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Analysis of Grinding and Chipping Processes beneath Disc Cutters of Hard Rock Tunnel Boring Machines (Case study: Uma-Oya water Conveyance Tunnel, SriLanka)

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Abstract

Mechanized tunneling in rocks is based on fracture propagation and rock fragmentation under disc cutters. Rock chipping is an efficient kind of fragmentation process, while the grinding process may occur under special conditions. The cutter-head penetration is an appropriate parameter involved in order to distinguish between the chipping and grinding processes in rock cutting. In this work, the grinding and chipping processes are investigated in the Uma-Oya water conveyance tunnel in Sri Lanka. The Uma-Oya project is a water transfer, hydropower, and irrigation system in the SE part of the central highland region of Sri-Lanka. From a geological viewpoint, most parts of the tunnel route in the studied section consist of very strong and abrasive metamorphic rocks that potentially are susceptible to grinding occurrence during the boring process under disc cutters. In this work, firstly, data processing is performed in order to identify the boundary between chipping and grinding. Then the chipping and grinding processes are modeled using the practical numerical and artificial intelligent methods. In the numerical modeling stage, we try to make the modeling as realistic as possible. The results obtained from these modeling methods show that for the penetrations less than 3 mm/rev, the grinding process is dominant, and for the penetrations more than 3 mm/rev, rock chipping occurs. Also, in the numerical modeling, no significant fracture expansion is observed in the rock when the penetration is less than 3 mm/rev. Moreover, it can be seen in the numerical modeling of the chipping process that the propagated fractures come together and the chips are created.

1. Introduction

Mechanized tunneling is a widely interesting method used in order to construct tunnels in soils and rocks. The design and selection of an appropriate Tunnel Boring Machine (TBM) is a vital problem, especially in the hard rock tunneling projects. Also, some machine and rock parameters that affect the performance of TBM are the rotational speed, thrust force, torque of cutter-head, and strength of rock units. Previously, several studies have been focused on the TBM performance and the design and calculation of its related parameters.

In the past decades, the prediction of TBM penetration rate has been an interesting subject for some researchers. For example, a statistical model for the prediction of the TBM penetration rate has been set up using the non-linear regression analysis

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[1]. This statistical prediction model has been created by combining the rock mass boreability conceptual model with the established database. This study has shown that the uniaxial compressive strength and the joint density have the main effects on the penetration rate [1]. The TBM penetration rate estimation has also been studied using rock mass classifications for two tunnels in Italy. The researchers in this study used RMR and Beniawski's classifications for this purpose [2]. In this regard, the penetration and advance rates have been estimated using the prediction models such as CSM[1] [3], NTNU[2] [4], [5], and Q_{TBM}[3] [6]. Yagiz (2008) has studied the effects of rock mass properties such as the uniaxial compressive strength, Brazilian tensile strength, rock brittleness/toughness, distance between planes of weakness, and orientation of discontinuities on the TBM performance for hard rock conditions [7]. In order to estimate the rock mass boreability and TBM penetration rate, a boreability classification system and a new empirical chart has been also suggested in [8]. In addition to the prediction of the TBM performance, some researches have concentrated on the field [9] and laboratory studies [10], [11]. Also a small-scale disc cutting process has been modeled in the laboratory in a range of soft to very hard rocks [12]. Moreover, a new empirical model has been developed based on the statistical analyses of machine performance [13]. Besides, rotary cutting tests on full-scale granite rock has been experimentally conducted using the TBM disc cutters [14].

In the previous studies, in order to study the TBM penetration and performance, numerical modeling of the fracture propagation due to mechanized tunneling was of interest. Numerical modeling is a flexible method used to simulate the penetration of disc cutters in rocks. In this regard, numerical simulation of the influence of discontinuity spacing on rock fragmentation has been carried out in [15]. In the mentioned study, the disc-cutter penetration in jointed rock mass has been numerically modeled using the Discrete Element Method (DEM). The rock fragmentation has also been modeled due to the TBM penetration. This paper presents an RFPA[4] based the numerical code, and is used to simulate the rock breakage process induced by fracture propagation due to one- and two-disc cutter penetration [16]. Micro-crack propagation in rocks due to TBM tunneling has been investigated numerically and in the laboratory [17]. In this work, DEM modeling has been utilized to simulate the disc-cutters penetration in rock and compared with some laboratory tests. Previously, the DEM simulation has also been used to model the influence of discontinuity orientation on rock fragmentation by TBM. The results obtained show that the joint orientation can mainly influence the crack propagation due to disc cutter penetration [18]. Another rock parameter that has significant affect the rate of TBM penetration is rock brittleness. The ratio of uniaxial compressive strength to Brazilian tensile strength has been identified as the rock brittleness by [18]. They investigated the effects of rock brittleness on the TBM performance using several laboratory and numerical tests. Moreover, a new coupled RBD-DEM method has been proposed in order to investigate the TBM performance in 3D soft strata [19]. Investigation of the effects of disc cutter spacing to penetration depth ratio and rock strength effects on zone beneath the disc cutter has also been carried out using DEM [20].

Furthermore, the TBM performance in several past studies has been investigated using the artificial intelligence techniques. For example, the TBM penetration rate has been estimated using the Bayesian prediction approaches [21]. In this study, the researchers predicted the TBM penetration rate based on some parameters of rock mass and machine such as the UCS, brittleness of the intact rock, angle between the plane of weakness and tunnel axis, and spacing of weakness planes [21]. Acaroglu *et al.* (2008) have predicted the specific energy requirement of disc cutters (CCS or constant cross section type) in the rock cutting process by TBM using a fuzzy logic model [22]. In another study, fuzzy logic has been used for the TBM penetration rate prediction in hard rocks [23]. Additionally, the TBM performance modeling using Artificial Neural Networks (ANNs) has been previously studied by several researchers. Benardos and Kaliampakos (2004) have introduced an ANN to model the TBM performance in the Athens metro tunnels based on the geological and geotechnical properties of the studied site [24]. In order to predict the TBM penetration rate, some past studies have been used in various optimization techniques. Some different

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[1] Colorado School of Mines

[2] Norwegian University of Science and Technology

[3] Q-system for TBM

[4] Rock Failure Process Analysis

optimization techniques including DE[5], HS-BFGS[6], PSO[7], and GWO[8] have been utilized for the TBM performance prediction [25], [26]. The hybrid intelligent method has also been utilized for the TBM penetration rate prediction [27]. Rostami *et al*. (1996) have presented a comparison between two CSM and NTH models for the prediction of the TBM performance [28]. Furthermore, Farrokh *et al*. (2012) have presented an interesting review study to compare various models for the approximation of the penetration rate of the hard rock TBMs [29]. A novel fuzzy hybrid approach has been developed to assess the cutter penetration based on the geology and construction demand [30].

Some statistical, numerical, and intelligent techniques for the prediction and estimation of the TBM performance have been presented in the literature. As it can be seen, the problem is interesting for many researchers, and each one of them has tried to solve it using his/her particular method. The rock grinding and chipping processes, due to mechanized tunneling, are important as the TBM performance issues. Recently, a hybrid numerical code based on the discrete element and finite element methods has been proposed in order to model the rock chipping process due to the disc cutter penetration [31]. The grain-scale effects on the grinding and chipping processes have been numerically modeled using the finite difference method [32]. Villeneuve (2017) has utilized the TBM penetration tests as an indicator of two grinding and chipping phenomena in hard rocks. She showed that the rock strength was a very important parameter to control the necessary net thrust of the cutter for the change from the grinding to the chipping process [33]. Recently, some researchers have investigated and proposed the relationships between the rock mass properties (such as UCS and RMR) and measured the TBM parameters as a prediction model [34].

As it can be seen in the literature, the researchers have mostly focused on the effect of one or more properties on the rock and machine on the TBM performance using a special method. However, in the present work, an attempt was made to set a clear boundary for the chipping and grinding conditions for machine drilling. Generally speaking, the occurrence of rock grinding and chipping processes beneath the disc cutters were investigated using data processing, and numerical and artificial intelligent methods based on the data obtained from the Uma-Oya water conveyance tunnel. Numerical modeling, in this research work, was performed using DEM, and ANN was used as an artificial intelligent method.

2. Project description

The Uma-Oya underground hydropower project is located in the southern part of the central hills in Sri Lanka. The project will transfer 145,000,000 m^3 of water for irrigation purposes, and will develop a head of more than 700 m for the production of electricity in a power plant with a rated capacity of about 120 MW. Part of this huge project is a 15.2 km long water conveyance tunnel, which transfers water from a reservoir to the pressure shaft followed by the powerhouse cavern. Figure 1 shows the position of the Uma-Oya project and the water conveyance tunnel [35].

The tunnel transfers water from the Dyraaba dam reservoir to the shaft of the Uma-Oya underground hydropower. The technical specifications of the tunnel are tabulated in Table 1.

Table 1. Main technical specifications of the project.

Property	Description
TBM type	Double shield hard rock machine
Machine manufacturer	Herrenknecht company (Germany)
Lining type	Precast concrete tunnel segments
Tunnel length	15.2 km
Outer diameter of tunnel	4.3 m
Inner diameter of tunnel	3.8 m

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[5] Differential Evolution

[6] Hybrid Harmony Search

[7] Particle Swarm Optimization

[8] Grey Wolf Optimizer

The two similar double-shield hard rock TBMs employed in this tunnel were manufactured by Herrenknecht. The cutter-heads were equipped with 27, every 17 inches or 432 mm diameter cutters with a capacity of about 250KN. The other characteristics of the machines are listed in Table 2. Also the cutter-head design used in this tunneling project is shown in Figure 2.

Table 2. Main specifications of selected machines for the Uma-Oya project.

Parameter	**Value in two selected machine**	
	Lot A	**Lot B**
Machine type	D.S. TBM	D.S. TBM
Cutterhead diameter	4.3 m	4.3 m
Disc-cutter diameter	432 mm (17 inches)	432 mm (17 inches)
Amount of disc cutters	27	27
Max. operating cutter-head thrust	21287 KN	21287 KN
Power	1250 KW	1250 KW
Rotation speed	0 to 11 rpm	0 to 11 rpm
Torque (nominal)	1725 kN.m (11 rpm)	1725 kN.m (11 rpm)
Thrust cylinder stroke	1300 mm	1300 mm
Machine weight	247 ton	247 ton

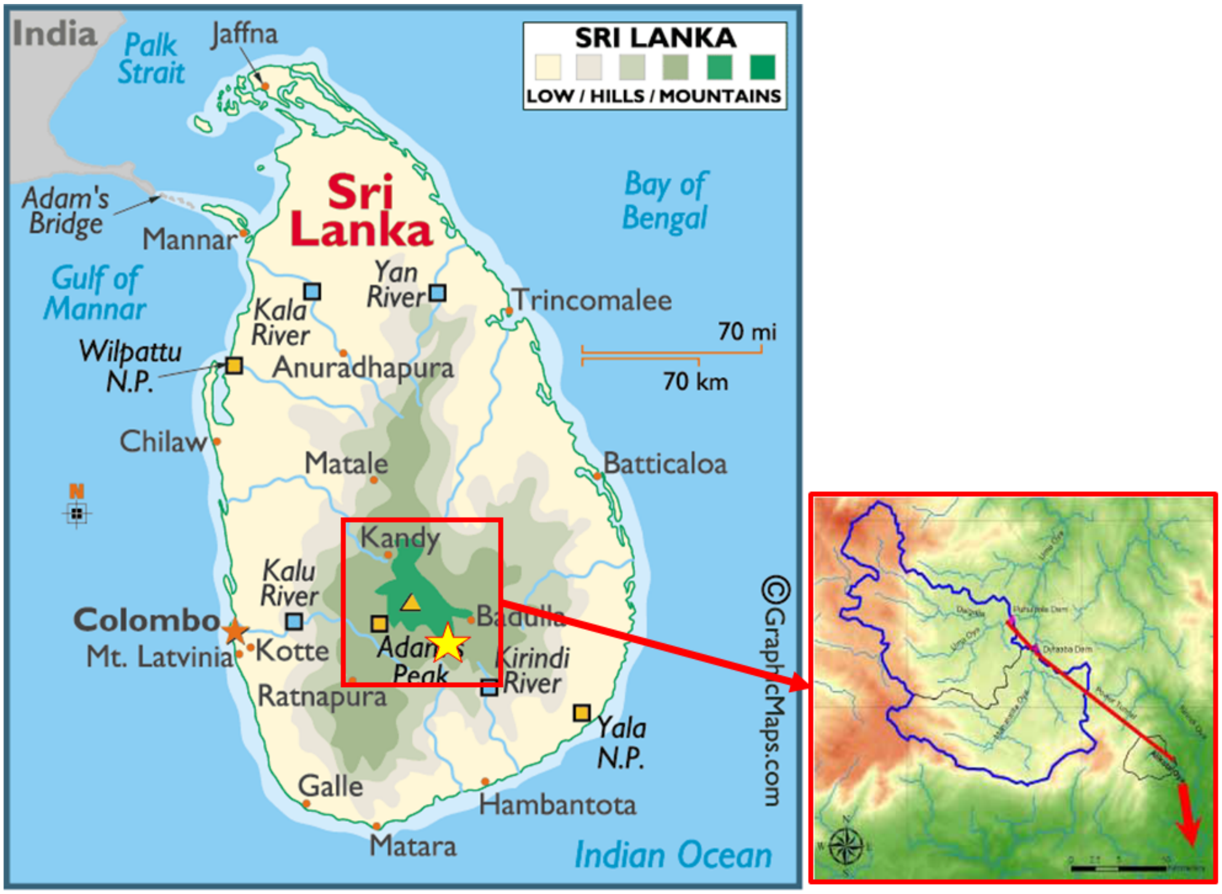


Figure 1. Position of the Uma-Oya project and its water conveyance tunnel.

As a geological viewpoint, about 90% of Sri Lanka contains Precambrian rocks. These rocks are sub-divided into three main lithotectonic units based on the rock type, metamorphic grade, structure, and isotopic characteristics. They are the 1) Wanni Complex (WC); 2) Highland Complex (HC); and 3) Vijayan Complex (VC).

Based on the geological viewpoint, the project area is located in the Highland Complex (HC) area forming the rugged high ground and occupying the center of Sri Lanka (Figure 3). This intensely tectonised complex contains a combination of ortho and para gneissic granulite units, and covers amphibolite grade rocks of Vijayan complex to the east and southeast. The actual contact between these two complexes is difficult to locate precisely but there is much evidence for a thrust fault–contact between the two units.

Based on the 1:100,000–scale geological maps, it is clear that the highland series rocks cover the whole project area, as already mentioned. The highland series rocks are Precambrian rocks formed under high-grade metamorphic conditions, and are composed of two main types of rocks namely meta-sediments and Charnockites or Charnockitic-gneisses. The metasedimentary rocks consist of garnet Sillimanite gneisses, garnet gneisses, quartz-feldspargranulites, marble, and impure crystalline limestone. Charnockitic gneisses are the most widespread rock units of the Highland series. All Charnockites have hypersthene, and a variety of pyroxenes are in common. The pegmatite veins are found occasionally.

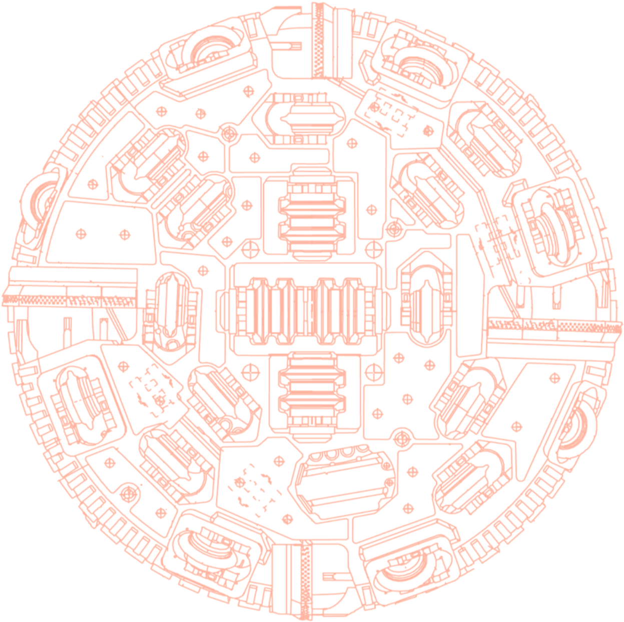


Figure 2. Design of the cutter-head used in the Uma-Oya project [35].

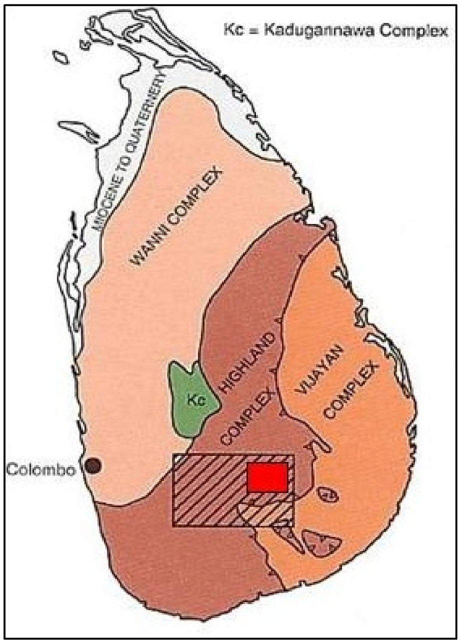


Figure 3. Tectonic map of Sri Lanka with project area in red [35].

Five lithological units are identified along the headrace tunnel alignment:

1. Leucocratic Feldspar Gneisses, banded to massive (Pmgqf)
2. Charnockitic Gneisses, undifferentiated, dark gray (Pmgk)
3. Garnet Gneisses, up to 70% Garnets and up to 3 cm Diameter (Pmgga)
4. Quartz-rich Gneisses to pure Quartzites, banded (Pmq)
5. Marbles and Calc-Silicate Gneisses, massive (Pmc/Pmqc)

Accordingly, the rock types of the project area mainly consist of Charnokitic Gneiss, Garnet-Sillimanite-Biotite-Graphite Gneiss, Quartzite, and Calc Gneiss. Figure 4 shows the geological cross-section along the tunnel. Also some outcrops of the rock mass in the project area are shown in Figure 5.

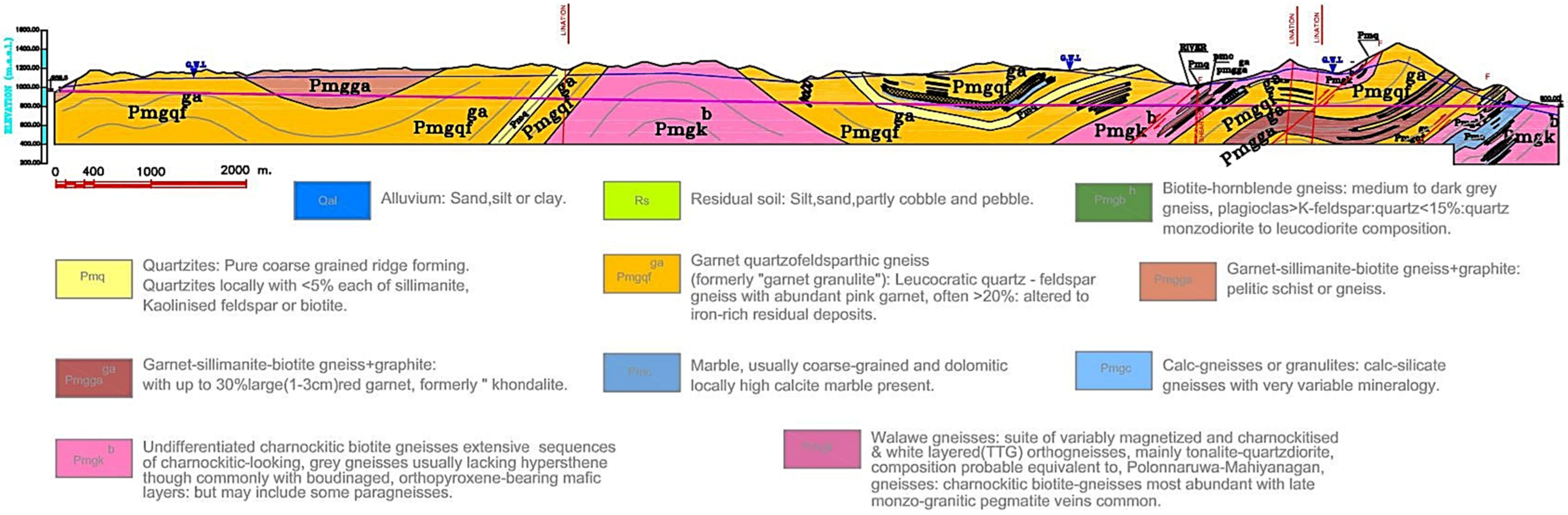


Figure 4. Geological cross-section prepared along the tunnel alignment [35].

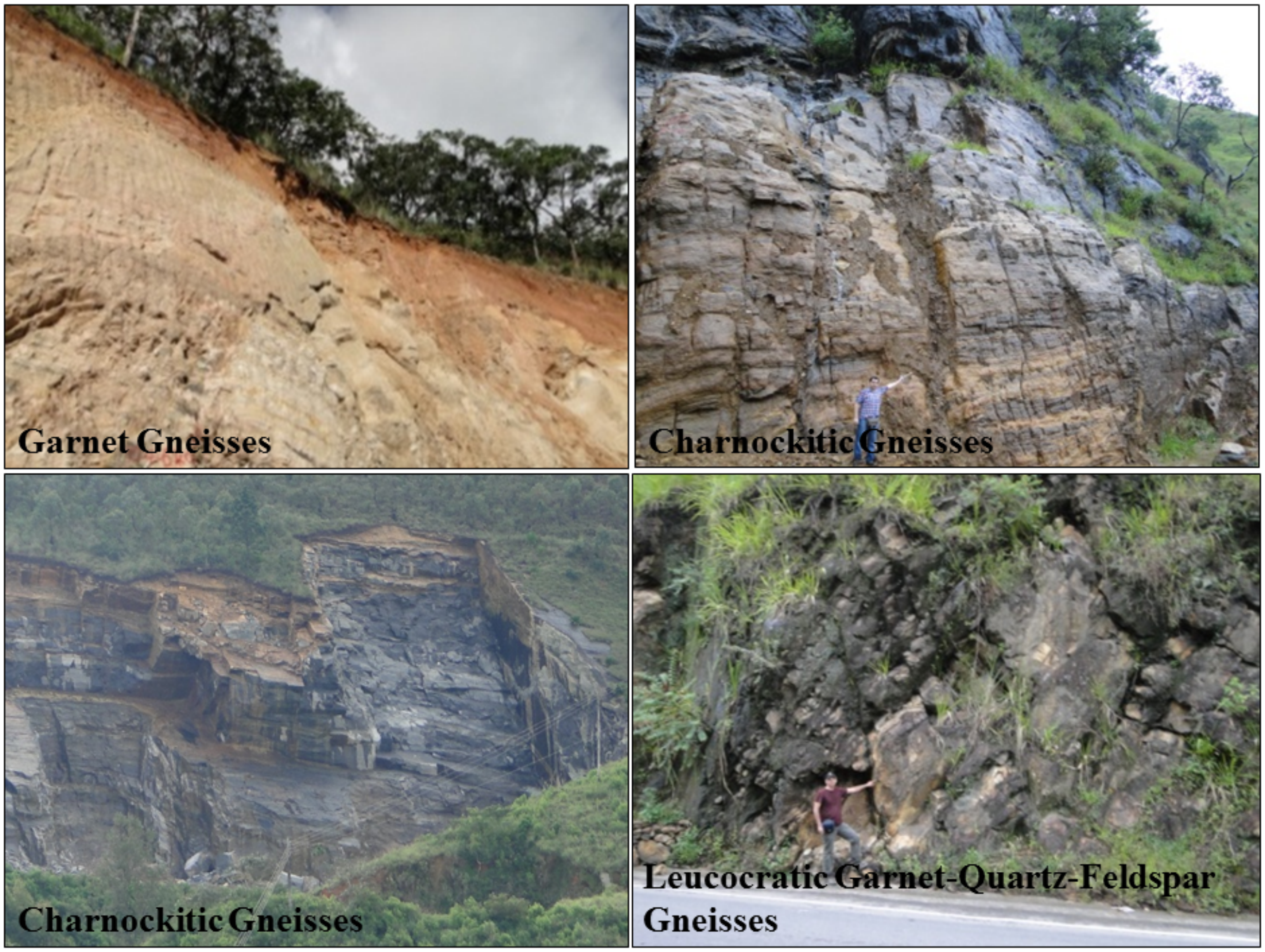


Figure 5. Pictures of some geological unit exposures in the project site [35].

The engineering geological units or types (RT) were defined using the relevant geological and geotechnical properties including the lithology, discontinuities, tectonic structures, and strength parameters of the intact rocks. In this work, based on the scale of studies and some visual and easy-measured engineering geological parameters such as the above-mentioned characteristics, the identified rock formations in the project area were categorized into four different engineering geological types. The main properties of these units are introduced in Table 3 [35].

Tab. 3 Geomechanical properties of the engineering geological types [35]

Eng. geol. type	RT-1	RT-2	RT-3	RT-4
Elastic modulus (GPa) Min-Max (Ave.)	25-40 (30)	19-33 (25)	10-20 (15)	19-33 (25)
Unit weight (t/m^3)	2.8	2.8	2.8	2.8
Poisson ratio Min-Max (Ave.)	0.15-0.3 (0.23)	0.17-0.24 (0.21)	0.17-0.24 (0.21)	0.17-0.24 (0.21)
UCS (MPa) Min-Max	150-250	100-150	30-80	80-100
Cohesion (MPa)	4	3.4	1.8	2.8
Friction angle (˚)	50	50	35	45

3. Rock grinding and chipping processes

The rock fragmentation process, due to disc cutter penetration, is mainly based on the fracture propagation in rocks. The thrust force and torque of TBM are the effective parameters of the machine to complete this process. The chipping process is the basic process that occurs through the rock cutting process beneath disc cutters, and is believed to be done by inducing the radial tensile fractures into the rock, which then propagate parallel to the tunnel face [32]. Due to the propagation of these fractures and coalescence to inherent cracks or fractures induced by other cutters, the chips are created. Therefore, a good rock cutting process has happened in this condition. Figure 6 schematically shows the fracture propagation due to the chipping process. The grinding phenomenon takes place when the fractures do not spread through the rock beneath the cutters, and only fine particles are produced. The generation of these fines reduces the efficiency of the cutting process, and it wears out the disc cutters.

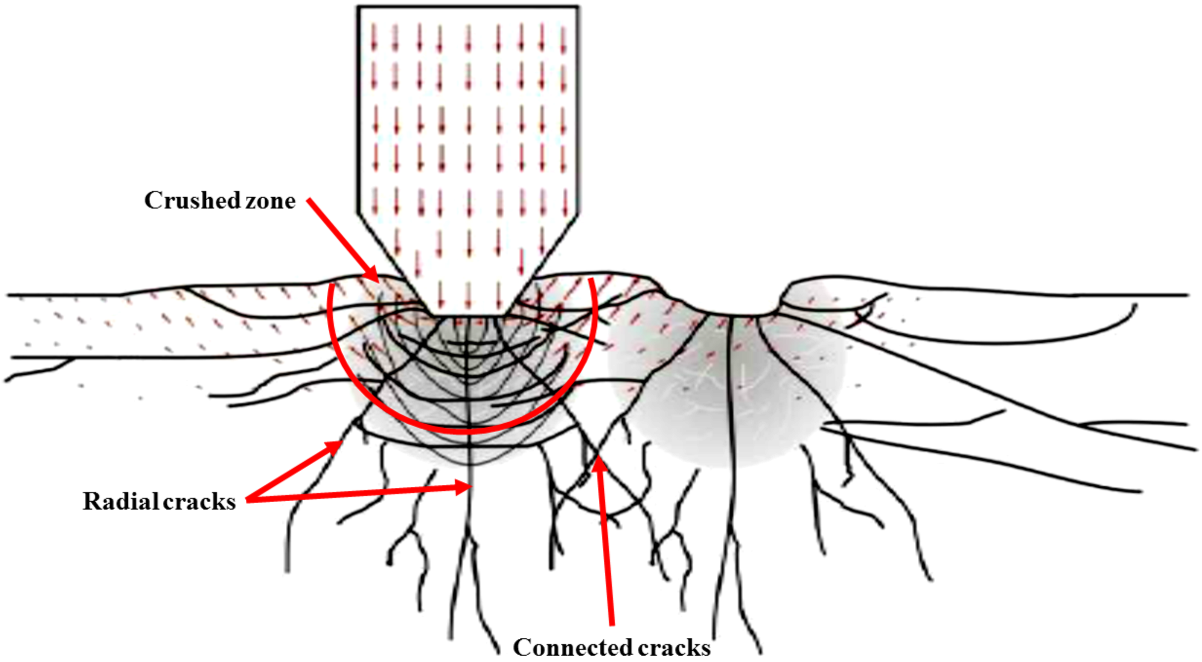


Figure 6. Fracture propagation beneath the disc cutters [32].

The past experiences show that when the cutter-head penetration is plotted versus the net thrust force, there is a critical point between the grinding and chipping processes due to the disc cutter penetration into the rocks. Villeneuve (2017), has analyzed the data from the results of a penetration test in the Alpine hard igneous and metamorphic rocks. These tests show that the critical penetration rate between the grinding and chipping processes is about 2 mm/rev [33]. The relation between the net thrust force and the penetration rate in the above-mentioned tests is plotted in Figure 7. Moreover, Gehring (2009) has identified a critical thrust force between the rock grinding and the chipping. The penetration related to this critical thrust force has been presented equally to (2 to 3) mm/rev [36].

In the headrace tunnel of the Uma-Oya project, the grinding phenomenon has happened along with some parts of its pathway. The grinding conditions have occurred between 650 and 3000 m of the headrace tunnel pathway that generally has the Charnokitic Gneiss, Garnet-Sillimanite-Biotite-Graphite Gneiss, and Quartzite rock types. Hence, the grinding process of the rocks is particularly important in this work. Figure 8 shows the tunnel face in this part of the headrace tunnel. As shown, due to the incomplete chipping process, the rock ridges have remained between grooves. In such situations, the cutter-head structure may be in direct contact with the rock face, which causes extra wear and destruction in the cutter-head, enhancement in the torque level, and decrease in the TBM advance rate.

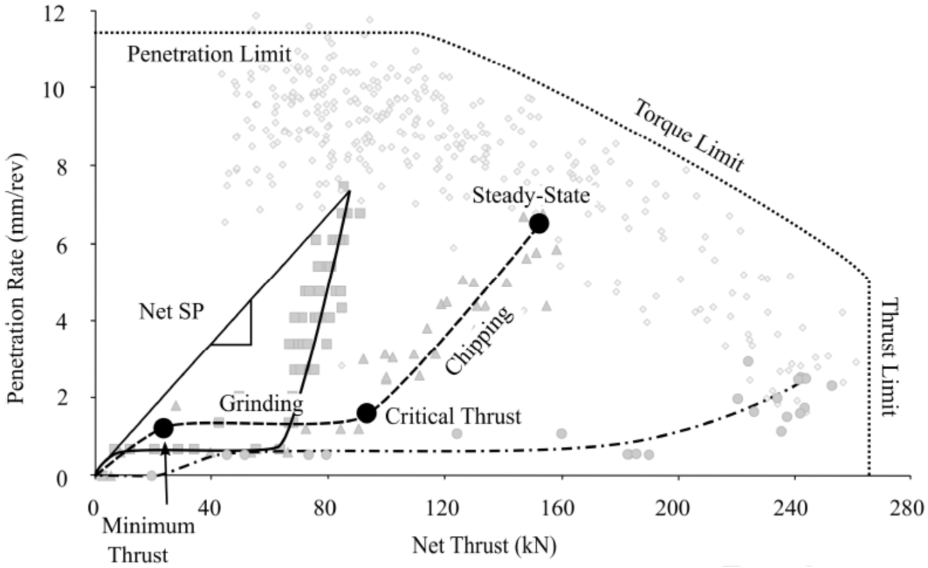


Figure 7. Relationship between the net thrust force and the penetration of each disc cutter [33].

Figure 8. An example of a tunnel face in a part of the tunnel, where grinding was dominant. The creation of ridges and adjacent deep grooves are indications of an incomplete chipping [35].

4. Statistical analysis of recorded data

In the Uma-Oya project in Sri Lanka, all the available data during the TBM excavation have been collected and recorded in a comprehensive database. There are 1289 datasets, each belonging to one stroke. This data includes the gross and net thrust force, penetration rate, cutter-head penetration, rotation speed, torque, and strength (UCS) of the rocks. All the geological data along the tunnel pathway were accessible since the tunnel lining was not continuous along the way. This data was analyzed statistically using the Minitab software, and the results obtained were shown in Figure 9 and Table 4.

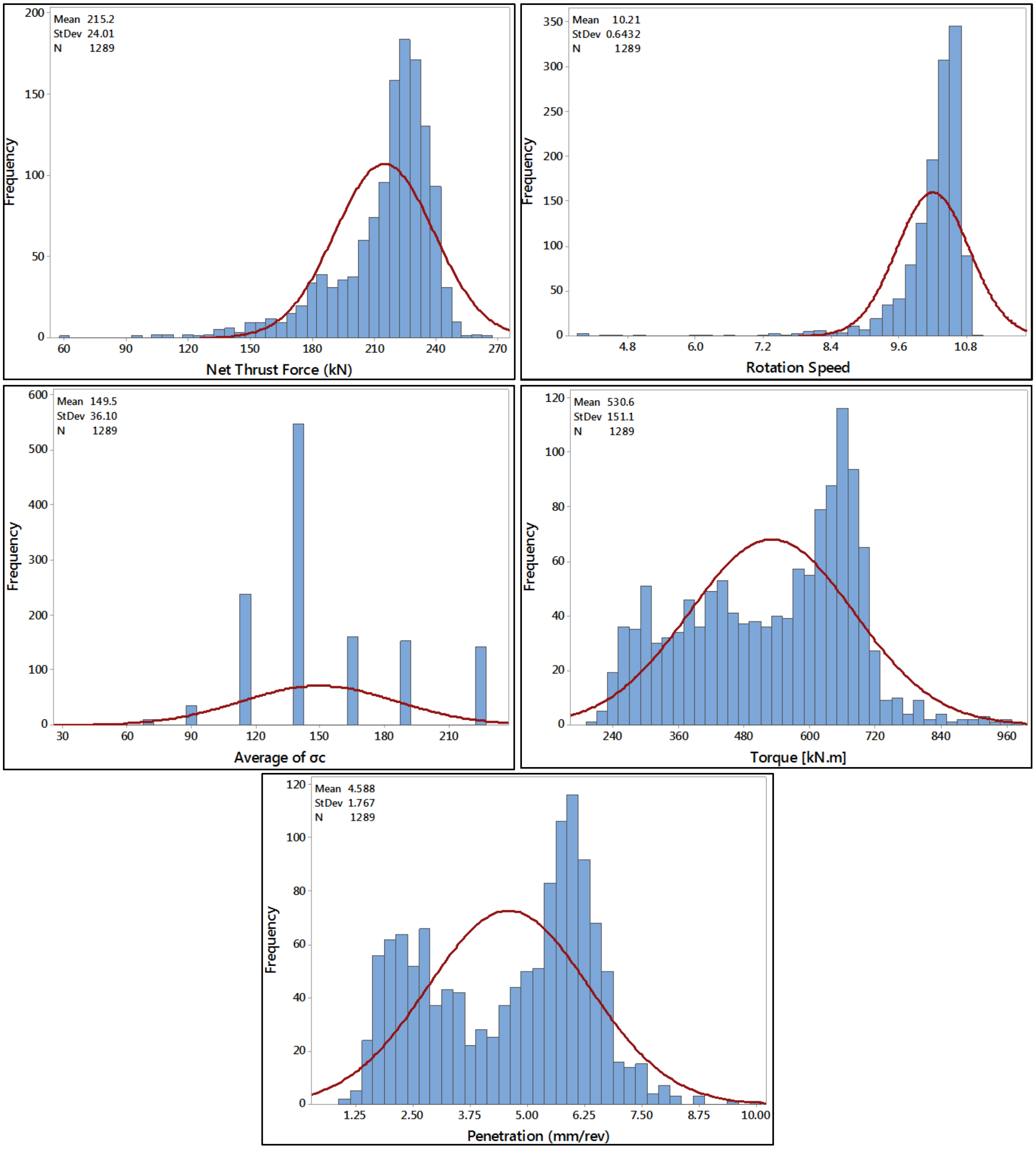


Figure 9. Frequency histogram of different parameters recorded in database.

Table 4. Statistical features of the datasets.

Available data	Min.	Max.	Mean	Standard deviation	Number of data
Net thrust force (kN)	58	267	215.2	2401	1289
Rotation speed (rpm)	4	11	10.21	0.64	1289
σ_c (MPa)	30	225	149.5	36.1	1289
Torque (kN.m)	208	981	530.6	151.1	1289
Penetration rate (mm/rev)	1	10	4.59	1.77	1289

As it can be seen in Table 3, all the datasets are placed in 4 categories based on the rock strength (USC < 80, 80 < UCS < 100, 100 < UCS < 150, 150 < UCS < 250, in MPa). This division is based on the measurements done in different engineering geological types recognized along the completed section of the tunnel. The relationships between the net thrust force and the penetration (P) of these categories are as for Figure 10.

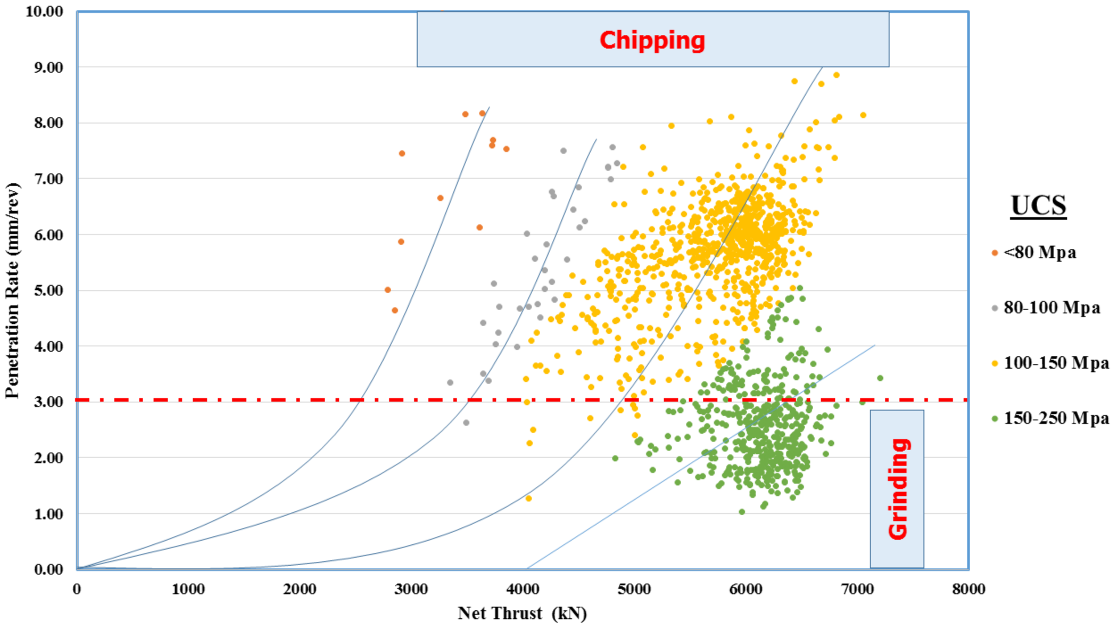


Figure 10. Relationships between net thrust force and penetration (P) for different UCS values.

As it can be seen in Figure 10, the required net thrust force for stronger rocks is greater than that of the rocks with lower strength. Moreover, based on the trend graphs (the best trend is exponential for UCS < 150 MPa and linear for UCS > 150 MPa), it can be said that the critical penetration for our case study is about 3 mm/rev. With a little care in the diagrams of Figure 10, it can be seen that increasing the penetration rate by thrust force increasing is significantly slow for PR < 3 mm/rev. On the other hand, this increase is faster in PR > 3 mm/rev. Therefore, it can be considered that in this case, PR = 3 mm/rev is the critical penetration rate and the boundary of the rock grinding and rock chipping processes. Also as shown in Figure 10, for hard rocks with a UCS of more than 150 MPa, despite the increase in the thrust force to about 7000 kN, there is little change in the penetration rate, and drilling is still performed under the grinding conditions.

5. Numerical modeling of rock grinding and chipping processes

Numerical modeling, especially discrete element modeling of fracture extension in the rock mass and fractured rock due to the disc cutting process [15], [18], [37] or other phenomena [38], has previously been performed in some studies. The distinct element method is an explicit finite difference numerical method that is commonly used for the stability assessment, failure, and deformation of rock masses. After being proposed by Cundall [39], the method was widely used for model rock mass in geo-mechanics. The equations of motion are the governing equations of DEMS for systems of rigid or deformable blocks. These governing equations are the Newton–Euler equations of motion for rigid bodies, cauchy equations of motion for deformable bodies [40].

Based on what earlier mentioned, numerical modeling of rock grinding and chipping has been performed using a practical discrete element (DEM) software called UDEC. The purpose of numerical modeling is the simulation of the fracture propagation in the rock when grinding or chipping are dominant. Also the critical penetration rate in numerical modeling is considered to be 3 mm/rev. Therefore, two types of numerical modelings were performed, one of them is for PR < 3 mm/rev and the other for PR > 3 mm/rev. The models are built-in dimensions of 0.5 × 0.5 m with two discs in the spacing of 0.1 m that penetrate from the right side of the rock models. Figure 11 schematically shows the geometry of the numerical models. In DEM, the intact rock can have a linear or non-linear elastoplastic behavior, individually. Also the intact rock is simulated by the Mohr-Coulomb plastic constitutive model. The geo-mechanical rock properties are considered in Table 3. In order to define the boundary conditions, the upper, lower, and left bounds were fixed, and the disc cutters penetrated from the right bound. After the numerical models were constructed, they were solved under 1,000,000 cycles in the UDEC software. The results of each type of modeling in fracture propagation due to disc cutter penetration in the rock are shown in Figure 12.

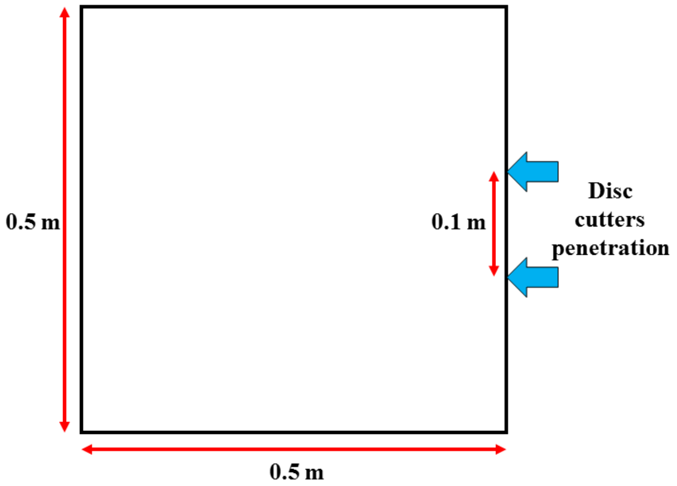
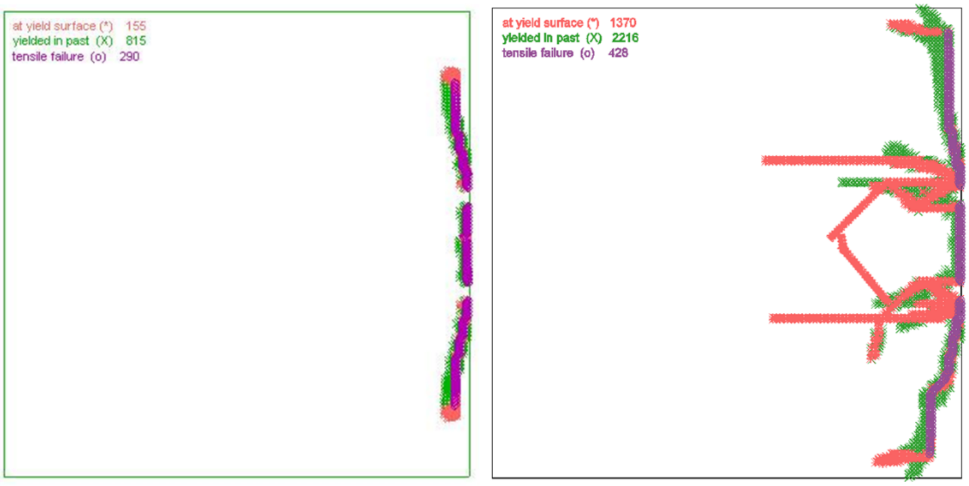


Figure 11. Geometry of the numerical modeling.

All of the models shown in Figure 12 were simulated in 1,000,000 cycles in the UDEC software. As it can be seen in Figure 12-a, no significant fracture expansion is observed in the rock medial when the penetration is less than 3 mm/rev (P = 2 mm/rev). In this condition, just a rock material in a zone near the tunnel surface is grinded and the fractures are not propagated in depth (Figure 12-a). On the other side, there are several obvious fractures propagated in the rock when the penetration is more than 3 mm/rev (P = 4 mm/rev in Figure 12-b). As shown in Figure 12-b, several fractures have been extended into the tunnel surface. Moreover, these fractures (created by a two-disc cutter) come together and rock fragmentation happens in the chipping process.



(a) (b)

Figure 12. Fracture propagation due to disc cutting process for a) P = 2 mm/rev (P < 3 mm/rev), and b) P = 4 mm/rev (P > 3 mm/rev).

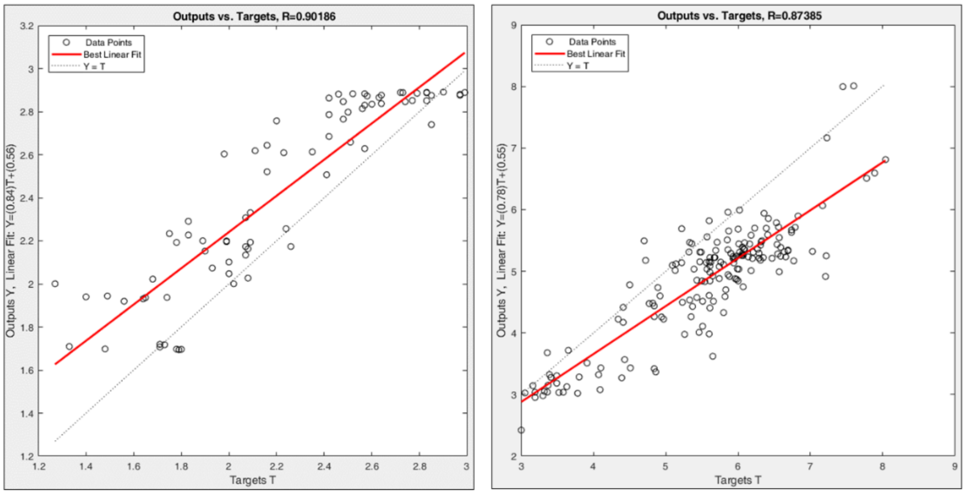
6. Artificial intelligent simulation of TBM performance

In addition to the utilized method in the past sections, the artificial intelligent methods are useful techniques to model the TBM performance, as it can be seen in the previous studies [24]. Among these methods, ANN is of applicable approaches in this field. ANN tries to imitate the parallel-information processing characteristic of the human brain. The growing interest in the black box type models based on ANN is due to its efficiency in well modeling non-linear multivariate problems in geo-mechanical problems. In this case, the authors modeled the TBM penetration in rocks using ANN.

There are about 1289 available datasets in the Uma-Oya TBM project. Based on the results obtained from the above sections, the ANN simulations were performed in two parts. At first, the simulation was done for the grinding conditions. To this end, the datasets in which the penetration rate was less than 3 mm/rev were considered. These available data were about 355 sets. Secondly, the chipping conditions were considered, and the ANN simulation was performed. At this part, the datasets in which the penetration was more than 3 mm/rev were modeled. This available data was about 934 sets.

The overall structure of ANNs is inspired by the human biological network, which is a combination of simple elements called neurons. ANNs transfer the relationship between the input and output data to the network structure by processing the experimental data. The neurons in the network are placed in certain layers depending on their performance. Each ANN has at least three layers: the input layer, the middle or hidden layer, and the output layer. ANN contains two working stages called learning and testing [41]. The known datasets are generally used as a training signal in the input and output layers during the learning stage. The recall stage is accomplished by one pass using the weight achieved in the learning stage. The ANN simulation in this work was done using the back-propagation (BP) network. A BP is a multi-layer neural network, which uses a gradient-descent technique similar to error minimization.

In this work, the input parameters in the ANN simulation of TBM penetration are the net thrust force, rotation speed, torque, and rock strength (UCS). Moreover, the goal parameter or output parameter is the cutter-head penetration. The simulation was performed using an appropriate code in the MATLAB software. A BP network was used for the simulation of the grinding conditions with the neuron pattern of 2-5-1 in its hidden layers. In this case, 278 datasets were used in order to train the BP network, and then the testing step was performed using the 77 datasets. Moreover, the BP network used for simulation of chipping conditions had a 5-2-1 neuron pattern in its hidden layers. Also in this case, 753 datasets were used to train the BP network, and then the testing step was performed using the 181 datasets. Figure 13 shows the results of the ANN simulation of the grinding and chipping processes due to the TBM penetration in comparison to the real data.



(a) (b)

Figure 13. Results of ANN simulation of disc cutting process for a) grinding (P < 3 mm/rev), and b) chipping (P > 3 mm/rev) conditions.

Generally speaking, in this section, the grinding and chipping P were predicted using an artificial intelligence technique called ANN. As shown in Figure 13-a, the results of the P prediction of TBM had good agreements with the real data (R = 0.9). Besides, P was well-predicted in the chipping conditions using ANN with R = 0.87 (Figure 13-b).

7. Conclusions

In the Uma Oya hydropower project, the grinding conditions have occurred between 650 and 3000 m of the headrace tunnel pathway that generally has the Charnokitic Gneiss, Garnet-Sillimanite-Biotite-Graphite Gneiss, and Quartzite rock types. In this work, the rock grinding and chipping processes were investigated using data processing, and numerical and artificial intelligent methods due to the tunnel boring procedure.

Field investigations and data processing of the TBM performance in the Uma Oya project show that there is a significant boundary between the grinding and chipping processes in terms of the cutter-head penetration. Thus data processing was performed in order to identify the boundary between the chipping and grinding conditions. As it could be seen in the results obtained, the critical penetration for this case study was about 3 mm/rev. For $P < 3$ mm/rev, the grinding conditions were dominated, whereas the chipping process was dominated when $P > 3$ mm/rev.

Then the chipping and grinding processes were modeled using a practical numerical method. As it could be seen in the numerical modeling, no significant fracture expansion was observed in the rocks when the penetration was less than 3 mm/rev ($P = 2$ mm/rev). On the other side, there were several obvious fractures propagated in the rock when the penetration was more than 3 mm/rev ($P = 4$ mm/rev in Figure 7-b). Moreover, it could be seen in the numerical modeling of the chipping process that the propagated fractures came together, and the chips were clearly created.

Moreover, the penetration rates in the grinding and chipping conditions were predicted using an artificial intelligent technique called ANN. The BP network was used for simulation of the grinding and chipping conditions with the neuron patterns of 2-5-1 and 5-2-1, respectively, in the hidden layers. As mentioned, the results of the P prediction of TBM had good agreements with the real data.

Generally speaking, the cutter-head penetration is a determining factor to distinguish between the chipping and grinding processes in rock cutting. In this work, the rock grinding and chipping processes were placed under scrutiny due to the tunnel boring procedure using three different approaches. The presented technique could be utilized for modeling and prediction of how rocks fragmented under disc cutting in similar project conditions. To this end, the data from the considered project should be processed and then used in a similar technique. Eventually, in this work, we presented an applicable approach in order to predict the rock fragmentation behavior due to the disc cutting process.

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آنالیز فرآیندهای آسیاب شوندگی و تشکیل تراشه زیر دیسک برشی در عملیات حفاری ماشین حفر تونل در سنگ سخت (مورد مطالعاتی: تونل انتقال آب اوما-اویا، سریلانکا)

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چکیده:

تونل‌سازی مکانیزه در سنگ بر اساس انتشار شکستگی و خردایش سنگ در زیر دیسک‌های برشی انجام می‌شود. تشکیل تراشه نوع کارآمدی از فرآیند خردکردن سنگ است، در صورتی که فرآیند آسیاب شوندگی در شرایط خاصی رخ می‌دهد. نفوذ کله حفار، یک پارامتر مناسب جهت تمایز میان فرآیندهای آسیاب شوندگی و تشکیل تراشه در برش سنگ است. در این مطالعه، فرآیندهای آسیاب شوندگی و تشکیل تراشه در پروژه انتقال آب اوما-اویا در سریلانکا مورد بررسی قرار گرفته است. پروژه اوما-اویا یک پروژه انتقال آب، نیروگاهی و آبیاری زهکشی در بخش جنوب شرقی نواحی مرتفع مرکزی سریلانکا می‌باشد. از نقطه نظر زمین‌شناسی، بیشتر قسمت‌های مسیر تونل در بخش مورد مطالعه، شامل سنگ‌های دگرگونی بسیار محکم و ساینده است که به طور بالقوه مستعد پدیده آسیاب شوندگی در طی فرآیند برش زیر دیسک‌های برشی هستند. در این مطالعه، ابتدا به منظور تشخیص مرز بین آسیاب شوندگی و تشکیل تراشه، داده‌های پروژه مورد پردازش قرار گرفته‌اند. سپس فرآیندهای آسیاب شوندگی و تشکیل تراشه با استفاده از روش‌های عددی و هوش مصنوعی شبیه‌سازی شده‌اند. در مرحله مدل‌سازی عددی، تلاش شده است تا مدل‌های ساخته شده به واقعیت نزدیک شوند. نتایج کسب شده از این روش‌های مدل‌سازی نشان می‌دهند که برای نرخ‌های نفوذ کمتر از ۳ میلیمتر بر دور پدیده آسیاب شوندگی غالب بوده و برای نرخ نفوذ بیشتر از ۳ میلیمتر بر دور تشکیل تراشه اتفاق می‌افتد. همچنین، در مدل‌سازی عددی هنگامی که نرخ نفوذ دیسک‌های برشی کمتر از ۳ میلیمتر بر دور باشد هیچگونه گسترش ترک قابل توجهی در سنگ دیده نمی‌شود. علاوه‌براین، در مدل‌سازی فرآیند تشکیل تراشه مشخص است که شکستگی‌های مختلف در سنگ ایجاد و به یکدیگر نیز متصل شده و تراشه‌ها تشکیل می‌شوند.

کلمات کلیدی: پدیده‌های آسیاب شوندگی و تشکیل تراشه‌های سنگی، نرخ نفوذ ماشین حفار، عملکرد ماشین حفار ، مدل‌سازی عددی، شبکه عصبی مصنوعی.