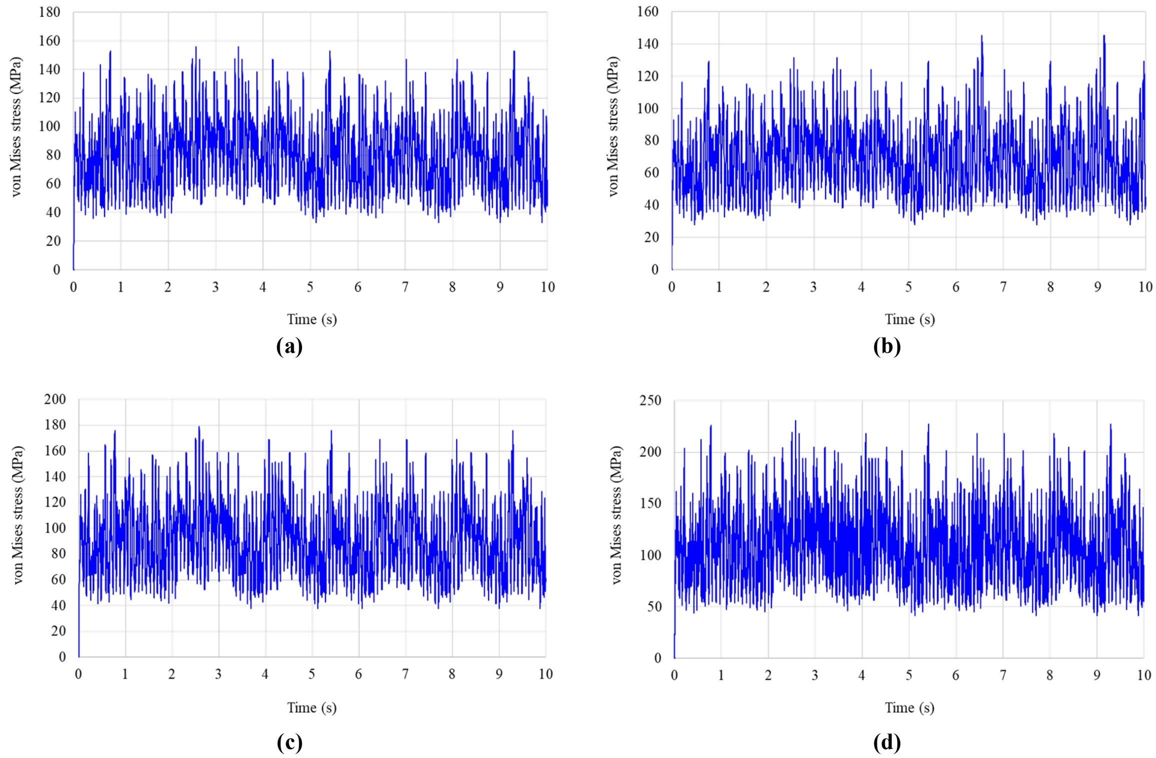


Figure 18. Von Mises stress oscillation graph versus to dynamic analysis time for TBM disc cutters of the geological unit RT-1: (a) center group; (b) face group; (c) pre-gage group; (d) gage group.

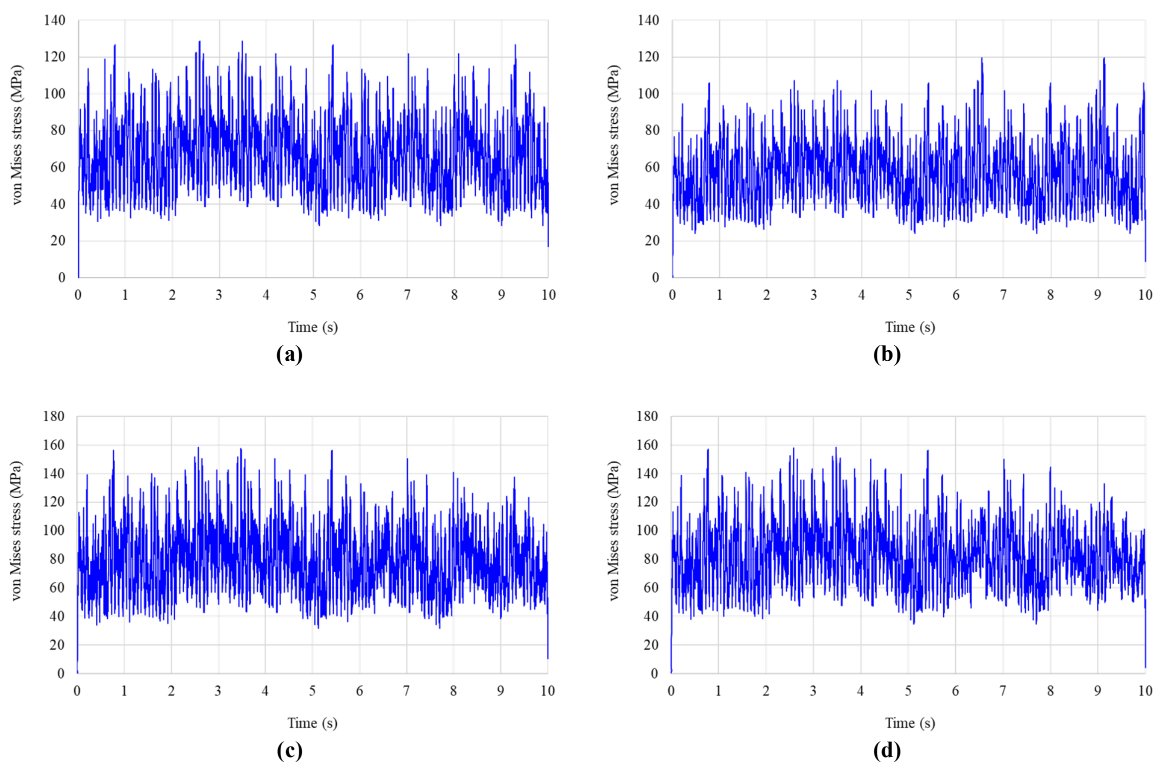
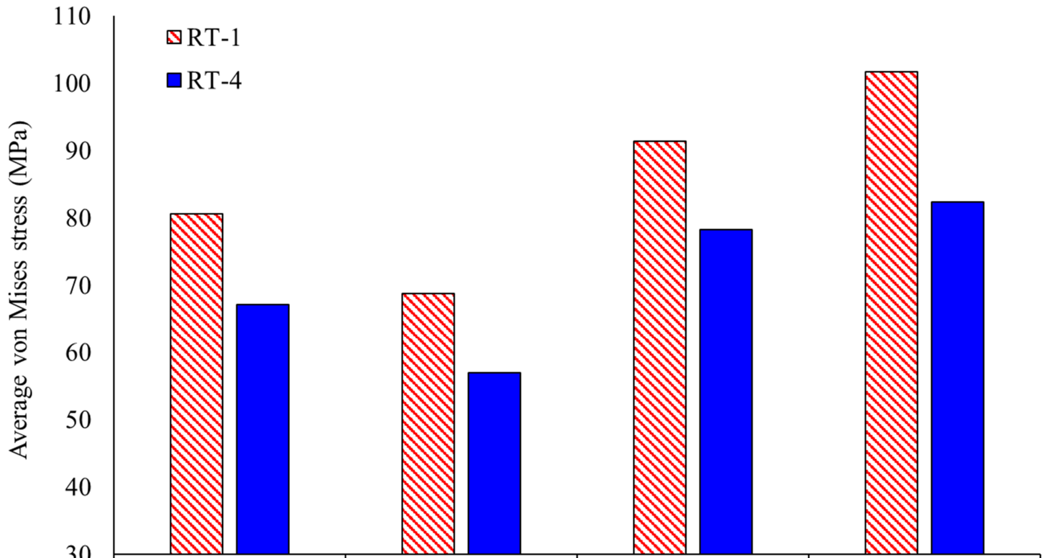


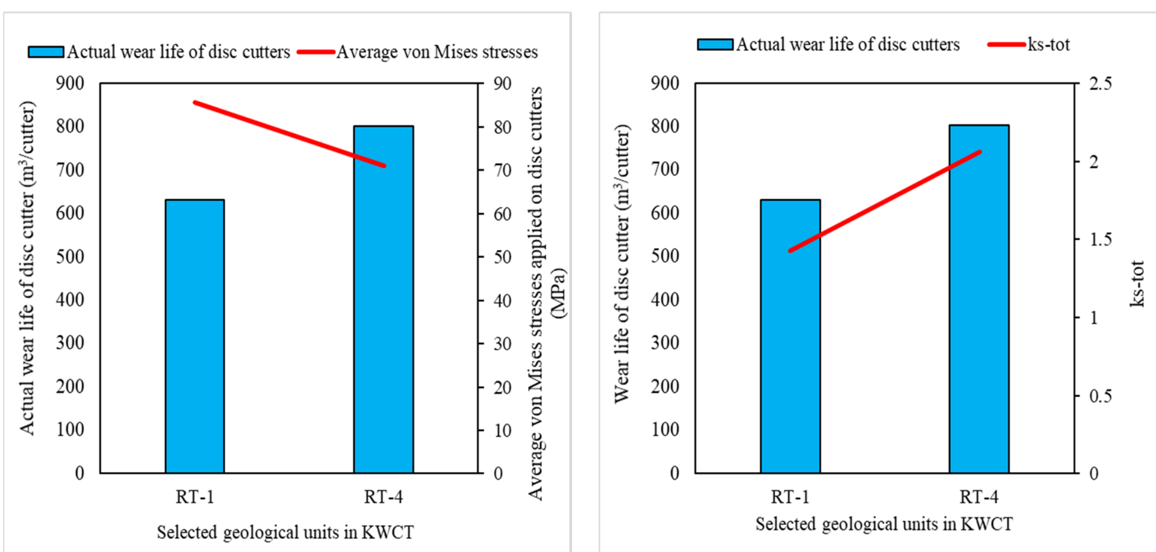
Figure 19. Von Mises stress oscillation graph versus to dynamic analysis time for TBM disc cutters of geological unit RT-4: (a) center group; (b) face group; (c) pre-gage group; (d) gage group.



	Center discs	Face discs	Pre-gage discs	Gage discs
RT-1	80.6	68.8	91.4	101.7
RT-4	67.1	56.9	78.3	82.3

Figure 20. Average von Mises stresses for different groups of disc cutters in units RT-1 and RT4 of KWCT.

Figure 21 shows the relationship between the actual wear life of the disc cutters (H_f) in the selected geological units RT-1 and RT-4 of KWCT with the average von Mises stress applied on the TBM disc cutters and also with the rock mass fracturing parameter ($k_{s\text{-}tot}$). H_f has been presented in Table 5, and the average von Mises stress applied on the TBM disc cutters can also be calculated based on Figure 20. According to Figure 21, increasing the mass fracturing can lead to an increase in the wear life of the TBM disc cutters (reduction of abrasive wear). On the other hand, average von Mises stresses can also be considered an influential factor in the wear life of disc cutters because by reducing the stresses, the wear life of the TBM disc cutters increases.



(a) **(b)**

Figure 21. Relationship between actual wear life of disc cutters (H_f) in selected geological units RT-1 and RT-4 of KWCT with: (a) average von Mises stresses; (b) rock mass fracturing parameter ($k_{s\text{-}tot}$).

The results of the analysis confirm the ability of the numerical simulation using the discrete element method for estimating the cutting forces applied to the disc cutters, the extension of the damaged zone at the tunnel face or the volume of the excavated material, and the magnitude of induced stresses in the disc cutter ring, which corresponds to the wear rate of the disc cutters. This combination will offer the ability to assess the impact of rock mass properties in the rock cutting process and TBM performance, as well as the estimation or evaluation of the cutter life in rock mass conditions.

6. Conclusions

In this work, the effects of the joint sets on rock fragmentation and the disc cutter wear were investigated. $K_{s\text{-}tot}$ was used to represent fracturing for evaluating the rock mass conditions since it combined the spacing between the joint sets and joint sets orientation. Rock mass fracturing has direct and indirect effects on the mechanized tunneling process. One of the direct effects of fracturing is the ease of crushing the rock and the higher penetration rate of TBM. The other impact of rock mass fracturing is that since it requires less power to overcome the rock, TBM disc cutters experience a lower wear rate than when the rock is intact or is less fractured. In this work, the numerical model was validated by comparing the results with the CSM theoretical with the acceptable differences in the average normal and rolling forces between the numerical and theoretical models. The most important results of the numerical analysis in this study are summarized as follows:

1. The numerical model presented in this work is capable of applying the time-based velocities according to the mathematical equations governing the TBM disc cutters and simulating three main dynamic movements: rotation of the disc cutters around their axis, rotation of the disc cutters around the cutterhead axis, and finally, penetration of the disc cutters into the rock. This was done in conjunction with control of the rock properties including the intact properties of rock as well as rock mass discontinuities in a discrete element modelling program. In the numerical model, the cutting path of the disc cutter is circular, which is unlike the direct path in the theoretical models based on laboratory testing on linear cutting machines. Therefore, the numerical models, in addition to normal and rolling forces, can estimate the lateral or side forces.

2. Full-scale numerical analysis was conducted for the entire cutterhead based on one rotation of the cutter-head. The study of two selected geological units from the KWCT project with the same intact rock by different joint conditions allowed the comparison of the machine performance and potential cutter wear between the models and observations in the field. The results proved the quality and accuracy of the numerical responses for both geological units.

3. Using the volume of the rock plastic zone at the face in the numerical modelling using DEM to represent the excavated material in the TBM boring process proved to be a reasonable assumption. The real-scale numerical modelling showed that the volume of the rock plastic zone developed in the geological unit with more fracturing under the TBM (set of disc cutters) boring was about up to 40% more, while the other operational parameters were almost the same. In addition, the actual penetration depth can be estimated by dividing the plastic volume by the area of the tunnel section area and compared with the nominal penetration rate. In this work, the actual penetration depth in the uint RT-4 was higher than the nominal penetration rate at about up to 42% more than unit RT-1. This confirmed the ability of the numerical modelling to be used for estimating the production and penetration rate of TBMs.

4. The average von Mises or induced stresses can represent the rate of wear on the disc cutters and be constantly increasing in the disc cutters from the center to the gage cutters in the numerical analysis. One of the reasons could be the increased linear velocity of disc cutters for a given cutterhead RPM, hence, justifying the faster wear rate of the discs as one moves from the center to the gage area. However, given the magnitude of the side forces at the center, the elevated wear of the disc at center of the cutterhead can be explained. Similarly, the observation of a lower wear rate for face disc cutters that showed minimal values of induced stresses seems to be logical given the rate of wear in this area relative to the actual length of the travelling on the face. This result indicates that the gage disc cutters are most at risk of wearing due to the induction of maximum von Mises stresses, partly because of the higher velocity of travelling in this area and perhaps elevated side loading. Due to the number of disc cutters and the appropriate spacing between them, the face group has good participation in rock crushing. The face disc cutters on the cutterhead should experience a longer life than other disc cutters relative to the linear length they move on the face, as has been observed on hard rock TBMs in various projects.

5. The average von Misses stress in the TBM disc cutters in more fractured rocks is anticiapted to be less than induced stresses in intact or less fractured rocks. In this work, based on the numerical results, this difference was recorded about 16% to 23%.

Therefore, it can be said that the wear rate of the disc cutters in rocks with more fracturing is lower.

The results of this work show the potential for using DEM modeling to study the impact of rock mass conditions on TBM performance and disc cutter life. Additional studies are underway to compare the results of this approach with field data from other projects.

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Conflicts of interest/Competing interests

The authors declare that there is no conflict of interest.

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شبیه‌سازی عددی فرآیند دینامیکی حفاری TBM در سنگ‌های درزه‌دار در مقیاس واقعی؛ مطالعه موردی: تونل انتقال آب کرمان، ایران

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چکیده:

یکی از هزینه‌های بسیار مهم در تونل‌سازی مکانیزه، هزینه تعمیر و یا تعویض دیسک کاترهایی است که در فرایند خرد کردن سنگ‌های ساینده و سخت دچار ساییدگی نرمال می شوند. برای بررسی وضعیت ساییدگی دیسک کاترها، عملیات حفاری باید متوقف شده و پس از بازرسی کاترهد، دیسک کاترهای فرسوده تعویض شوند. در این مطالعه، فرآیند دینامیکی حفاری TBM در سنگ‌های درزه‌دار با استفاده از تحلیل عددی به روش اجزای گسسته (DEM) شبیه‌سازی شده است. در این تحلیل که در مقیاس واقعی و با در نظر گرفتن ضریب درزه‌داری سنگ انجام شده، توزیع تنش القایی در دیسک کاترها و نیز توسعه زون خرد شده در سنگ بررسی و با نتایج واقعی ثبت شده در تونل انتقال آب کرمان مقایسه شده است. نتایج عددی نشان می‌دهند که با افزایش ضریب درزه‌داری سنگ، مقدار تنش‌های القایی در دیسک کاترها کاهش و حجم زون خردشده در سنگ افزایش می‌یابد. به عبارت دیگر، در سنگ‌هایی با درزه‌داری زیاد می‌توان نرخ نفوذ و طول عمر بیشتری را برای دیسک کاترهای TBM تجربه کرد. علاوه بر این، پیش‌بینی می شود که تنش فون میسس در دیسک کاترها در زمان حفاری سنگ‌هایی با درزه‌داری زیاد، به طور متوسط ۱۶ تا ۲۳ درصد کمتر از حالتی باشد که حفاری در سنگ‌هایی با درزه‌داری کمتر انجام می شود. همچنین در اثر حفاری TBM تحت پارامترهای عملیاتی یکسان، حجم زون خرد شده در سنگ و نیز عمق نفوذ واقعی کاترهد برای سنگ‌هایی با درزه‌داری زیاد به ترتیب حدود ۴۰٪ و ۴۲٪ بیشتر از سنگ‌هایی با درزه‌داری کمتر است.

کلمات کلیدی: دیسک کاتر، ساییدگی نرمال، تحلیل عددی در مقیاس واقعی، روش اجزای گسسته، تنش فون میسس، زون خرد شده