



Evaluation of TBM Cutter Wear in Naghadeh Water Conveyance Tunnel and Developing a New Prediction Model

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Abstract

Replacing worn disc cutters in a tunnel boring machine (TBM) operation is a time-consuming and expensive process. This article presents the study of disc cutter wear rate during the excavation of 36 km Naqadeh water conveyance tunnel with a diameter of 6.325 m. The construction of this tunnel in northwest Iran has been recently completed. The geological setting of the tunnel consists of variable lithology, including limestone, shale, granite, and granodiorite units. Field data were collected and analyzed from TBM tunneling of 9.5 km of the tunnel. The analysis was performed by incorporating the types of wear and comparing the accuracy of traditional cutter wear prediction models. The new model was developed using statistical analysis of the observed cutter wear in this project. The validity of the proposed model was evaluated using the excavation data for the following 2 km of the tunnel. The model developed in this study allows estimating wear rate and cutter life using common rock characterization parameters such as the Cerchar abrasivity index (CAI) and the uniaxial compressive strength (UCS).

Keywords Hard rock · Mechanized tunneling · Disc cutter life · Cerchar · Abrasivity

Abbreviations

| | | | |
|------------|--------------------------------------|-----------|----------------------------------|
| AVS | Abrasion value | Ni | Cutter position number |
| B1, B2, B3 | Brittleness indices | N_{TBM} | Actual number of disc cutters |
| BTS | Brazilian tensile strength | R | Coefficient of regression |
| CAI | Cerchar abrasivity index | R^2 | Coefficient of determination |
| CLI | Cutter life index | rri | Relative position of disc cutter |
| CSM | Colorado school of mines | S20 | Brittleness test |
| DRI | Drilling rate index | SJ | Sievers J-value test |
| d_{TBM} | TBM diameter | TBM | Tunnel boring machine |
| Ef | Average cutter life | UCS | Uniaxial compressive strength |
| Es | Specific energy of entire cutterhead | Vc | Average cutter life (m^3) |
| F | Test for the analysis of variance | OM | Optical microscopy |
| H_f | Average cutter life (m^3 /cutter) | HRC | Rockwell hardness c scale |
| H_h | Average cutter life (h/cutter) | VHNR | Vickers hardness number |
| H_m | Average cutter life (m/cutter) | | |
| H_n | Number of replaced disc cutters | | |
| TBM | Tunnel boring machine | | |
| Hri | Relative cutter life | | |
| Is50 | Point load index | | |

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1 Introduction

Disc cutter wear is one of the challenging issues in TBM tunneling through abrasive and hard rock formations. Daily inspection and replacing of worn disc cutters is a time-consuming process that may impact project schedule and causes machine downtime and delays in projects. Therefore, accurate estimation of disc cutter life could help in planning, management, and optimization of mechanized tunnel construction projects.

Considering the importance of disc cutter wear and adverse effects on the performance of TBMs, numerous studies have been conducted to investigate the effect of rock and soil abrasiveness on cutting tools (Barzegari et al. 2012, 2015; West 1989; Deketh et al. 1998; Kasling and Thuro 2010; Jakobsen and Lohne 2013; Liu et al. 2017 and Roby et al. 2009). Frough and Torabi (2017) studied the rock engineering system for estimation of TBM stoppage. In a study by Zhang et al. (2019), which was based on the analyses of disc cutter wear and cutter motion in the rock breaking process, they postulated a theoretical model for prediction of disc cutter wear in TBM applications. Repetto and Fidelibus (2017) introduced a decision plot for a single shield TBM design. Barzegari et al. (2014) and Filbà et al. (2016) studied the encounter of TBM with boulders in mechanized tunneling. Lin et al. (2017) carried out research to investigate the specific matching characteristics of the cutter ring (hardness and toughness) on rock samples using friction tests on a TBM cutter performance test bench. In a study by Zhang et al. (2017), they studied the wear behavior of the TBM disc cutter ring under dry, wet, and seawater conditions and conducted a series of cutter-rock wear tests on the performance of specially designed TBM cutter. Karami et al. (2020) conducted research to investigate disc cutter wear issue in the Kerman water conveyance tunnel and developed a new empirical model to predict cutter wear using CAI and RQD.

The most commonly used models for predicting disc cutter wear include the Colorado School of Mines (CSM), Norwegian University of Science and Technology (NTNU), and Gehring models. The CSM model is based on a basic cutter life, using the Cerchar abrasivity index (Rostami et al. 2005). The NTNU model utilizes special charts and simple equations for predicting the cutter life. The main input parameter of this model is the cutter life index (CLI), which is an indicator of rock abrasiveness. In a study by Gehring (1995), they applied data from various projects to determine the relationship between the CAI and wear-induced cutter weight loss. Nelson et al. (1994) suggested empirical method for the cutter life prediction. This model is based on comparing input data with a real database obtained from TBM. The input data for this method include rock type, joint frequency, and some machine parameters. Oparin and Tanaino (2015) proposed a new method for identifying rock abrasion based on physical, mechanical, and structural properties of rock. They indicated that the wear process mainly depends on the material properties and contact mechanism between a cutter and rock surfaces. Hassanpour et al. (2014, 2015) and Hassanpour (2018) found a relationship between disc cutter life and geological parameters including rock strength and Vickers hardness via statistical analysis on actual engineering data. Based on their work, they proposed an empirical model for the prediction of disc cutter wear. Ko et al. (2016) examined the influence of CAI and CLI values on disc cutter life

using the Gehring, CSM, and NTNU models and reported that variations of CAI have an effect on the Gehring model. Table 1 presents a brief summary of some existing models for predicting disc cutter wear.

The present study was conducted to provide more reliable relationships between geological properties and disc cutter wear in hard rock TBM tunneling. The data were collected from Naqadeh water conveyance tunnel lot 2, located in the northwest of Iran, some 9.5 km southwest of city of Naqadeh. The studied tunnel was excavated using a TBM with a diameter of 6.325 m through various igneous, sedimentary, and metamorphic rocks. The disc cutter wear and accuracy of traditional cutter wear prediction models were evaluated. Statistical analysis was employed to develop a new statistical model between rock parameters and disc cutter wear.

2 Geological Characteristics

The Naqadeh tunnel area is part of the metamorphic and ophiolitic belt of Sanandaj–Sirjan zone (SSZ) (Aghanabati 2004). The SSZ mainly consists of igneous, sedimentary, and metamorphic rocks ageing from Precambrian to the present. The zone has endured a series of tectonic activities that caused some faults and discontinuity in the region. The carbonatic and calcareous units and the volcanic rocks created the mountains in the region due to the uplift and resistance against erosion, while the plains were formed by the shaly and sandy units in the areas. Alteration of the Cretaceous and earlier units and the intrusion of granitic layers during Laramid tectonic event is the other important feature in an extended area of the zones mentioned earlier. The intrusive units including granite, granodiorite, diorite, and granite–hornfels ranging in age from the upper Cretaceous to the Paleocene are the most frequent lithological features along the tunnel alignment. A geological map of the study tunnel alignment is provided in Fig. 1.

To evaluate the engineering geological characteristics of the rock mass along the tunnel alignment, exploratory boreholes were drilled. A series of laboratory tests including Petrographic analysis (ASTM C295), uniaxial compressive strength (UCS) (ASTM D2938), point-load strength index (Is50) (ASTM D5731), Brazilian tensile strength (BTS) (ASTM D3967), and CAI (ASTM D7625) were carried out on specimens obtained from subsurface coring. A description of the main geological units encountered along the tunnel alignment is provided in Table 2.

Two important granite and granodiorite geological units were encountered during the tunneling. These units are composed of minerals with a Vickers hardness of 595–1120 including coarse-grained quartz, potassium feldspar, and plagioclase. The geotechnical profile of the studied tunnel is illustrated in Fig. 2. The main physical and mechanical

Table 1 Summary of existing models for predicting disc cutter wear (after Liu et al. 2017)

| No | References | Required geomechanical tests | Input geomechanical parameters | Output cutter wear parameters |
|----|--------------------------------|---|--|--|
| 1 | Ewendt (1992) | Petrographic analysis and point load index | Quartz content, grain size, and point load index | Wear rate |
| 2 | Wijk (1992) | Cerchar abrasivity test, UCS test, and point load test | CAI, UCS, tensile strength | Rolling distance |
| 3 | Gehring (1995) | Cerchar abrasivity test and UCS test | CAI, UCS | Average cutter ring life |
| 4 | Rostami (1997) | Cerchar abrasivity test | CAI | Average rolling distance, delays and the total number of changed cutters |
| 5 | Bruland (1998) | Sievers' J miniature drill test and AVS test | CLI | Average cutter life, delays, and the total number of changed cutters |
| 6 | Dahl et al. (2007) | Sievers' J interception point test | SJIP start, and SJIP steepest | Cutter life index |
| 7 | Maidl et al. (2008) | Cerchar abrasivity test and UCS test | CAI and UCS | Average rolling distance |
| 8 | Bieniawski et al. (2009) | Cerchar abrasivity test, UCS test, brittleness test (S20), and Sievers' J miniature drill test (SJ) | CAI, UCS, and DRI | Specific cutter consumption |
| 9 | Frenzel (2011) | Cerchar abrasivity test | CAI | Net cutter life, the total number of changed cutters |
| 10 | Wang et al. (2012) | | Specific energy of entire cutterhead (Es) | Average wear extent and number of ineffective cutters |
| 11 | Hassanpour et al. (2014, 2015) | Vickers hardness test and UCS test | Vickers hardness number of rock (VHNR), UCS, and ABI | Average cutter ring life |
| 12 | Yang et al. (2015) | UCS test | UCS | Wear rate and linear wear rate |
| 13 | Liu et al. (2017) | Cerchar abrasivity test and UCS test | CAI and UCS | Average cutter life (E_r) |

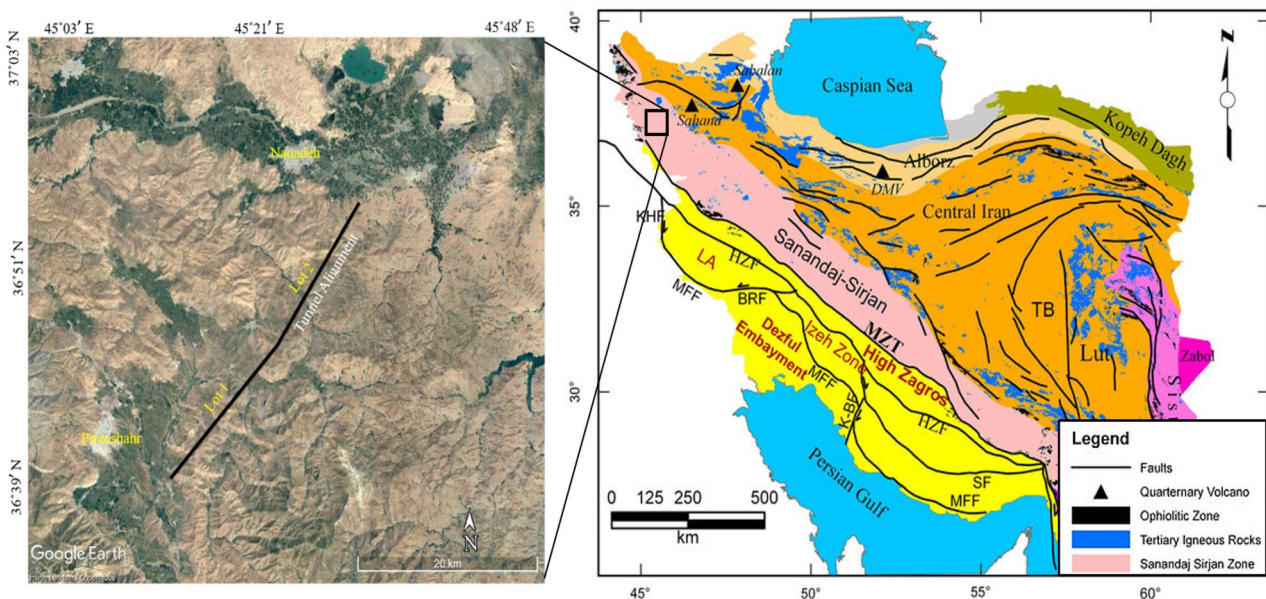


Fig. 1 Geological map of Iran (Aghanabati 2004) and the location of Naqadeh tunnel alignment shown on the satellite image

characteristics of the aforementioned lithologies are summarized in Table 3. Based on the geological units, the TBM field performance database for the study of disc cutter life includes eight sections. The ranges of the input parameters

into the database and their basic descriptive statistics are given in Table 4.

Table 2 Descriptions of main engineering geological units encountered along the Naqadeh tunnel alignment

| Geological unit | Description | Lithology | Quartz content (%) | Porosity (%) |
|-----------------------|---|--------------------------------------|--------------------|--------------|
| Wgr ₁ | Slightly weak, blocky to irregular, weathered, and broken; unstable | Granite and granodiorite | 50 | 2.8 |
| Wgr ₂ | Strong to moderately strong, blocky to massive, and fresh to slightly weathered; stable | Granite and granodiorite | 50 | 2.3 |
| K _{d.ds} | Moderately strong, blocky, and slightly weathered; stable | Dolomite and sandy dolomite | > 10 | 0.55 |
| K _{d.sh} | Moderately strong, blocky, and slightly weathered; stable | Dolomite with shale and slate layers | 1 | 1.16 |
| K _{sh.sl.ph} | Moderately strong, blocky to tabular, and slightly weathered; stable | Shale, slate, and phyllite | – | 1.1 |
| K _{ld} | Moderately strong, blocky, and slightly weathered; stable | Limestone and dolomite | 1–15 | 1.4 |
| D _b | Moderately strong, blocky and irregular, and slightly weathered; stable | Dyke and basaltic sill | 50 | 0.3 |
| K _{ml} | Moderately strong, blocky to columnar, and slightly weathered; stable | Marble | – | 0.58 |
| Wgr ₃ | Strong, massive to blocky, and un-weathered; stable | Granite and granodiorite | 30 | 1.6 |

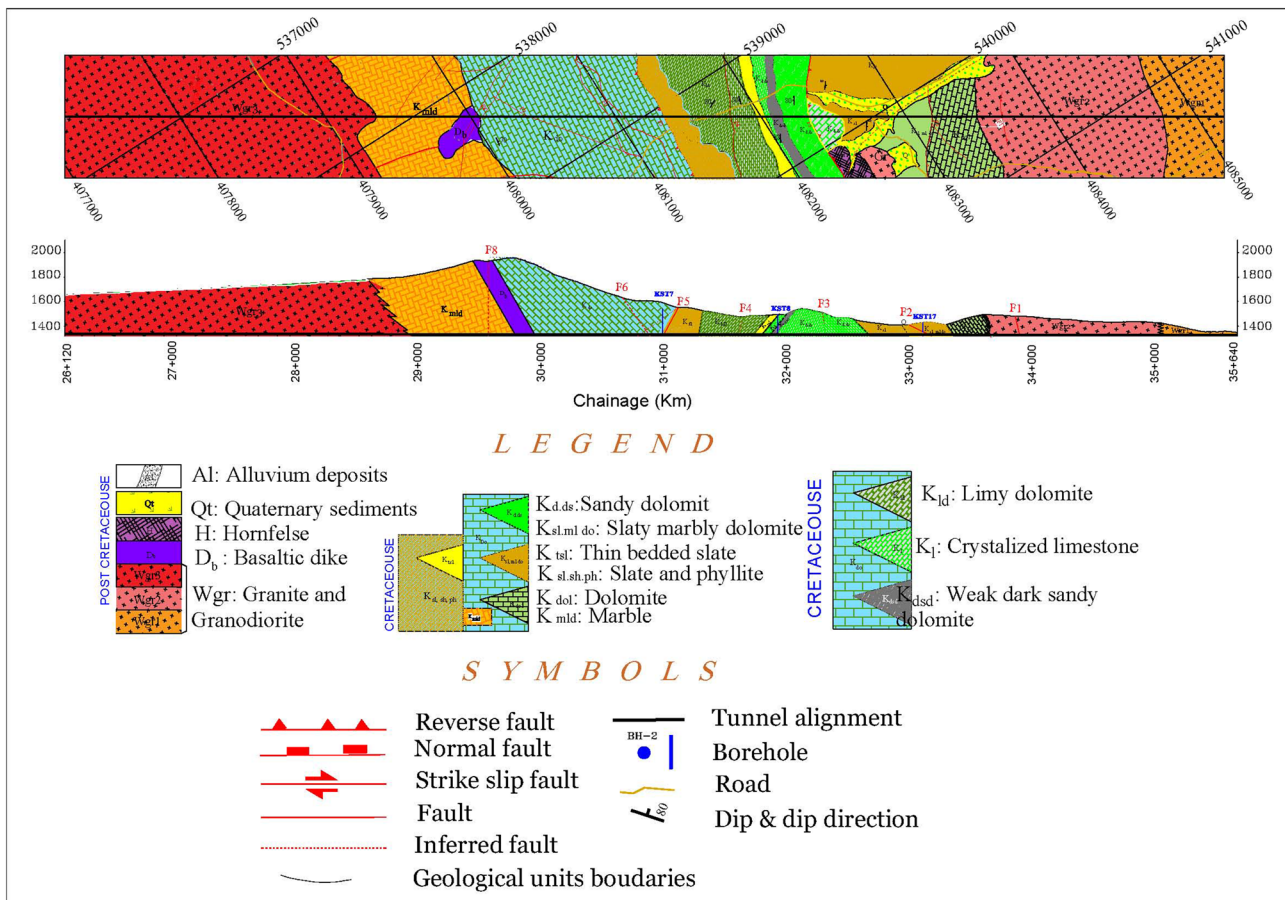


Fig. 2 Geotechnical setting along Naqadeh tunnel

Table 3 Engineering properties of the geological units in the study tunnel

| Geological Unit | Distance (m) | UCS* (MPa) | BTS** (MPa) | CAI*** | Is50**** | Brittleness indices | | |
|-----------------------|--------------|------------|-------------|--------|----------|---------------------------------------|--|---|
| | | | | | | B1 ($\frac{UCS}{BTS}$) ^a | B2 ($\frac{UCS \times BTS}{2}$) ^b | B3 (UCS × BTS) ^{0.72} ^c |
| Wgr ₁ | 204 | 20.7 | 3.1 | 2.5 | 1.5 | 6.67 | 32.08 | 20.01 |
| Wgr ₂ | 1526 | 53.8 | 8.3 | 4.5 | 4.5 | 6.48 | 223.27 | 80.89 |
| K _{d,ds} | 870 | 50 | 6.7 | 1.45 | 1.7 | 7.46 | 167.5 | 65.77 |
| K _{sh,sl,ph} | 605 | 30.3 | 5 | 1.31 | 2.2 | 6.06 | 75.75 | 37.14 |
| k _{ld} | 525 | 30 | 9.4 | 1.1 | 3.5 | 3.19 | 141 | 58.10 |
| D _b | 170 | 68.4 | 5 | 3.3 | 2.8 | 13.68 | 171 | 66.75 |
| K _{mld} | 940 | 42.7 | 3.8 | 1.85 | 2.6 | 11.23 | 81.13 | 39.02 |
| Wgr ₃ | 3020 | 88 | 7.6 | 3.8 | 7.3 | 11.57 | 334.4 | 108.19 |

*Unconfined compressive strength, **Brazilian tensile strength, ***Cerchar abrasivity index, ****Point load index

^aHucka and Das (1974), ^bAltindag (2002), and ^cYarali and Soyer (2011)

Table 4 Basic descriptive statistic of the generated database for this study*

| Variable | Minimum | Maximum | Average | Standard deviation |
|---------------------------------------|---------|---------|---------|--------------------|
| Unconfined compressive strength (UCS) | 20.7 | 88 | 47.98 | 22.24 |
| Brazilian tensile strength (BTS) | 3.1 | 9.4 | 6.11 | 2.23 |
| Cerchar abrasivity index (CAI) | 1.1 | 4.5 | 2.47 | 1.26 |
| Point load index (Is50) | 1.5 | 7.3 | 3.26 | 1.89 |
| Brittleness indices | | | | |
| B1 = $\frac{UCS}{BTS}$ | 3.19 | 13.68 | 8.29 | 3.50 |
| B2 = $\frac{UCS \times BTS}{2}$ | 32.08 | 334.4 | 153.26 | 95.82 |
| B3 = (UCS × BTS) ^{0.72} | 20.01 | 108.19 | 59.48 | 27.77 |

*A number of eight measurement for each parameter

Table 5 Main specifications of the TBM selected for excavating Naqadeh tunnel

| Parameter | Value |
|----------------------------------|----------------------|
| Machine diameter | 6.325 m |
| Number of disc cutter | 39 single + 4 double |
| Max. operating cutterhead thrust | 27,744 kN |
| Max. cutterhead speed | 7.3 rpm |
| Max. cutterhead power | 2100 kW |
| Disc cutter diameter | 432 mm |
| Average tip width | 17.8 mm |

3 TBM and Disc Cutter Specifications

A double-shield hard rock TBM with diameter of 6.325 m was selected in this study. The main specifications of the TBM are provided in Table 5.

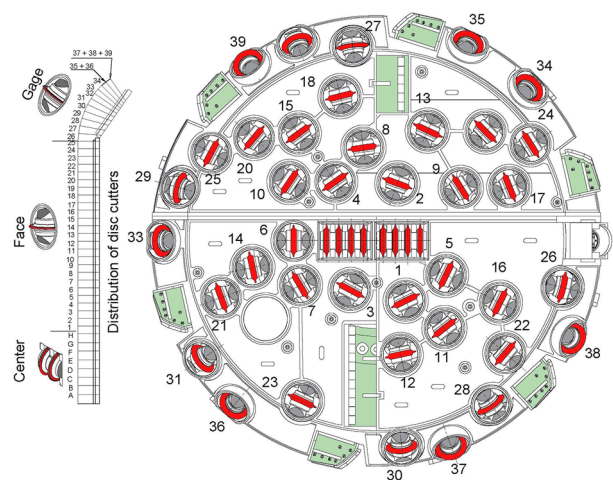


Fig. 3 General layout, cutter patterns and position numbers on the TBM cutterhead, and disc cutter spacing in the cutterhead section, Center cutters: # A to H; Face cutters: # 1 to 25; Gage cutters: # 26 to 39

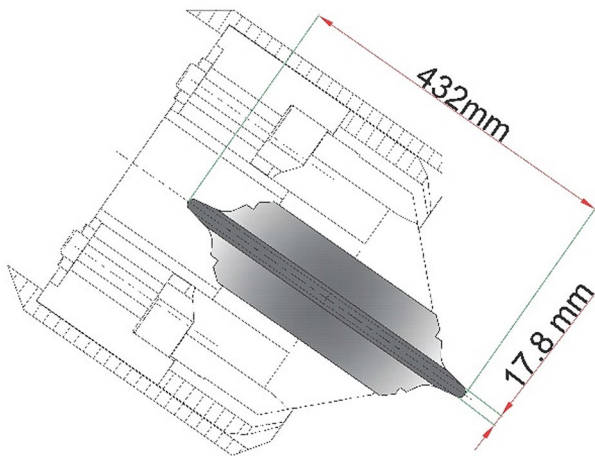


Fig. 4 A cross-section of the disc cutter with 432 mm diameter

The cutterhead has 42 disc cutters including four double rings at the center, 22 single discs in the face, and 14 single discs in the gauge (peripheral) part. Figure 3 illustrates the general layout of the TBM cutterhead and disc cutter configuration.

The load capacity of the used disc cutters was 250 kN and cutter spacing decreases in the gage part (peripheral with

distance from the center of cutterhead. The diameter and tip width of the disc cutter rings in the studied project were 432 (17 inch) and 17.8 mm, respectively (see Fig. 4). The cutter rings were made of X50CrVMo51 steel. The chemical composition of this steel is summarized in Table 6.

The disc cutters were manufactured by different manufacturers and have different hardnesses ranging from 55 to 58 Rockwell hardness C scale (HRC).

4 Disc Cutter Wear

The wear phenomenon was identified as a gradual removal of material from a solid surface due to abrasion, corrosion, and erosion (Budinski 2007). The occurrence of wear on the disc cutter classified as normal and abnormal wear. Normal wear was identified as a uniform radial wear of cutter ring tip and is the focus of disc cutter prediction models. This type of wear is categorized as a geotechnical issue and is of interest to mechanical, metallurgical, and geotechnical engineers. The term abnormal wear includes all types of disc cutter failures, except due to normal wear, such as tapering, mushrooming, blockage, brittle fracture, and bearing failure (see Fig. 5). Abnormal wear is related to mechanical issues, mainly owing to manufacturing, assembly, and perhaps due

Table 6 Chemical composition of X50CrVMo51 steel (%) used in manufacturing of disc cutter rings

| C | Si | Mn | Cr | Mo | V | Fe |
|-----|------|-----|------|------|------|---------|
| 0.5 | 1.00 | 0.3 | 5.00 | 1.40 | 1.00 | balance |

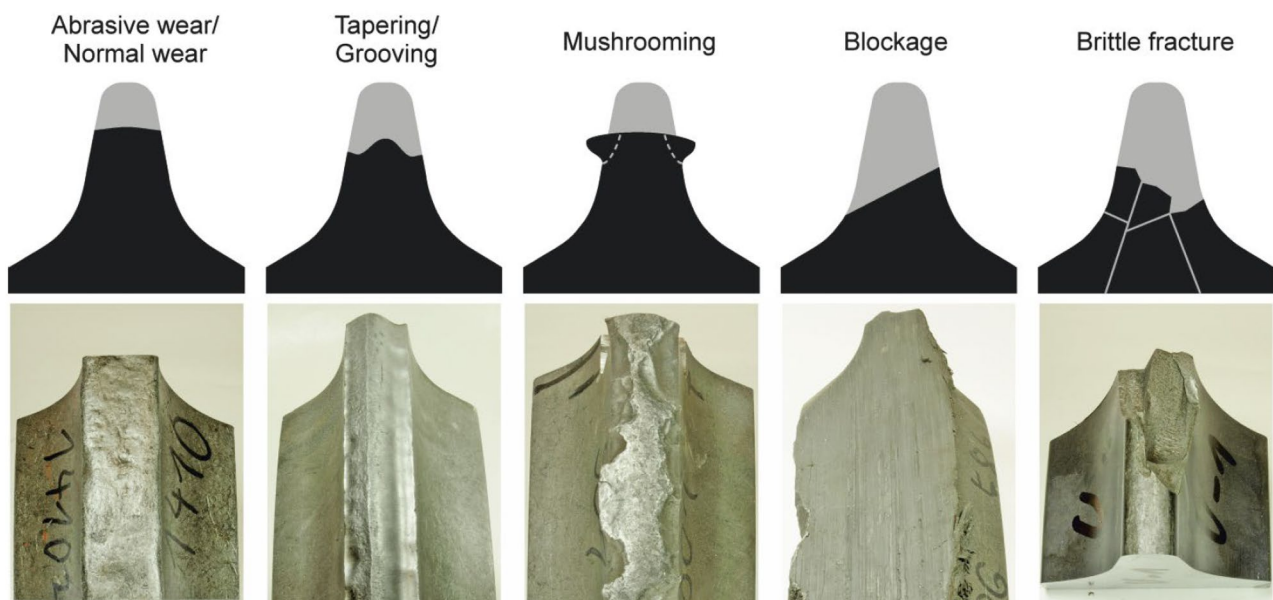


Fig. 5 Different forms of disc cutter wear after Ellecosta et al. (2018)

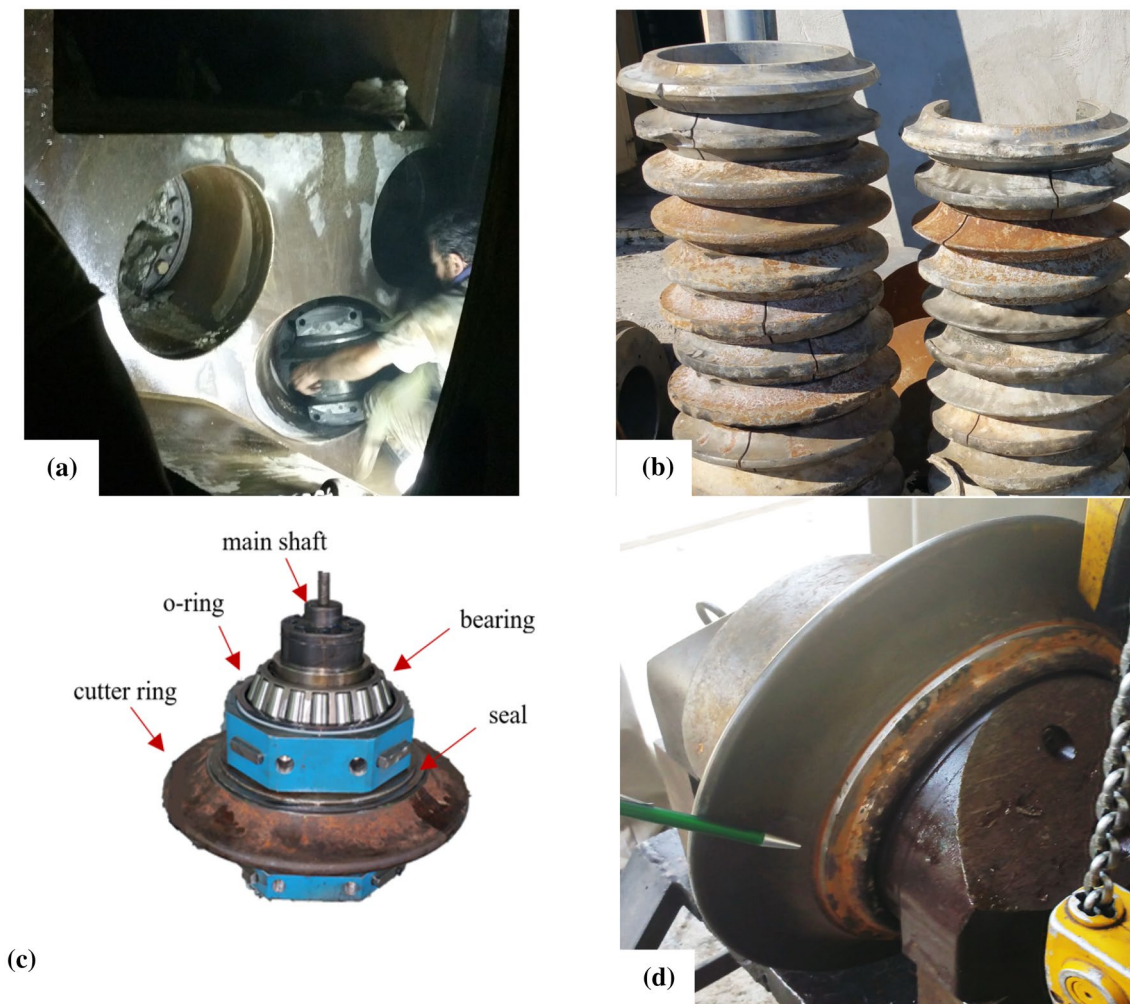


Fig. 6 **a** Removing of the worn disc cutters via cutting chamber, **b** dismantled worn cutter rings, **c** disc cutter internal components, and **d** normal wear of disc cutter

to the eccentric loading of cutter and bearing failures. If disc cutter wear is not detected on a timely basis, it may spread to adjacent cutters like a domino effect and wipe out the cutters on the cutterhead in short time, possibly lead to severe damage to the cutterhead. Figure 6 illustrates disc cutter types, components, and normal wear of cutter rings.

In some projects, the frequency of abnormal wear of disc cutters is more than that of normal wear. A significant share of abnormal wear is associated with the cutter ring. Failure of disc cutter components (i.e., bearing, O-ring, hub, and seal) may cause abnormal wear that mainly is related to the manufacturing process. Wear flat is due to cutter rotation stoppage as a result of bearing failure. Chipping, spalling, and cracking of cutter ring are directly related to hardness/toughness of cutter steel. Selecting an appropriate alloy is the key issue that influences the wear of the cutters in the material to be excavated by cutting tools. The extreme hardness of cutter steel could lead to cracking and, conversely,

increased ductility and toughness increases the possibility of mushrooming of cutter ring. Figure 7 shows pictures of normal and abnormal wear types of disc cutters.

Design optimization of disc cutter and increasing the cutter performance is considered as a cutting-edge technology in mechanized tunneling. This issue requires involvement of researchers from different fields such as metallurgical, tribological, geotechnical, mechanical, and wear studies.

The allowable wear of a disc cutter, or tip loss varied depending on the position and type of disc cutter. In this project, the allowable wear limit for the face and gage cutters were determined about 20 and 15 mm, respectively. To ensure operation of TBM without cutter failure, the inspection of the cutterhead was scheduled as a daily routine or for every 3–5 rings (4.5–7.5 m) of excavation. The amount of disc cutter wear was measured in millimeters and recorded in every inspection of the cutting tools using a special ruler

Fig. 7 Abnormal wear of 432 mm disc cutter ring: **a** unilateral flat wear, **b** polygonal flat wear, **c** cracking, and **d** chipping or spalling of cutter ring

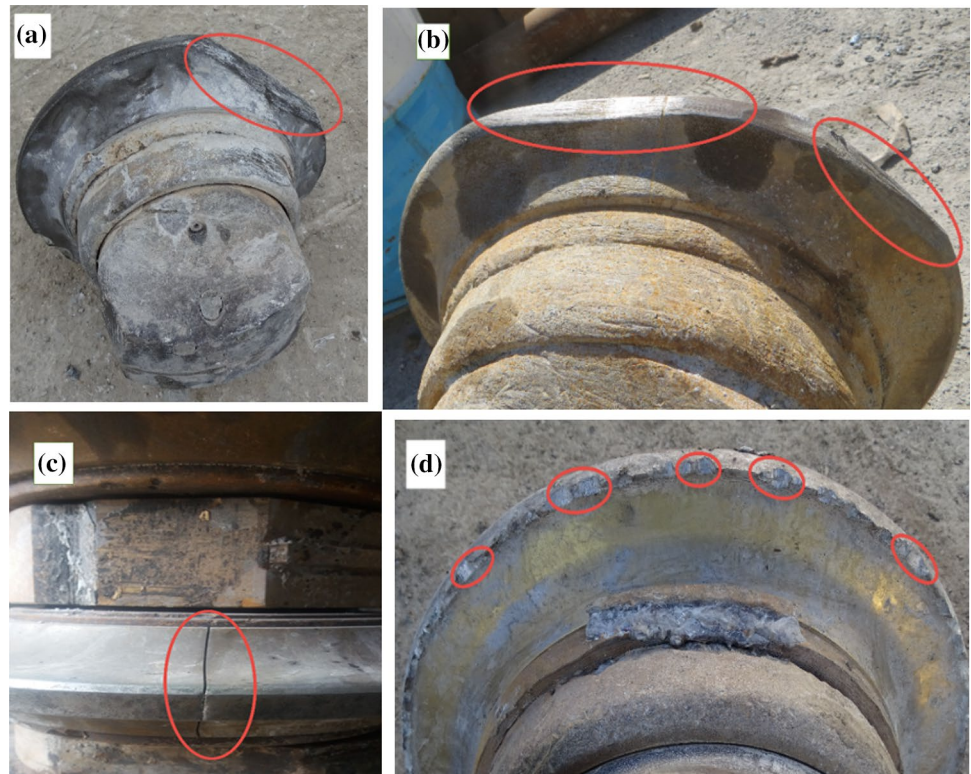
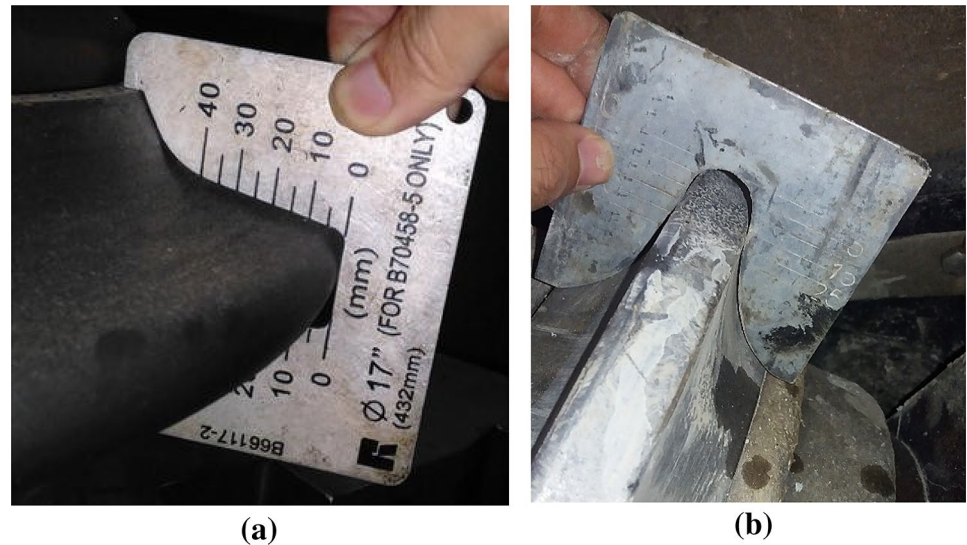


Fig. 8 Special tool for measuring wear extent of the cutter ring in a daily inspection of the cutterhead, **a** a new disc cutter with zero wear (after Liu et al. 2017), **b** measuring of 15 mm wear depth of the used cutter ring on the cutterhead



through the cutting chamber behind the cutterhead. The worn cutters were removed from the cutterhead through the cutting chamber and assembled by placing a new cutter ring and changing lubricant, or completely rebuilt by replacing seals, bearing, cutter ring, and other components, especially in the case of abnormal wear. Figure 8 shows a picture of the measurement tool as a special ruler for measuring the depth of normal wear of the cutters ring in this project.

In the studied part of this tunneling project, 1275 disc cutters were replaced for excavating a distance of 9.143 km,

where 630 (some 49%) of the disc cutters were subjected to normal wear and 645 (~51%) were replaced due to abnormal wear. Figure 9 presents the amounts abnormal wears encountered in this project.

To evaluate the wear rate with regard to placement of individual disc cutters on the cutterhead, the cutter life for the relevant positions on the cutterhead was determined using Eqs. (1) and (2), as suggested by Bruland (1998).

Fig. 9 Number and percentage of different types of abnormal wear of disc cutters in the studied project

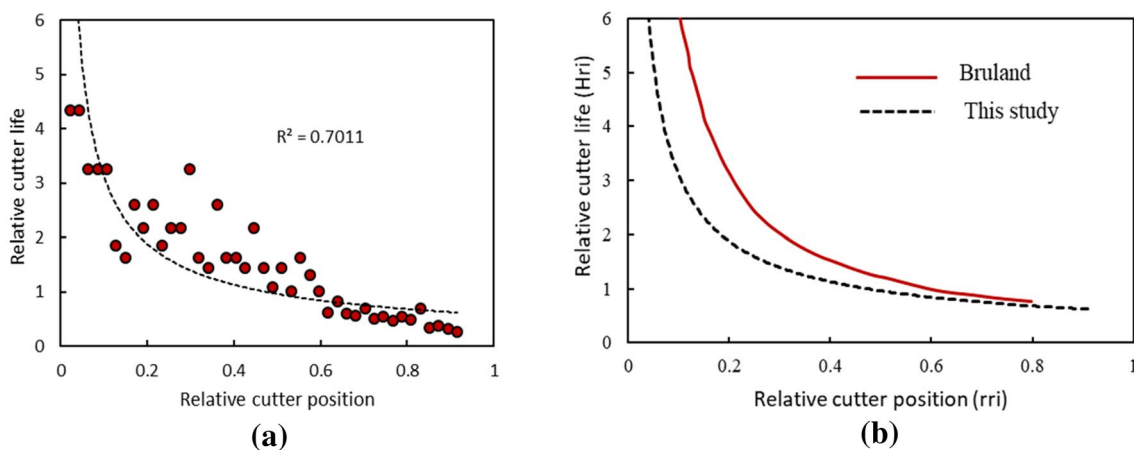
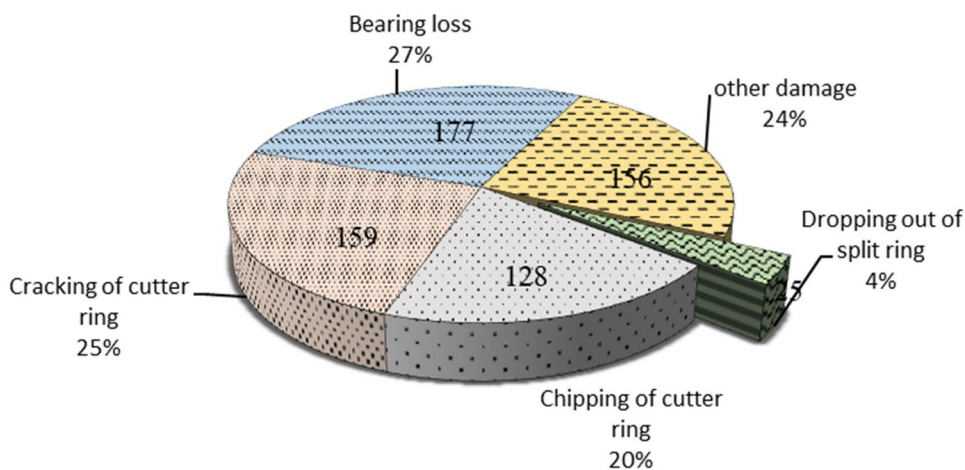


Fig. 10 Relationship between the relative cutter life (H_{ri}) and the relative cutter position (r_{ri}) (a) for normal wear (b) compared with the trend line proposed after Bruland (1998)

$$r_{ri} = \frac{N_i}{N_{TBM}}, \tag{1}$$

$$H_{ri} = \frac{\sum H_{ni}}{N_{TBM} \cdot H_{ni}}, \tag{2}$$

where r_{ri} is the relative radius or relative position of the disc cutter in the position no. i , N_i is the cutter position number, N_{TBM} is the overall number of cutters on the cutterhead, H_{ri} is the relative cutter ring life in the position i , and H_{ni} is the number of cutter rings used (worn cutters) at position i . It is clear that the rolling path and consequently the wear rate of disc cutters increases with the distance from the center of the cutterhead. In other words, the relative cutter life (H_{ri}) decreases from center to the gauge cutters. Figure 10 presents relative cutter life of this study for (1) normal wear rate according to the relative cutter position and (2) compared with the relationship proposed by Bruland (1998). As

is clear, the number of disc cutters changes due to normal wear in the positions from the face toward gage part of the cutterhead have increased in agreement with relation proposed by Bruland (1998).

Figure 11 demonstrates the number of disc cutter changes due to normal, abnormal and total wear for different positions on the cutterhead.

The high abnormal wear rate of the disc cutter at the center part of cutterhead is due to the smaller rotational radius, cutter skidding and extreme vibration of cutterhead, and excessive eccentric loading on the bearing.

The applied thrust force during the excavation of the tunnel and the number of worn cutter changes in different lithologies is shown in Fig. 12.

In the process of excavation of a rockmass by a TBM, the disc cutters penetrate into the rock caused by the applied thrust force on the cutterhead. The rolling force and generated friction at the contact between a disc cutter and hard rock caused to cutter wear (Wang et al. 2015). The excessive

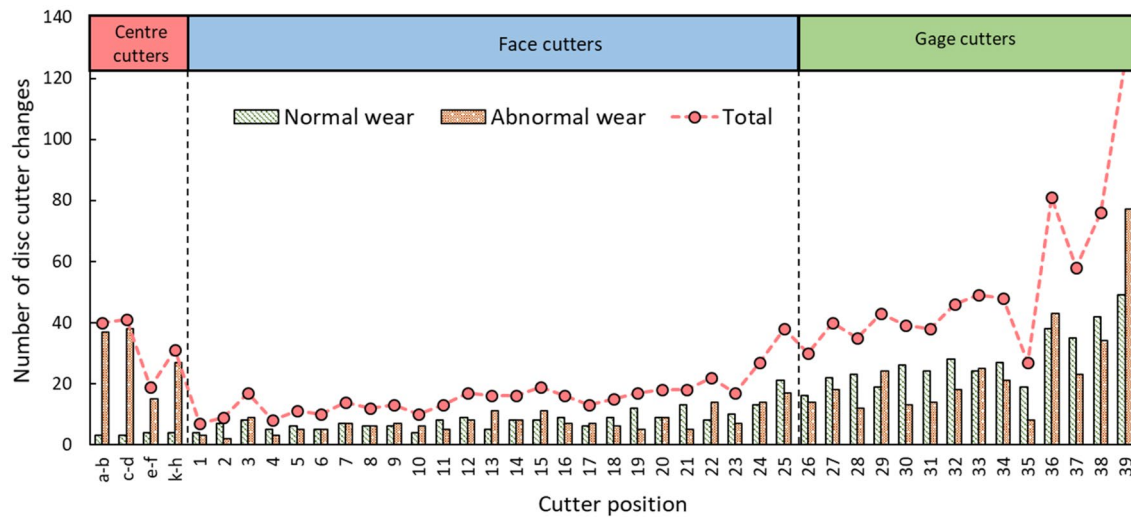


Fig. 11 Number of normal and abnormal wear of the disc cutters in various positions on the cutterhead

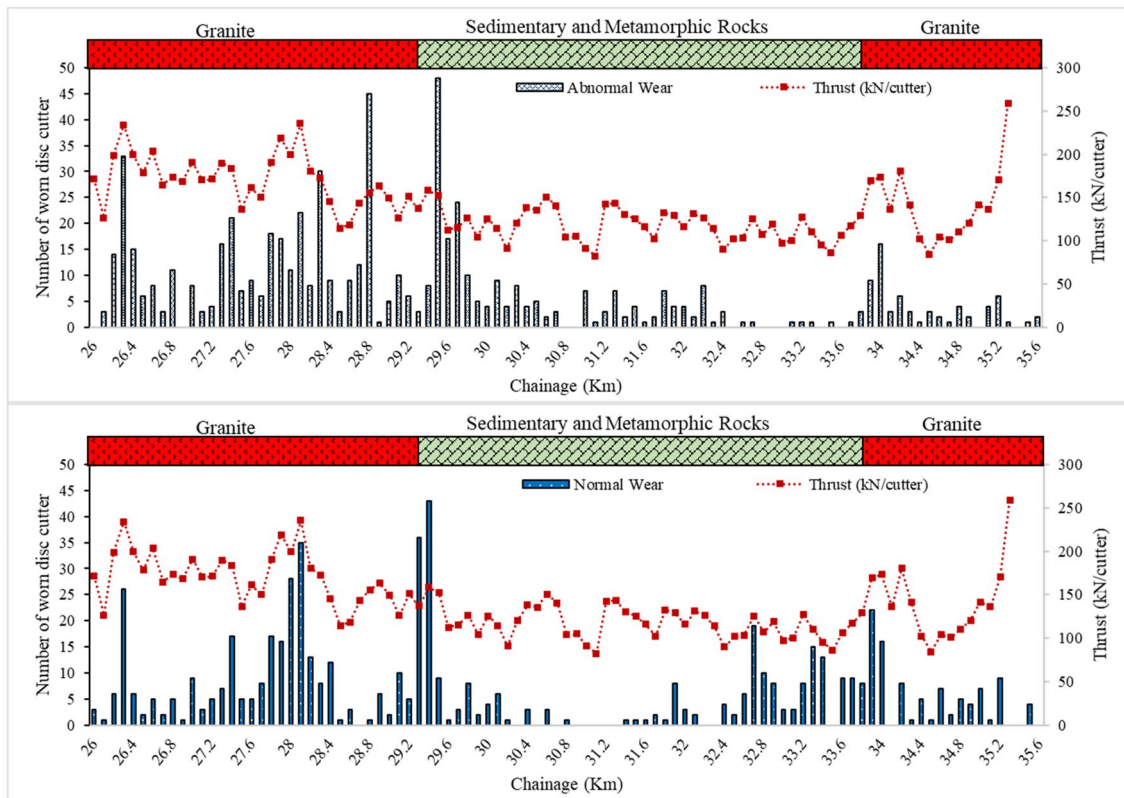


Fig. 12 Variations of the applied thrust force on the disc cutters and the number of normal and abnormal cutter wear in various geological units along the tunnel alignment

trust force is one of the main parameters that affects wear rate of disc cutters. As shown in Fig. 12, there is good relation between the thrust force and the number of cutter changes especially due to abnormal wear.

Bruland (1998) described disc cutters life as drilled tunnel length per cutter (H_m) or excavated volume of rock per cutter (H_p) using Eq. (3) and (4), respectively:

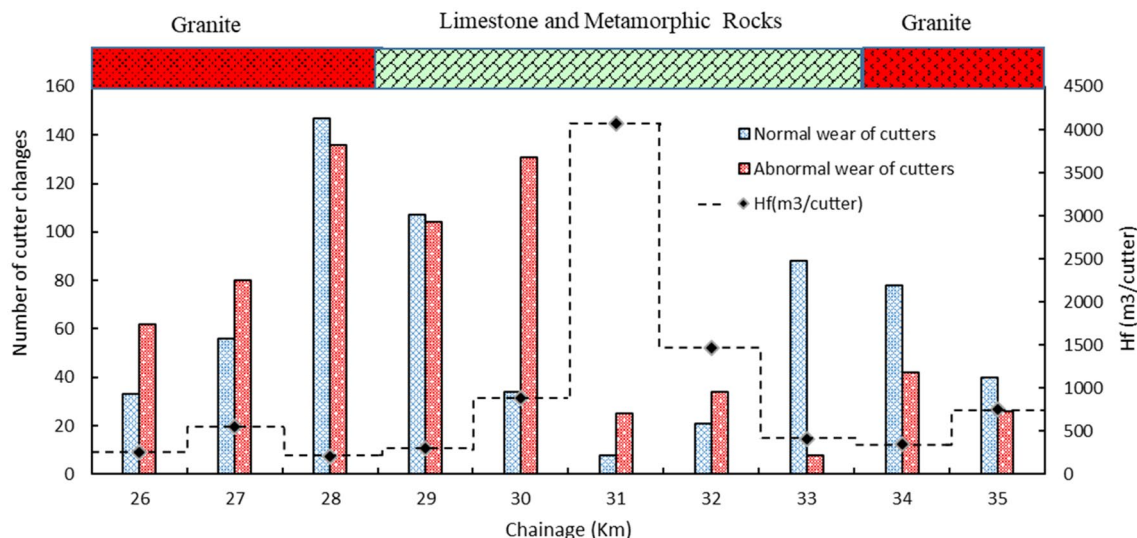


Fig. 13 Number of disc cutter changes and cutter life in various geological units along the selected part of the tunnel alignment

$$H_m = \frac{L_{(m)}}{N_{TBM}} \left(\frac{m}{\text{cutter}} \right), \tag{3}$$

$$H_f = \frac{H_m \cdot \pi \cdot d_{\text{tbn}}^2}{4} \left(\frac{\text{m}^3}{\text{cutter}} \right), \tag{4}$$

where N_{TBM} is the overall number of disc cutters, d_{tbn} is TBM diameter, and L is the excavated tunnel length. It is anticipated that cutters in the gage part are replaced at a faster rate. The number of worn disc cutter changes and H_f along the tunnel alignment with respect to the geological units is shown in Fig. 13.

5 Disc Cutter Wear Prediction Using the Traditional Models

The CSM, NTNU, Hassanpour (2018) and Hassanpour et al. (2015) models were applied for predicting cutter wear in the studied project. The CSM method is based on CAI to obtain a basic cutter life (CL) in rolling meters (Ozdemir 1995). The NTNU method applies the CLI based on Siever’s J -value (SJ) and abrasion value steel (AVS) (Bruland 1998). The models of Hassanpour et al. (2015) and Hassanpour (2018) are based on a Vickers hardness number (VHNR) and UCS. Figure 14 illustrates the estimated rock excavation volume per cutter or H_f (m3/cutter) for each geological unit using the above-mentioned prediction models. As can be seen, there is no agreement between predicted values by different models and also in comparison with the recorded wear rate.

The absolute error (Eq. 5) was used to compare the results of prediction models in various tunnel sections (see Fig. 15).

$$\text{Absolute error (\%)} = \left| \frac{\text{Actual } H_f - \text{Estimated } H_f}{\text{Actual } H_f} \right| \times 100. \tag{5}$$

Table 7 provides basic descriptive statistics of absolute errors for comparing traditional prediction models with the actual wear rates. The results show that the NTNU model predicted lower values than the actual ones, while the models of Hassanpour et al. (2015) and Hassanpour (2018) over-estimated cutter life. The CSM model predicted values had lower relative error compared to the observed cutter life in different geological units. It is of note that the Hassanpour (2018) model was developed for sedimentary and low to medium grade metamorphic rocks. It can be assumed that that each model is valid for certain geological conditions with similar characteristics to those used in the development of the models.

6 Statistical Analysis of Cutter Life Data

6.1 Simple Regression Analysis

To predict disc cutter life, simple regression analyses with the linear, power, exponential, and logarithmic relations were applied between disc cutter life and rock characteristics (Fig. 16). The type of regression, equation and coefficient of determination (R^2) between excavated tunnel length or rock produced per cutter change (H_f), and intact rock parameters (i.e., CAI, UCS, BTS, Is50, and brittleness indices) are listed in Table 8. As can be seen, various coefficients of

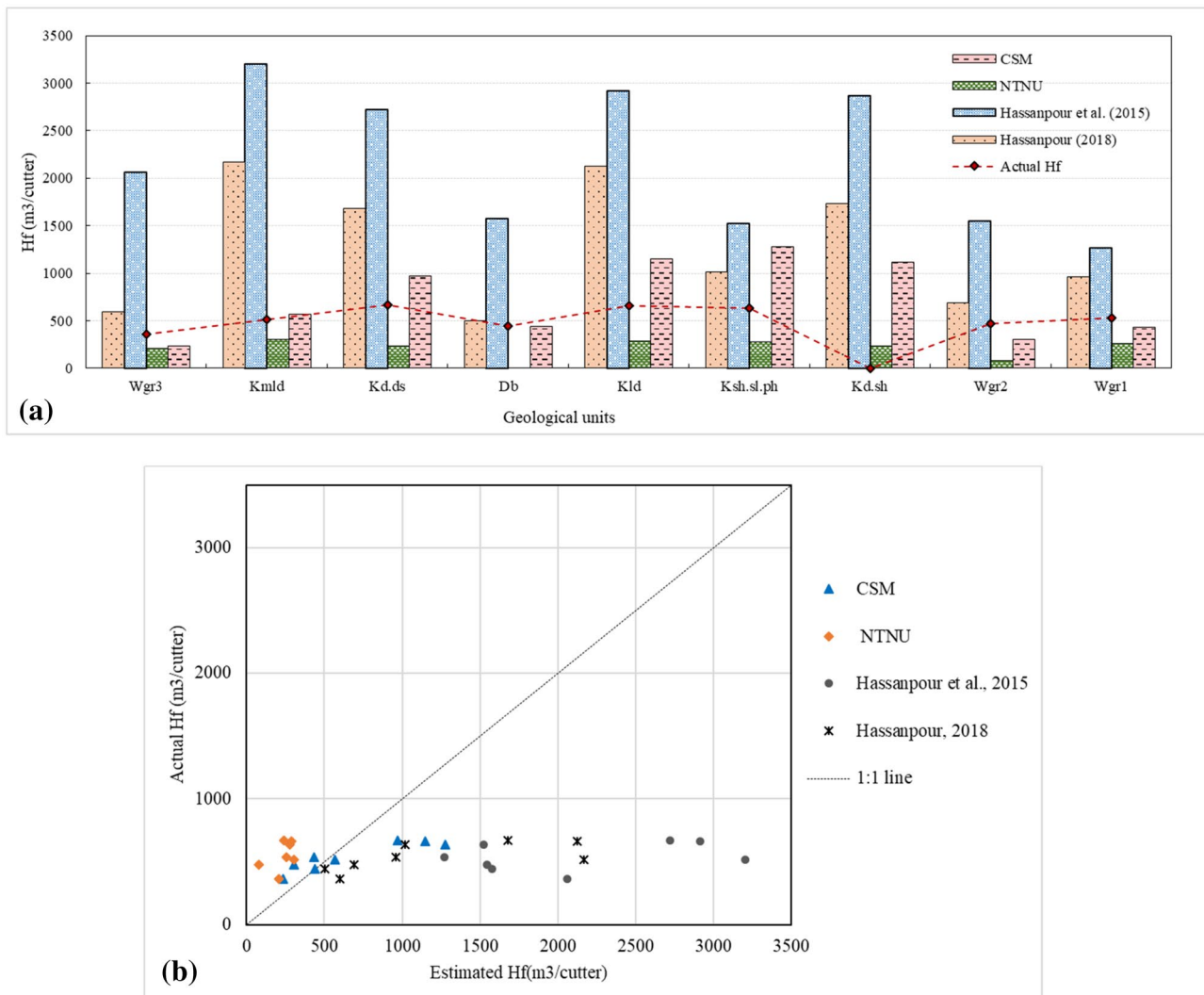


Fig. 14 Disc cutter wear prediction by existing models compared to the actual H_f (m^3/cutter) data, **a** predicted values of H_f (m^3/cutter) using existing models and actual data in various geological units, **b** scatter plot of predicted values of H_f (m^3/cutter) vs. actual data

determination were observed between disc cutter life and rock characteristics for the all data sets (R^2 ranging from 0.006 to 0.802). Moreover, the relation between the Brazilian tensile strength (BTS) and cutter life was very poor ($R^2 = 0.006$), while the best relation was between the CAI and cutter life ($R^2 = 0.802$).

6.2 Multiple Regression

Multiple regression analysis was performed to determine the relationships between disc cutter life (H_f) as the dependent variable with rock characteristics as input variables. In the regression analysis using SPSS software, the model of the best fitting line with regression coefficient of 95% confidence level was developed for each relation. The effect of each variable on H_f was evaluated and a statistical model

with input variables was generated. In this study, the maximum coefficient of determination ($R^2 = 0.75$) was obtained using CAI and UCS as input variables. The statistical parameters of the model are provided in Table 9.

The analysis of the significance of t value and coefficient for the generated model are detailed in Table 10. The t -test shows that the coefficients of the model is correct (Sig. < 0.05). The analysis of variance (F test) for the model is summarized in Table 11.

As a result, a new empirical disc cutter life prediction model is introduced using UCS and CAI as universally measured intact rock characteristics in mechanized tunneling projects (Eq. 13). Comparison of the predicted disc cutter life using the suggested equation with actual data is illustrated in Fig. 17. Histograms of the actual and predicted

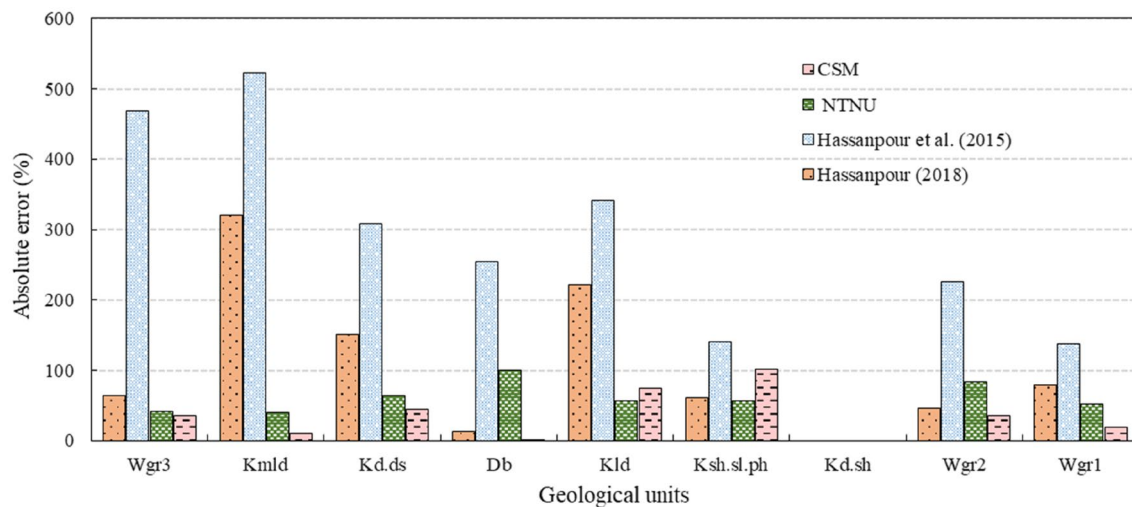


Fig. 15 Variations of the absolute error for the prediction models in various geological units

Table 7 Basic descriptive statistics of absolute errors for the existing prediction models

| Prediction Model | Minimum (%) | Maximum (%) | Mean (%) | Std. deviation (%) |
|--------------------------|-------------|-------------|----------|--------------------|
| CSM | 1.49 | 101.73 | 40.32 | 33.47 |
| NTNU | 40.53 | 100.00 | 61.94 | 20.47 |
| Hassanpour et al. (2015) | 137.82 | 521.75 | 299.74 | 140.70 |
| Hassanpour (2018) | 12.98 | 320.40 | 119.67 | 104.71 |

values of disc cutter life for various geological units is presented in Fig. 18.

$$H_f = (1339.355UCS^{-0.204}) * (CAI^{-0.204}) \tag{13}$$

7 Validation of the Model

To validate the proposed model, the predicted values of cutter life were compared to recorded cutter life in the tunnel at chainage between 25,630 and 23,644 m (some 1986 m) in the granitic unit. The mean values of rock characteristics in this section of the tunnel are presented in Table 12.

In the selected section, 224 discs (26 center and 198 face and gauge cutters) were replaced; 126 (64%) due to normal wear and 72 (36%) due to abnormal wear. The predicted cutter life values obtained using the proposed model are in good agreement with the actual values presented in Table 13. The newly developed model for cutter life prediction is illustrated in Fig. 19. This is a chart in which the horizontal and vertical axes are the CAI and UCS parameters, respectively. The lines which separate various cutter life (H_f) areas indicate wear categories. As shown, the wear of the cutters due to excavating rock mass with high strength and low abrasivity

might be the same as wear caused by a low strength but extremely abrasive rock. Obviously, the lowest cutter life is related to high strength with high abrasivity index rock mass.

8 Conclusions

In this study, a limited database of disc cutter wear and geotechnical parameters of rock formations for a TBM tunneling project was developed and analyzed. The database included geological features, disc cutter wear rate and wear types. About 49% of worn disc cutters were subjected to normal wear and more than 50% (especially for the disc cutters mounted in the central part of the cutterhead) were replaced due to abnormal wear. A significant percentage (> 45%) of the abnormal wear was associated with the cutter ring failure (i.e., cracking, spalling, mushrooming, and chipping) due to the inaccurate and un-matching of hardness/toughness of the steel used for cutter ring. The cutter rings in the studied project were made from X50CrVMo51 steel with different hardnesses ranging from 55 to 58 HRC due to specific process used by different manufacturers. To reduce the cutter wear, it is important to study the wear type and to conduct more experimental tests for selecting appropriate properties

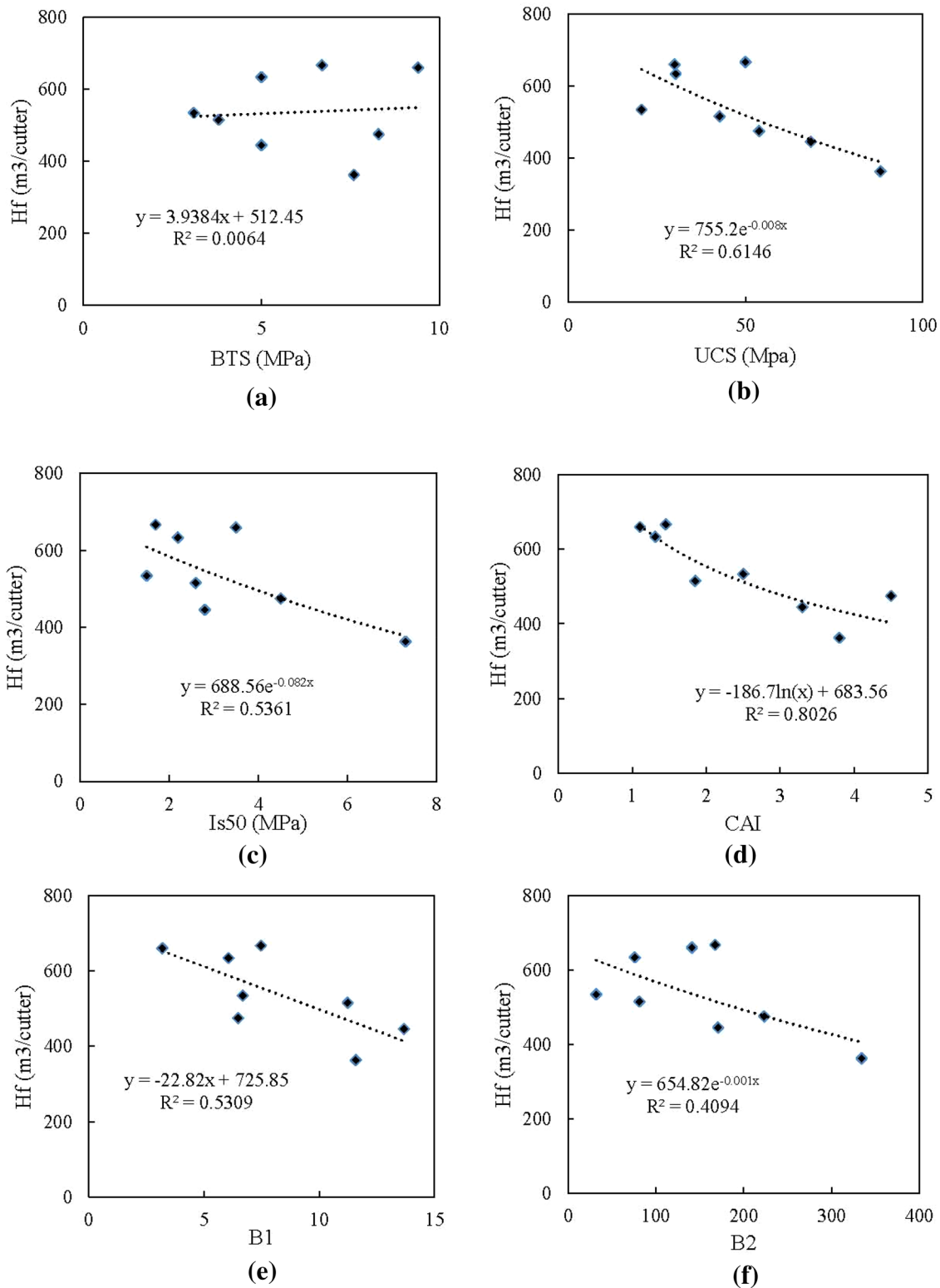


Fig. 16 The relationship between the recorded disc cutter life (H_f) and different rock parameters including **a** Brazilian tensile strength (BTS); **b** unconfined compressive strength (UCS); **c** point load index

(Is50); **d** Cerchar abrasivity index (CAI); **e** brittleness, B1 ($\frac{UCS}{BTS}$); and **f** brittleness, B2 ($\frac{UCS \times BTS}{2}$)

Table 8 Summary of simple regression analysis results between average cutter life and rock characteristics

| Independent variables | Coefficient of Determination (R^2) | Regression type | Relationship | Eq |
|-----------------------|--|-----------------|---------------------------------|----|
| UCS (Mpa) | 0.614 | Exponential | $H_f = 755.2e^{-0.008(UCS)}$ | 6 |
| BTS (MPa) | 0.006 | linear | $H_f = 3.9384(BTS) + 512.45$ | 7 |
| Is50 (MPa) | 0.536 | Exponential | $H_f = 688.56e^{-0.082(Is50)}$ | 8 |
| CAI | 0.802 | Logarithmic | $H_f = -186.7\ln(CAI) + 683.56$ | 9 |
| B1 | 0.530 | linear | $H_f = -22.82(B1) + 725.85$ | 10 |
| B2 | 0.409 | Exponential | $H_f = 654.82e^{-0.001(B2)}$ | 11 |
| B3 | 0.353 | Exponential | $H_f = 690.63e^{-0.005(B3)}$ | 12 |

Table 9 The summary of the regression analysis of the generated model

| Method | Stepwise (criteria: probability-of-F-to-enter ≤ 0.050 , Probability-of-F-to-remove ≥ 0.100) | | | |
|---------------|--|----------|-------------------|----------------------------|
| Model summary | R | R square | Adjusted R square | Std. error of the estimate |
| | 0.86 ^a | 0.75 | 0.65 | 58.49 |

Dependent variable: H_f

^aPredictors: (constant), CAI, UCS

Table 10 The significance of t value and coefficients of the generated model

| Parameter | Value | Standard error | t value | 95% confidence | Sig |
|-----------|----------|----------------|---------|----------------|-------|
| a | 1339.355 | 290.90 | 4.60 | 627.54 | 0.003 |
| b | -0.204 | 0.04 | -4.09 | -0.32 | 0.006 |

^aDependent variable: H_f

^bPredictors: (constant); CAI, UCS

Table 11 The significance of F value and coefficients of the generated model

| | Sum of squares | df | Mean square | F | Sig |
|------------|----------------|----|-------------|-------|--------------------|
| Regression | 63,895.72 | 1 | 63,895.72 | 18.67 | 0.004 ^b |
| Residual | 20,529.73 | 6 | 3421.62 | | |
| Total | 84,425.46 | 7 | | | |

^aDependent variable: H_f

^bPredictors: (constant), CAI, UCS

for the cutter ring with the optimal hardness/toughness to match the rock with specific mineral composition.

The comparison of the normal wear of disc cutter by traditional prediction models with the actual wear rate in the

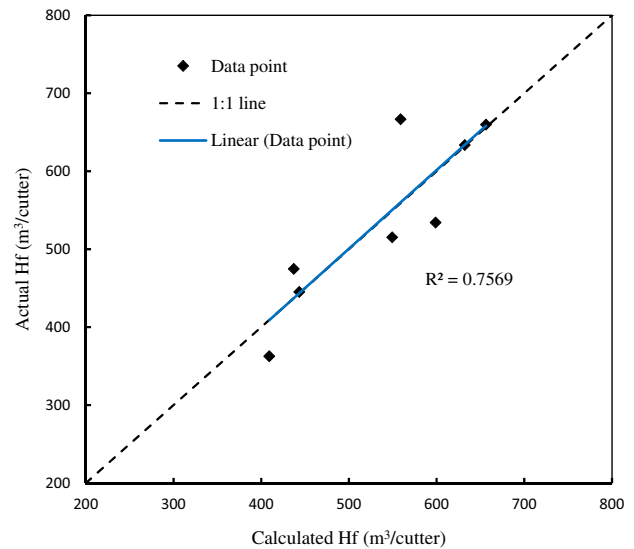


Fig. 17 Comparison between the actual and predicted values

project showed large differences. The subject of wear of the cutter ring in TBM tunneling is an interdisciplinary issue. To obtain an accurate prediction model, an extensive experimental test with a contribution of multiple research fields including geotechnics, geology, metallurgy, and mechanical engineers is required.

Statistical analysis was used to develop a relationship between the average disc cutter life (H_f) and rock characteristics. Regression analysis showed a high correlation with the $R^2 = 0.7569$ of cutter life (H_f) with Cerchar abrasivity index (CAI) and UCS. A simple empirical model was proposed for predicting cutter disc life. The newly developed model was validated in 2 km of tunnel with reasonable results. It is worth to note that, due to the limited data in the database, the proposed model can only be used for the prediction of cutter life due to normal wear for constant cross-section (CCS) cutter rings with diameter of 432 mm, in granitic rocks. Clearly, the newly developed model can be improved using additional data from other tunneling projects over time.

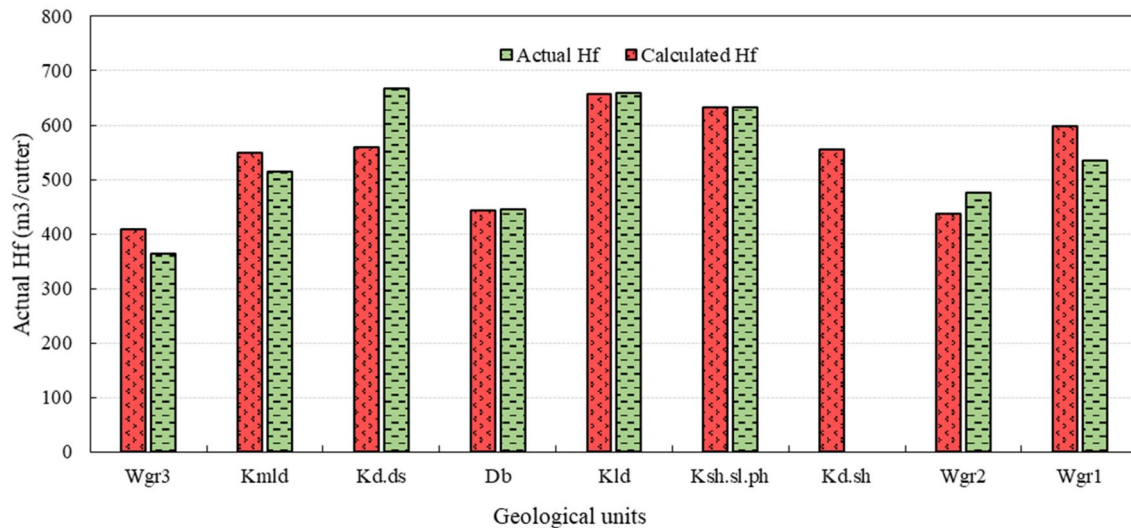


Fig. 18 Histograms of the actual and predicted values of H_f (m^3/cutter) in various geological units

Table 12 Rock characteristics in the tunnel at a distance from 25,630 to 23,644 m

| Geological unit | UCS (MPa) | BTS (MPa) | B1 | CAI |
|-----------------|-----------|-----------|------|-----|
| Granite | 46 | 4.8 | 9.58 | 3.8 |

Table 13 Predicted and actual disc cutter life at the distance from 25,630 to 23,644 m

| | H_f (m^3/cutter) | H_m (m/cutter) |
|-----------------|--------------------------------------|------------------------------------|
| Actual value | 494.46 | 15.76 |
| Predicted value | 467.10 | 14.88 |

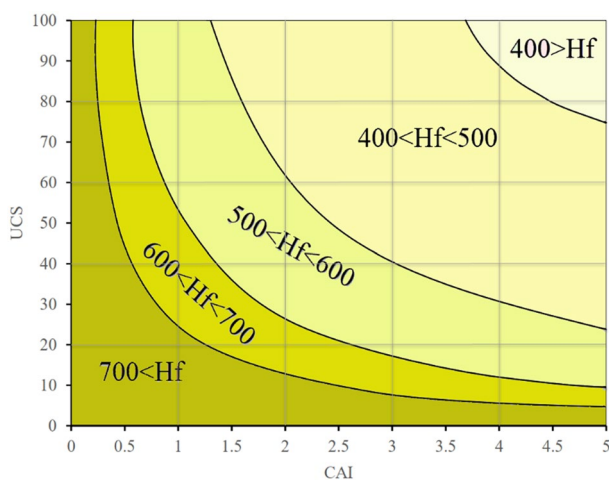


Fig. 19 Prediction chart of cutter life (m^3/cutter) based on the developed model derived from Eq. 13

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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