Prediction of performance and cutter wear in rock TBM: Application to Koralm tunnel project

Prediction of performance and cutter wear in rock TBM: application to Koralm tunnel project

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Excavation by Tunnel Boring Machines is the tunnelling method most frequently used nowadays in long infrastructural projects, in a wide range of geological conditions. In the last 40 years, many prediction models were developed to estimate TBM performance and cutter wear, using as input geological parameters. The research gives an overview of the existing penetration models for hard rock TBMs, identifies the most frequently used input parameters and summarizes the characteristics of the datasets on which the models are based on. Theoretical background is tested through the example of Koralm tunnel project, a 32.9-km-long base tunnel in Austria, in a 1000-m-long portion of the South tube in the construction lot KAT 2. The outcomes shows that the estimation of the penetration is reasonably accurate when applying models that are based on a database consistent with the project data, especially in terms of geology and typology of machine used in the excavation. The article proposes a design method for a system of TBM data analysis and prediction at the construction stage, based on a back-analysis process about machine data in different geological conditions. The methodology can be applied in any other project and the system is particularly useful in long tunnels, in which a continuous improvement of the ability of prediction can have an effective impact on time and costs.
Keywords: *TBM, penetration, wear, utilization, prediction*

Previsione delle prestazioni e dell'usura degli utensili di una TBM da roccia: applicazione al progetto del Koralm tunnel. *Lo scavo con Tunnel Boring Machine (TBM) è il metodo di scavo più utilizzato per grandi progetti infrastrutturali al giorno d'oggi, in un'ampia varietà di condizioni geologiche. Negli ultimi 40 anni molti modelli predittivi sono stati sviluppati per stimare le prestazioni della TBM e l'usura degli utensili, usando come input i parametri geologici. Questa ricerca fornisce una panoramica dei modelli esistenti per la stima della penetrazione degli utensili per una TBM in roccia, identifica i parametri di ingresso più frequentemente utilizzati e sintetizza le caratteristiche dei database da cui sono stati ricavati i modelli. I modelli teorici sono stati testati attraverso il caso studio del progetto del Koralm Tunnel, una galleria di base lunga 32.9 km in costruzione in Austria, in una porzione della canna Sud di lunghezza 1000 m, facente parte del lotto KAT 2. I risultati mostrano che la stima è ragionevolmente accurata se si applicano modelli che su fondano su una base di dati con caratteristiche simili a quelle del progetto, specialmente in termini di geologia e tipologia di macchina usato per lo scavo. L'articolo propone un metodo di progetto per la creazione di un sistema di analisi dei dati della TBM e di previsione in fase costruttiva, basata su un processo di back-analysis di dati macchina raccolti in differenti condizioni geologiche. La metodologia può essere applicata in qualsiasi altro progetto, e il sistema è particolarmente utile in tunnel di grande lunghezza, nei quali una miglioria continua dell'abilità di previsione può avere un impatto rilevante in termini di tempo e costi.*
Parole chiave: *TBM, penetrazione, usura, utilizzazione, previsione*

Prévision de la performance et de la consommation des molettes pour un tunnelier à roche dure : application au projet du tunnel du Koralm. *Le creusement avec un tunnelier à roche dure est désormais la méthode de construction plus utilisée dans les projets d'infrastructures longues, sur une fourchette très large de conditions géologiques. Dans les derniers 40 ans, beaucoup de modèles prévisionnels pour l'estimation de la performance et de la consommation des molettes pour un tunnelier à roche dure ont été développés, utilisant les paramètres géologiques comme données d'entrée. La recherche donne une vision globale des modèles existants en matière de pénétration pour les tunneliers à roche dure, elle identifie les paramètres d'entrée plus utilisés et elle synthétise les caractéristiques des séries de données à la base du modèle. Les hypothèses théoriques sont testées sur l'exemple du projet du tunnel du Koralm, un tunnel de base autrichien de 32,9 km de longueur, et notamment sur une section de 1000 m de longueur du tube sud du lot constructif KAT 2. Les résultats montrent que l'estimation de la pénétration est raisonnablement précise quand le modèle appliqué est basé sur une base de données cohérente avec les paramètres du projet, spécialement en terme de géologie et de type de tunnelier utilisé pour le creusement.*

1. Introduction

Tunnel Boring Machines are nowadays a common and fruitful option a tunnel designer can adopt, and technological advancements allowed using them in a wide range of geological conditions, from hard rock to loose soil.

From the adoption of disc cutter tools by James Robbins in 1956, TBM productivity improved year by year. Today peaks of advance rate per day can go over 100 m/day, but, in adverse geologic conditions, a production of less than 50 m/month may be experienced (Barla and Pelizza, 2000).

In the last 40 years, several authors (Cassinelli *et al.*, 1982; Innaurato *et al.*, 1990; Rostami and Ozdemir, 1993; Gehring, 1995; Alber, 1996; Bruland, 1998; Alvarez Grima *et al.*, 2000; Barton, 2000; Ribacchi and Lembo Fazio, 2005; Yagiz, 2008; Gong and Zhao, 2009; Hamidi *et al.*, 2010; Hassanpour *et al.*, 2011; Farrokh *et al.*, 2012) proposed models that allow to predict TBM performance and cutter wear.

The aim of the work is to understand if the quality of the prediction, obtained through the adoption of these models, can be influenced by the characteristics of the databases models in literature are based on (Bottero and Peila, 2005). Data analysed in the study has been recorded during the excavation of the Koralm tunnel, a railway tunnel excavated in hard rock in the southern Austria.

In mechanized tunnelling by TBM, the process of rock fragmentation is guaranteed by cutters, steel discs that are capable of dealing with

L'article propose une méthode de conception pour un système d'analyse des données du tunnelier et de prévision en phase de construction, basé sur un procès d'analyse à rebours des données machine en conditions géologiques différentes.
La méthode peut être appliquée sur d'autres projets et le système est particulièrement utile pour des longs tunnels, où l'amélioration continue de la capacité prévisionnelle peut avoir un retour effectif sur les délais et sur les coûts.
Mots-clés: *TBM, pénétration, consommation, utilisation, prévision.*

the high cutter loads required for hard rock and keeping a constant production and high abrasion resistance.

The thrust acting on a single tool consists of two forces: a component of the force normal to the face, F_N, and a force tangential to the face, the rolling force F_R.

Two different processes can cause rock breakage, when the TBM is pressed against the face, respectively single pass and multiple cutting process. *Single pass* cutting process consists in the detachment of rock chips, due to the action of two disc cutters and is the process that more frequently can occur.

The effect of cutters on the rock has been studied through full-size tests, as the linear cutting test equipment (Rostami and Ozdemir, 1993). When a single disc is pressed against the face, it creates a pulverised bulb of rock immediately below the cutter, the so-called crushed zone, and radial tension cracks propagation starts (fig. 1).

Another possibility for rock fragmentation, especially in case of hard rock, is the *multiple cutting* process. The chip is generated by the multiple passage of different discs in the same position, due to cutterhead design. This solution is used when the load applied to the cutter and/or the time of application of the force is not sufficient for the detachment of a complete chip (Rostami and Ozdemir, 1993; Bruland, 1998).

1.1. Prediction models

Prediction models produce forecast in terms of penetration rate (PR), that is the penetration of the cutterhead per revolution, utilization factor (UF), i.e. percentage of time in which the machine is actually working, and tools wear (Peila and Pelizza, 2009, Peila, 2009).

These predictive methods can be classified in two types, considering the hypotheses and the source of data each model is based on: *analytical* and *empirical models*. *Analytical models* are studies that start from theoretical assumptions, e.g. theories about force balance and stress distribution, while e*mpirical models* are based on the back-analysis of data from a database collected in tunnel projects, and equations proposed derive from their statistical treatment.

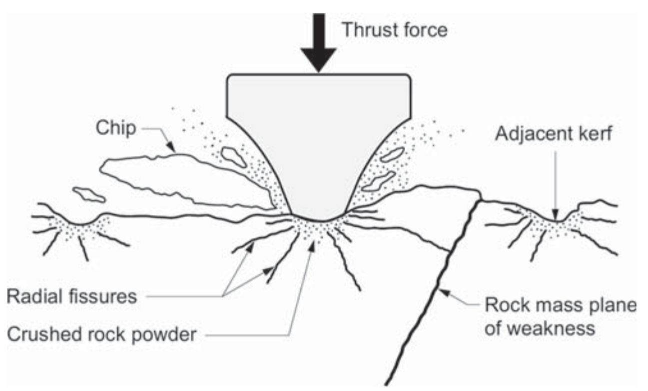

Fig. 1. Chip formation and detachment under the effect of a cutter disc (Bruland, 1998).
Formazione e distacco del chip di roccia per effetto dell'azione del disco (Bruland, 1998).

1.1.1. Analytical models

Analytical performance prediction models are based on the study of the rock fragmentation process with mechanical tools. From the results of full-size laboratory tests, as linear cutting and punch penetration, the authors individuated forces acting on the cutter, and thrust, torque and power requirement of the TBM are obtained from a balance of forces.

Analytical models usually combine intact rock characteristics (mainly uniaxial compressive and tensile strength, σ_c and σ_t) with information about the cutter (e.g. cutter diameter Φ_{disc}, spacing $s_{cutters}$, tip width w_{tip}, and thrust per cutter).

They do not take in deep account rock mass characteristics that recent studies (Bruland 1998; Ramezanzadeh, 2006; Gong and Zhao, 2007) proved to be very important to understand TBM performance, as joint frequency and joint orientation. The most frequently used analytical models had been modified recently to overcome this limitation and they can be considered semi-empirical. The most used ones are:

Colorado School of Mines (CSM) model was initially developed by Rostami and Ozdemir (1993), starting from the results of linear cutting tests and mathematical assumption on rock fragmentation process. It considers the formation of a pressure bulb of crushed rock immediately under the tip, assumed to be circular; the pressure decrease on the size, while maximum stress concentration is present immediately under the cutter. Parameters considered in the model are σ_c, σ_t, Φ_{disc}, w_{tip}, s_{cutter} and rotational speed v_{rot}. Ramezanzadeh (2006) integrated these studies taking into account joint spacing and the angle between the plane of weakness and the tunnel axis α. The study developed by Frenzel (2010) extended CSM model to include cutter wear prediction, by correlating cutter life, Cerchar Abrasivity Index

(CAI), and disk diameter with tools consumption.

Gehring model (1985) was developed in collaboration with Voest Alpine, a machines manufacturer. Base equation proposed by the author correlated the penetration rate to σ_c and F_N. Last version of the model included five correction factors that considered respectively fracture energy, joint spacing, state of stress, cutter diameter, and cutter spacing: these factors derived from empirical correlations. The model included an empirical equation that allows cutter wear prediction as a function of CAI.

1.1.2. Empirical models

Nowadays, new empirical models are continuously developed, because of the great number of parameters influencing TBM performance, and the high variability related to specific on-field conditions. Data collection programs could involve both rock face mapping and rock coring program on-field, with significant variations among models analysed, while TBM performance and machine data datasets in hard rock tunnelling are almost standardised.

One of the most important empirical model for performance, utilization factor and cutter wear prediction is *Norwegian University of Sciences and Technology (NTNU) model*. Last version of NTNU model was proposed by Bruland (1998) in its doctoral thesis.

The methodology proposed needs a series of laboratory tests that allows to define three NTNU/SINTEF indices, namely Drilling Rate Index (DRI), Bit Wear Index (BWI), and Cutter Life Index (CLI).

Penetration rate prediction is based on intact rock and rock mass characteristics (DRI, α, joint frequency J_f, and porosity n) as well as machine parameters, e.g. F_N, Φ_{disc}, v_{rot}, $s_{cutters}$, and number of cutters $n_{cutters}$). The model allows cutter wear and UF prediction, thanks to correlations with CLI, quartz content (q), and lithology.

Non-linear multiple regression analysis is often exploited in empirical models to find correlations between parameters (Alber, 1996; Yagiz, 2008; Gong and Zhao, 2009; Hassanpour *et al.*, 2011; Farrokh *et al.*, 2012). Other authors (Alvarez Grima *et al.*, 2000) tried to apply other strategies, as the neuro-fuzzy model, based on data clustering and a back-propagation algorithm.

Another group of models correlate machine performance and cutter wear with rock mass classification systems), primarily because they are accepted and known worldwide in rock mechanics.

Correlations with Rock Mass Index, RMR, were proposed by Cassinelli *et al.* (1982), Innaurato *et al.* (1990), Ribacchi and Lembo Fazio (2005), Hamidi *et al.* (2010), and Hassanpour *et al.* (2011); Rock Mass Quality Index for TBM, Q_{TBM}, was introduced by Barton (2000); a correlation with Geological Strength Index (GSI) was proposed by Hassanpour *et al.* (2011).

Globally all the 15 discussed models predict penetration rate, four of them give a solution for cutter wear prediction, and others four allow to foresee the utilization factor. As shown in tab. 1 and tab. 2, geological parameters most considered in prediction models are σ_c and J_s, with more than 70% of occurrences, and α (more than 60%). Also lithology, σ_t, and RQD are considered in more than 35% of the cases.

CAI and quartz content are considered in those models that study also the cutter wear, whereas joint condition, GSI, porosity, stress, water content and rock density register a low frequency.

More than 40% of the models studied are influenced by the thrust per cutter F_N.

In any case, low frequency of machine parameters is registered, also because all models referring to rock mass classifications are simple and they do not take into account the interaction between the machine and the face: CSM (1993), NTNU (1998) and Gehring (1995) models provide a most complete study of all parameters involved in the process (tab. 3).

Tab. 1. Prediction models: intact rock parameters.
Modelli predittivi: parametri della roccia intatta.

Model	Intact rock parameters					
	Rock	σ_c	σ_t	CAI	q	ρ
CSM (1993, 2006, 2010)	x	x	x	x	x	
Gehring (1995)		x		x		
NTNU (1998)	x	x		x	x	
Alber (1996)	x	x		x		
Yagiz (2008)		x	x			x
Gong, Zhao (2009)		x	x			
Hassanpour *et al.* (2011)	x	x				
Farrokh *et al.* (2012)	x	x				
Alvarez G. *et al.* (2000)		x				
Cassinelli *et al.* (1982)		x				
Innaurato *et al.* (1990)		x				
Barton (2000)			x		x	
Ribacchi, Lembo Fazio (2005)		x	x			
Hamidi *et al.* (2010)						
Hassanpour *et al.* (2011)		x				
Frequency	5	13	5	4	3	1

Tab. 2. Prediction models: rock mass parameters.
Modelli predittivi: parametri dell'ammasso roccioso.

Model	Rock mass parameters							
	J_s	RQD	J_w	J_c	α	σ,*w*	n	GSI
CSM (1993, 2006, 2010)	X				x			
Gehring (1995)	X				x			
NTNU (1998)	X				x		x	
Alber (1996)						x		x
Yagiz (2008)	X				x			
Gong, Zhao (2009)	X				x			
Hassanpour *et al.* (2011)		x						
Farrokh *et al.* (2012)	X							
Alvarez G. *et al.* (2000)	X							
Cassinelli *et al.* (1982)	X	x	x		x	x		
Innaurato *et al.* (1990)	X	x	x		x	x		
Barton (2000)	X	x	x	x	x	x		
Ribacchi, Lembo Fazio (2005)								x
Hamidi *et al.* (2010)		x		x	x			
Hassanpour *et al.* (2011)	x	x	x		x	x		x
Frequency	11	6	4	2	10	5	1	3

Tab. 3. Prediction models: disc and cutterhead parameters.
Modelli predittivi: parametri dell'utensile a disco e della testa di scavo.

Model	Disc				Cutterhead			
	F_N	Φ_{disc}	w_{tip}	v_{lim}	Φ_{TBM}	$n_{cutters}$	$s_{cutters}$	v_{rot}
CSM (1993, 2006, 2010)	x	x	x	x	x	x	x	
Gehring (1995)	x	x						
NTNU (1998)	x	x			x	x	x	x
Alber (1996)								
Yagiz (2008)								
Gong, Zhao (2009)								
Hassanpour *et al.* (2011)								
Farrokh *et al.* (2012)	x				x			
Alvarez G. *et al.* (2000)	x	x						x
Cassinelli *et al.* (1982)								
Innaurato *et al.* (1990)								
Barton (2000)	x				x		x	
Ribacchi, Lembo Fazio (2005)								
Hamidi *et al.* (2010)								
Hassanpour *et al.* (2011)								
Frequency	6	4	1	1	4	2	3	3

2. Materials and methods

The prediction models listed in previous chapter were tested through the example of Koralm tunnel project, in particular a 1000-m-long section of the South tube.

2.1. Koralm tunnel project

The Koralm tunnel project is a 32.9-km-long railway double-tube tunnel, part of the Koralm railway connecting the two main cities in the Southern Austria, Graz and Klagenfurt. The high-speed railway is one of the projects involved in the EU program Trans-European Transport Network (TEN-T); in particular, Koralm railway is part of the Baltic-Adriatic Corridor VI Helsinki/Gdànsk – Padova/Bologna.

Koralm tunnel crosses the mountains that divide Styria and Carinthia, from Frauental an der Lassnitz to St. Andrä.

The portion of alignment investigated is part of KAT 2 construction lot, in particular the area of the Middle Austro-Alpine crystalline complex (fig. 2). The crystalline complex, with an overburden up to approximatively 1,200 m, consists of a thick poly-metamorphic sequence. Main deposit is para-gneiss, with inclusions of marbles, amphibolites, eclogites, quartzites, orthogneisses, and pegmatites. Slightly fractured hard rock sections with highly to extremely abrasive rocks dominate. Ground water inflows with occasional high water pressures are usually related to areas with intense fracturing, damage zones or faults (Moritz *et al.*, 2011; Wagner *et al.*, 2009).

Koralm tunnel is excavated by two double shielded TBMs Aker-Wirth TB 993 E/TS, one per tube. The cutter head is driven by electric motors with an overall power rating of 4,800 kW, maximum cutting torque is 30,000 kNm. Two cylinders provide gripping thrust, with a maximum total clumping force of 115,000 kN, corresponding to a maximum contact pressure of 4.7 MPa. The cutterhead has a maximum boring diameter of 9.93 m (being 20 cm the maximum over-profile allowed), and total shield length is 13,860 mm, with a ratio $\Phi_{cutterhead}/L_{shield}$ = 1.396. The cutterhead is composed of 80 17" discs (77 at the face and 3 external gauge cutters), and average spacing between two cutters is 65 mm. Maximum rotational speed is 6 rpm.

All parameters are summarised in tab. 4.

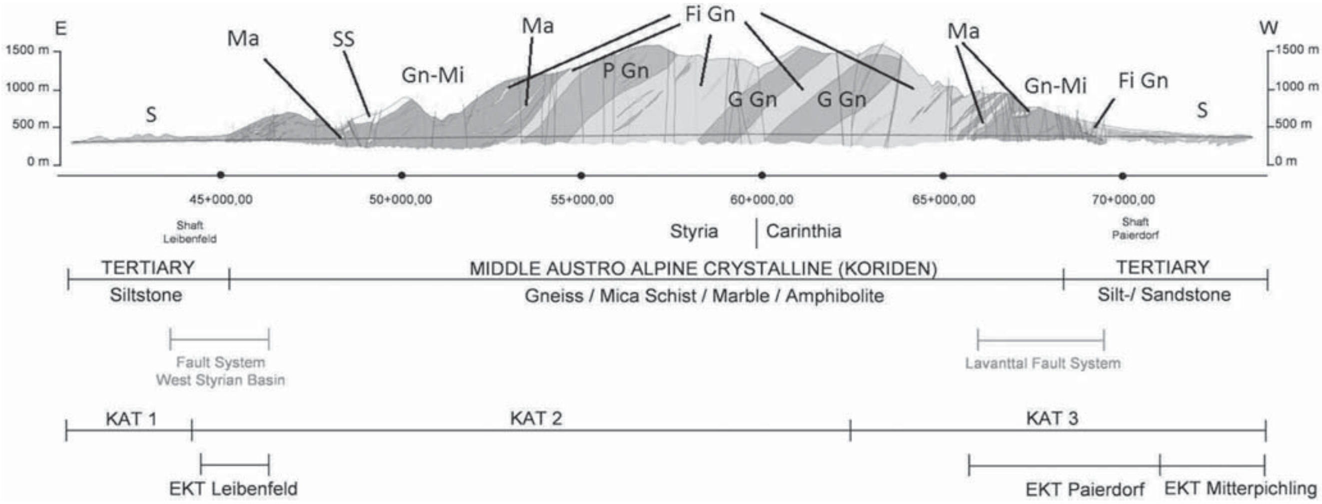

Fig. 2. Geological section and construction lots at Koralm tunnel: gneiss- and mica-schist (Gn-Mi), marble (Ma), fine-grain gneiss (Fi Gn), coarse-grain gneiss (G Gn), siltstone (S), sandstone (SS) and paragneiss (P Gn) (Harer and Koinig, 2010).
Sezioni geologiche e lotti costruttivi nel Koralm tunnel: gneiss- e mica-scisti (Gn-Mi), marmi (Ma), gneiss a grana fine (Fi Gn), gneiss a grana grossa (G Gn), limi (S), arenarie (SS) e paragneiss (P Gn) (Harer e Koinig, 2010).

Tab. 4. AkerWirth TB 993 E/TS characteristics.
Riepilogo caratteristiche AkerWirth TB 993 E/TS.

Parameter	Value
Cutterhead diameter	9.93 m
Shield length	13.86 m
Total number of cutters	80
Number of active cutters	77
Av. cutter spacing	65 mm
Discs diameter	17'' (432 mm)
Max. thrust per cutter	250-267 kN
Tip width	25 mm
Max. rotational speed	6 rpm
Max. total thrust	115,000 kN
Installed cutterhead power	4800 kW
Max. cutting torque	30000 kNm

2.2. Data analysis and methodology

All computations and plots have been processed with MathWorks MATLAB® release 2008a. A series of scripts have been created ad-hoc to process and filter data; the system of scripts has been designed in order to be easily applied to any other project.

The section of the tunnel investigated in the study is the area of the south tube in KAT2 lot between chainage 6,900 and 7,900, calculated from Leibenfeld construction site (from chainage 51,153 to 52,153 of the whole line, fig. 2). The portion of alignment was excavated from January to March 2014.

The segment was selected on the base of the variability of rock mass characteristics along the chainage and the high percentage of homogeneous sections. Knowing that prediction models consider the face as homogeneous, only 37 over a total amount of 46 sections were considered, on the 1000-m-long portion of alignment studied.

Input parameters come from geological-geomechanical surveys performed daily at the face, in particular a weighted average of parameters, based on the percentage of the deposit. σ_t and CAI values come from laboratory tests reported in the geological, hydro-geological and geotechnical report (BCG consult *et al.*, 2009), while NTNU drillability indices have been derived from literature studies (Bruland, 1998), in absence of laboratory test data. An additional hypothesis is an isotropic state of stress. Mean values of each class were used as input parameters for prediction models.

Machine producers provide a maximum value of thrust a cutter can sustain during its life.

$F_{N,max}$ is often used as input parameter, but not necessarily TBM is driven at its full capacity, for different causes, e.g., geological conditions, operational limits, machine limitations (Rostami, 2008; Barton, 2000).

A different approach is applied in the analysis performed on Koralm tunnel database at construction stage, based on back-analysis of F_N per cutter (F_{cutter}) distribution as a function of one geological parameter.

Correlations between F_N and rock mass classifications (GSI, RMR) highlight the variability of the thrust per cutter along the alignment, as well as F_N distribution as a function of the uniaxial rock mass strength. In fig. 3 a flow chart is proposed in order to obtain a continuously updated TBM performance prediction and analysis:
- definition of a database composed of geological survey parameters and TBM machine data;
- back-analysis regarding variability of F_N with rock mass classification (e.g. GSI) or rock compressive strength, and exploring

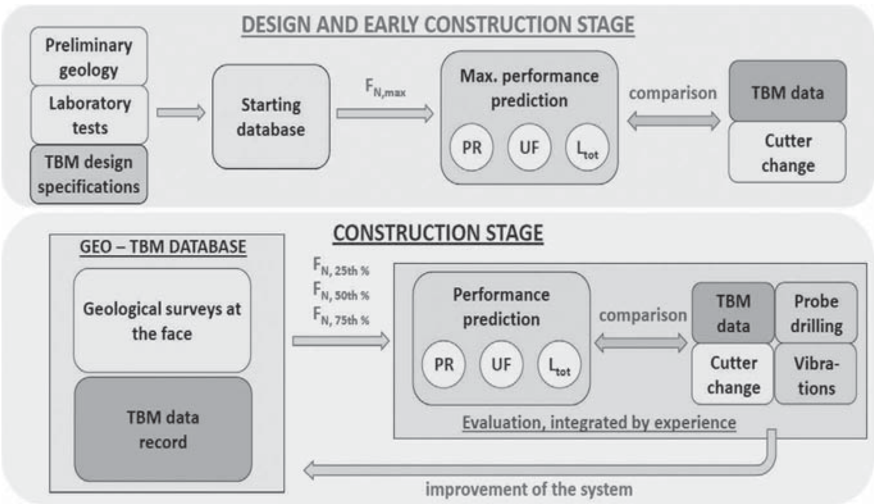

Fig. 3. Current method at design stage, and proposed new methodology for continuously updated TBM performance and cutter wear prediction at construction stage.
Metodo attuale a livello di progetto e nuova metodologia proposta per una previsione continuamente aggiornata delle prestazioni e dell'usura durante la fase di costruzione.

the influence of lithology on the thrust per cutter;
- using as geological inputs the data collected during a survey in a short-term view, or predicted geological parameters for next portions of chainage;
- obtaining 25-th, 50-th and 75-th percentile of F_N as a function of rock mass classification in the portion of alignment considered;
- computing all prediction models through a software, or a spreadsheet, designed for the task;
- comparing TBM performance with prediction, and evaluation by experienced engineers and geologists, taking into accounts also outcomes from exploration methods;
- analysing the distribution of the errors, and deciding best models for given geological conditions;
- updated estimation of costs and time.

In Koralm tunnel case, the distribution exploited in the method is F_{cutter} as a function of σ_c, reported in fig. 4, because it includes an adequate number of sections in each category (respectively 19 sections in the class 50-100 MPa, 13 in the class 100-150 MPa, and 5 sections in the class >150 MPa, as reported in tab. 5).

On the other hand, GSI classification does not provide a heterogeneous distribution in terms of sections per class.

3. Results

3.1. Performance

PR, ROP and SP prediction was investigated by applying prediction models to geological parameters in homogeneous sections. PR prediction performed on 37 sections are summarized in fig. 5 and tab. 6.

Each line represents the prediction obtened by adopting a specific model, estimated by using F_N values obtained from σ_c class statistics (see tab. 5).

Several models provide an accurate prediction of PR on the whole database; in particular NTNU model (1998), CSM modified model (1993), Q-TBM model (2000), and the equations proposed by Farrokh (2012), and Hassanpour *et al.* (2011) provide a little underestimation; a little overestimation can be found by adopting Gehring model (1995), and Hamidi's equation (2010). From the chart, one can notice that the

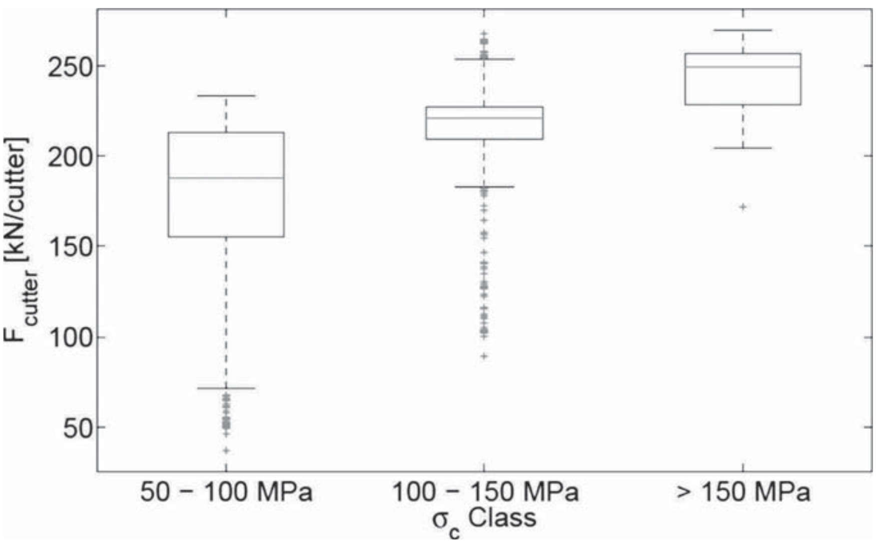

Fig. 4. Boxplot, F_{cutter} as a function of σ_c.
Boxplot, F_{cutter} in funzione di σ_c.

Tab. 5. F_{cutter} as a function of σ_c, table of statistics.
F_{cutter} in funzione di σ_c, tabella riassuntiva.

Par.	Group	Nr. Sec.	F_{cutter} [kN/cutter]				
			μ	σ	25^{th}	Med.	75^{th}
σ_c	50 – 100 MPa	19	177.52	44.00	154.98	187.51	213.07
	100 – 150 MPa	15	212.93	34.31	209.45	220.76	227.41
	> 150 MPa	5	243.58	16.00	228.74	249.36	256.58

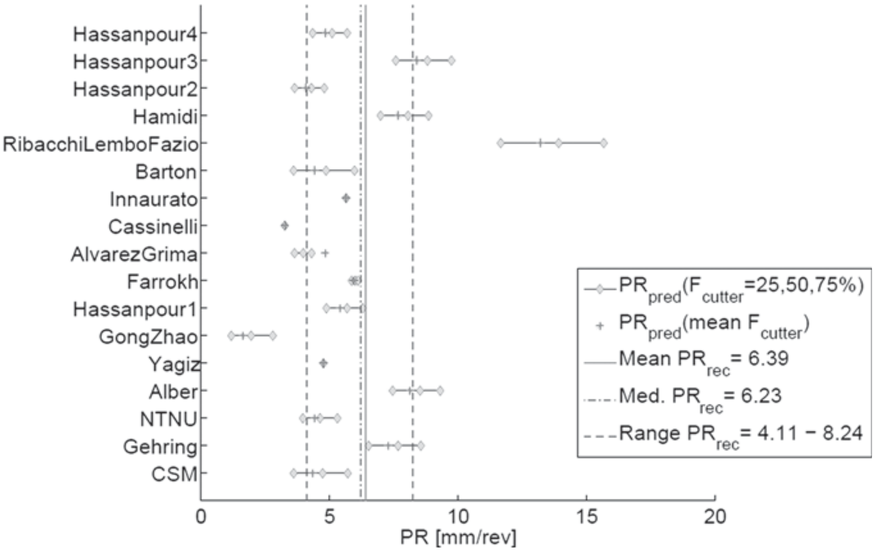

Fig. 5. PR prediction outcomes on the whole dataset (37 sections); diamonds correspond to PR obtained by 25th, 50th and 75th percentile of F_N, star symbol to mean value. Mean value from TBM data in the section is reported with a solid line, median with a dash-dot line, and 25th/75th percentile with two dashed lines.
Risultati della previsione di PR sull'intero campione (37 sezioni); i quadri corrispondono ai valori di PR corrispondenti al 25° percentile, la mediana e il 75° percentile di F_N, la stella al valore ottenuto con la media. Il valor medio dei dati TBM nella sezione di studio è riportato con una linea continua, la mediana con una linea tratto punto e i percentili 25° e 75° con due linee tratteggiate.

Tab. 6. PR prediction, summary table.
Previsione di PR, tabella riassuntiva.

Model	Acc.	Under	Over	TME
CSM mod., 1993, 2006	13	23	1	0.52
Gehring, 1995	19	7	11	0.29
NTNU, 1998	6	22	9	0.57
Alber, 1996	13	2	22	0.98
Yagiz, 2008	4	23	10	0.38
Gong, Zhao, 2007	3	34	0	1.83
Hassanpour1, 2011	13	18	6	0.36
Farrokh, 2012	8	16	13	0.32
Alvarez Grima, 2000	10	22	5	>>1
Cassinelli, 1982	2	31	4	0.45
Innaurato, 1990	6	22	9	0.28
Barton, 2000	12	23	2	0.84
Ribacchi, 2005	2	17	18	0.88
Hamidi, 2010	18	1	18	0.62
Hassanpour2, 2011	6	27	4	0.85
Hassanpour3, 2011	9	6	22	0.84
Hassanpour4, 2011	4	27	6	0.78

equations proposed by Innaurato *et al.* (1990), Cassinelli *et al.* (1982), and Yagiz (2008) are independent of thrust per cutter.

However, a deeper analysis of the prediction for each section is needed, in order to understand which sections are critical, and if there are the premises to perform a short-term analysis.

In order to understand the prediction accuracy, three flags variables (”Accepted”, ”Underestimation”, and ”Overestimation”) define the behaviour of the model referred to a given section. If the range of performance predicted falls within the range of data recorded, model can be considered satisfactory, otherwise it is recognized as an underestimation or an overestimation.

Model error ME_{ik}, i.e. the error of k-th model at i-th section, is calculated as the normalized difference between mean F_N predicted and mean F_N recorded, multiplied for the ratio between 75th and 25th percentile:

$$ME_{ik} = \frac{F_{ik,pred}^{\;+}}{F_{ik,pred}^{\;-}} \cdot \frac{\overline{F_{ik,pred}} - \overline{F_{ik,rec}}}{\overline{F_{ik,rec}}}$$

where:

– $F_{ik,pred}^{\;+}$ is the 75th percentile of the predicted thrust per cutter at section i-th referred to model k-th;
– $F_{ik,pred}^{\;-}$ is the 25th percentile of the predicted thrust per cutter at section i-th referred to model k-th;
– $\overline{F_{ik,pred}}$ is the mean thrust per cutter predicted at section i-th referred to model k-th;
– $\overline{F_{ik,rec}}$ is the mean thrust per cutter recorded at section i-th.

Tab. 6 shows the outcomes of the computation obtained for the 37 sections analysed.

Mean model error referred to model k-th TME_k is the average value of |ME| in the N sections considered (in this case N=37), calculated as follows:

$$TME_k = \frac{\sum_{i=1}^{N} |ME_{ik}|}{N}$$

Most accurate models in terms of accepted cases and TME are CSM modified model, proposed by Rostami and Ozdemir (1993), and corrected by adding the influence of fractures (Ramezanzadeh, 2006), Gehring model (1995), Q-TBM model by Barton (2000), the equation proposed by Farrokh *et al.* (2012), first equation proposed by Hassanpour *et al.* (2011), and the equation proposed by Hamidi *et al.* (2010).

The number of section whose performance is over- and under-estimated is balanced in Gehring model (1995), as in equations proposed by Hassanpour *et al.* (2011) and by Farrokh *et al.* (2012). Models proposed by CSM (1993) and by Barton (2000) are subjected to errors of underestimation in many cases, while equation by Hamidi *et al.* (2010) usually overestimates the performance.

NTNU model, 1998 version, proposed by Bruland, and the equation proposed by Innaurato *et al.* (1990) present low error, but they have a low number of accepted cases, and they usually underestimates Aker-Wirth machine performance.

Other equations have a higher threshold of error and are often unbalanced.

The class-by-class analysis (tab. 7, 8, 9, and 10) reveals that some models are more appropriated to certain geological conditions, and they do not produce good results if extrapolated.

As shown in fig. 6a and in fig. 6b, NTNU (1998) and CSM (1993) models have a low degree of accuracy for low σ_c, while they improve their accuracy for $\sigma_c > 100$ MPa with absolute values of TME always sensibly lower than 0.5. This effect is due to datasets prediction models computation is based on. NTNU model (1998) comes from the analysis of tunnels excavated in Scandinavian igneous rocks, with high uniaxial compressive strength, and this effect can be seen in the categories "100-150 MPa" and "> 150 MPa", where TME goes closer to zero. CSM model (1993) prediction is less influenced by σ_c, if compared to NTNU (1998).

The model proposed by Gehring (1995, fig. 6c) is the one that provide predictions closer to data recorded. Its dataset consists on rock samples with high σ_c (100-300 MPa) from South-African and South-Korean projects in different rocks (granite, sandstone, gneiss, amphibolite), so the variety of lithology considered in the database allows better results. Error plot shows good results at low compressive strength, while at high σ_c there is an underestimation, probably because the improvement of discs performance at high compressive strength.

The importance of lithology crossed in comparison with model database is clear in case of the equation proposed by Hamidi *et al.* (2010, fig. 6d): the dataset is composed of records from a tunnel excavated by a double shielded TBM in metamorphic rocks, exactly as in Koralm tunnel KAT 2. The same observations can be done for the equations proposed by Alber (1996), and by Hassanpour *et al.* (2011) in their studies, in great part performed in metamorphic and sedimentary rocks.

The first equation by Hassanpour *et al.* (2011, fig. 6e) and the equation proposed by Farrokh *et al.* (2012, fig. 6f) have good results in all compressive strength classes. Many empirical models based on rock mass classification show a better response at high values of σ_c, as Q-TBM model (2000), and the equations by Innaurato *et al.* (1990), Cassinelli *et al.* (1982), and Ribacchi and Lembo Fazio (2005).

Best models in terms of error and accepted cases were chosen for each range of compressive strength and reported in tabs. 7, 8, and 9:

– Gehring model (1995), Alber equation, Hassanpour *et al.* (2011) equation, and Hamidi *et al.* (2010) equation, if $50 < \sigma_c < 100$ MPa;
– CSM model modified (1993), Gehring model (1995), and equations proposed by Hassanpour *et al.* (2011) and Innaurato *et al.* (1990) if $100 < \sigma_c < 150$ MPa;
– NTNU model (1998), and equa-

Tab. 7. PR prediction by the filter "σ_c-based", 50-100 MPa group.
Previsione di PR con il filtro "σ_c-based", gruppo 50-100 MPa.

Model	Acc.	Under	Over	TME
CSM mod., 1993, 2006	8	11	0	0.63
Gehring, 1995	14	0	5	0.22
NTNU, 1998	3	16	0	0.66
Alber, 1996	13	2	4	0.31
Yagiz, 2008	0	19	0	0.38
Gong, Zhao, 2007	0	19	0	2.96
Hassanpour1, 2011	8	11	0	0.34
Farrokh, 2012	3	13	3	0.23
Alvarez Grima, 2000	6	13	0	0.37
Cassinelli, 1982	0	19	0	0.57
Innaurato, 1990	2	14	3	0.21
Barton, 2000	9	10	0	0.85
Ribacchi, 2005	0	6	13	1.33
Hamidi, 2010	16	0	3	0.20
Hassanpour2, 2011	6	11	2	0.68
Hassanpour3, 2011	7	5	7	0.54
Hassanpour4, 2011	4	11	4	0.64
Av. 50 – 100 MPa	15	0	4	0.22

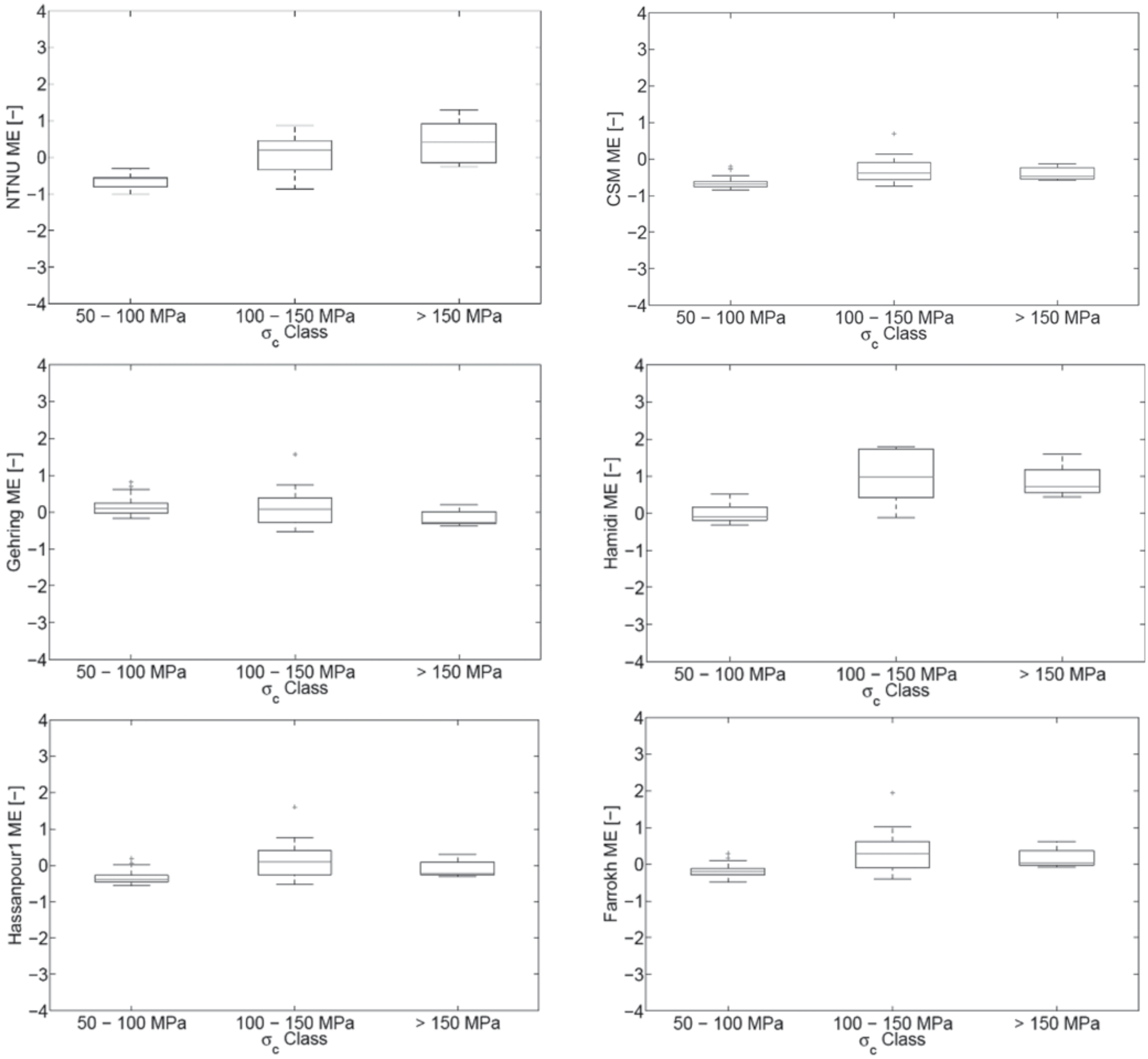

Fig. 6. Error boxplots for PR prediction on the whole dataset (37 sections).
Boxplots riguardo gli errori nella previsione di PR sull'intero campione (37 sezioni).

Tab. 8. PR prediction by the filter "σ_c-based", 100-150 MPa group.
Previsione di PR con il filtro "σc-based", gruppo 100-150 MPa.

Model	Acc.	Under	Over	TME
CSM mod., 1993, 2006	4	8	1	0.41
Gehring, 1995	4	4	5	0.42
NTNU, 1998	1	5	7	0.45
Alber, 1996	0	0	13	1.63
Yagiz, 2008	2	4	7	0.42
Gong, Zhao, 2007	1	12	0	0.73
Hassanpour1, 2011	4	4	5	0.43
Farrokh, 2012	2	3	8	0.51
Alvarez Grima, 2000	4	4	5	>>1

Model	Acc.	Under	Over	TME
Cassinelli, 1982	1	9	3	0.38
Innaurato, 1990	3	5	5	0.43
Barton, 2000	1	10	2	1.03
Ribacchi, 2005	1	7	5	0.45
Hamidi, 2010	2	1	10	1.14
Hassanpour2, 2011	0	11	2	1.17
Hassanpour3, 2011	2	1	10	1.29
Hassanpour4, 2011	0	11	2	1.11
Av. 100 – 150 MPa	4	5	4	0.39

Tab. 9. PR prediction by the filter "σ_c-based", > 150 MPa group.
Previsione di PR con il filtro "σ_c-based", gruppo > 150 MPa.

Model	Acc.	Under	Over	TME
CSM mod., 1993, 2006	1	4	0	0.40
Gehring, 1995	1	3	1	0.24
NTNU, 1998	2	1	2	0.57
Alber, 1996	0	0	5	1.78
Yagiz, 2008	2	0	3	0.28
Gong, Zhao, 2007	2	3	0	0.43
Hassanpour1, 2011	1	3	1	0.22
Farrokh, 2012	3	0	2	0.20
Alvarez Grima, 2000	0	5	0	>> 1
Cassinelli, 1982	1	3	1	0.22
Innaurato, 1990	1	3	1	0.18
Barton, 2000	2	3	0	0.31
Ribacchi, 2005	1	4	0	0.28
Hamidi, 2010	0	0	5	0.88
Hassanpour2, 2011	0	5	0	0.65
Hassanpour3, 2011	0	0	5	0.83
Hassanpour4, 2011	0	5	0	0.46
Av. > 150 MPa	2	1	2	0.21

tions proposed by Gong and Zhao (2007), Farrokh *et al.* (2012) and Q-TBM model (2000), if σ_c > 150 MPa.

Looking at the whole database, the prediction is acceptable in 21/37 sections, corresponding to 56.8% of the sections analysed (tab. 10).

Results for low level of compressive strength are satisfactory (15/19 sections correctly predicted), thanks to good outcomes coming from the best models in terms of accepted values and TME, as Gehring model (1995) and the equation proposed by Hamidi *et al.* (2010). The analysis for high σ_c level presents lower reliability, 2/5 sections correctly predicted, but they still have a low error. Worst results derive from sections with σ_c ranging from 100 to 150 MPa, just 4/13 sections correctly assessed and a higher error.

Marble is the main deposit in two sections (309 and 310), and in this case the underestimation can be due to the fact the great majority of this models does not take into account rock drillability, very high in marble (Bruland, 1998). A better assessment is provided by models that take into account DRI, i.e. NTNU (1998) and Barton (2000) models, as well as using Hamidi *et al.*'s equation (2010). In fact, these models take into account excavation in sedimentary rocks with high drillability, as shale and limestone.

Tab. 10. Summary, PR prediction by the filter "σ_c-based.
Riassunto, previsione di PR con il filtro "σ_c-based".

Model	Acc.	Under	Over	TME
Av 50 – 100 MPa	15	0	4	0.22
Av. 100 – 150 MPa	4	5	4	0.39
Av. > 150 MPa	2	1	2	0.21
Filter "σ_c-based"	21	6	10	0.28

3.2. *Utilization factor*

Utilization factor (UF) can be predicted by using four different approaches: NTNU model by Bruland (1998), the correlation proposed by Alber (1996), the equation proposed by Innaurato *et al.* (1990), and Q-TBM model by Barton (2000), reported in tabs. 11, 12, 13, and 14.

The analysis is similar to the one performed for PR, even if, in this case, UF can be calculated just on a portion of alignment and not continuously. In this case, the test is considered passed if data stay in a range of 25% from the mean value.

What emerges from the analysis on the whole database is that NTNU (1998) and Q-TBM (2000) models allow a successful prediction of the utilization factor of the machine in a long-term perspective. The equation found by Innaurato *et al.* (1990) overestimates the utilization factor, but it must be said it is a simple model, based on a polynomial correlation with RMR classification.

Relationship proposed by Alber (1996) induces an underestimation in UF prediction, even if deeper analysis should be performed; in fact, it is based on the in-situ state of stress, here assumed isotropic.

Following the same methodology proposed for machine performance analysis, NTNU model (1998) lead to an absolute value of TME lower than 0.5 in all σ_c ranges.

A constant overestimation can be seen in UF values calculated with the equation proposed by Innaurato *et al.* (1990), especially when considering high values of σ_c (tab. 13).

This trend is justified from the characteristics of the dataset, i.e. tunnels excavated by open shield TBMs. The choice of an open shield TBM is linked to a high rock sta-

Tab. 11. UF prediction by the filter "σ_c-based", 50-100 MPa group.
Previsione di UF con il filtro "σ_c-based", gruppo 50-100 MPa.

Model	Acc.	Under	Over	TME
NTNU, 1998	13	3	3	0.71
Alber, 1996	7	11	1	0.75
Innaurato, 1990	9	1	9	0.84
Barton, 2000	9	7	3	0.94
Av. 50 – 100 MPa	14	2	3	0.76

Tab. 12. UF prediction by the filter "σ_c-based", 100-150 MPa group.
Previsione di UF con il filtro "σ_c-based", gruppo 100-150 MPa.

Model	Acc.	Under	Over	TME
NTNU, 1998	9	0	4	0.25
Alber, 1996	12	0	1	0.16
Innaurato, 1990	8	0	5	0.34
Barton, 2000	9	1	3	0.20
Av. 100 – 150 MPa	12	1	0	0.13

Tab. 13. UF prediction by the filter "σ_c-based", > 150 MPa group.
Previsione di UF con il filtro "σ_c-based", gruppo > 150 MPa.

Model	Acc.	Under	Over	TME
NTNU, 1998	2	1	2	0.33
Alber, 1996	2	1	2	0.22
Innaurato, 1990	1	0	4	0.53
Barton, 2000	4	0	1	0.29
Av. > 150 MPa	3	0	2	0.28

Tab. 14. Summary, UF prediction by the filter "σ_c-based.
Riassunto, previsione di UF con il filtro "σ_c-based".

Model	Acc.	Under	Over	TME
CSM mod.(Frenzel), 1993, 2006, 2010	5	14	0	0.69
Gehring, 1995	0	19	0	0.79
NTNU, 1998	7	12	0	0.60
Alber, 1996	0	19	0	0.96
Av. 50 – 100 MPa	7	12	0	0.65

bility, so a higher UF is a natural consequence in case of a portion of alignment excavated in double shield mode. Equation proposed by Innaurato *et al.* (1990) and Q-TBM (2000) model present a higher variability, if compared with all other models.

Best models in terms of error and adequate predictions, grouped by their range of compressive strength, are:

- NTNU (1998) and Q-TBM (2000) models, and Innaurato *et al.* (1990) equation, if $50 < \sigma_c < 100$ MPa;
- Alber (1996) equation and Q-TBM (2000) model, if $100 < \sigma_c < 150$ MPa;
- NTNU (1998) and Q-TBM (2000) models, and equation proposed by Alber, if $\sigma_c > 150$ MPa.

Prediction is within the range of UF in 29 cases, over a total number of 37 sections, corresponding to the 78.4 % of sections analysed. Results are balanced for each class of σ_c, even if prediction for low level of compressive strength present a quite high value of TME, if compared with other groups. It has to be noticed UF is often overestimated in the portion of alignment under analysis.

3.3. Cutter wear

The average tunnel length covered by the TBM till the consumption of a cutter occurs (L_{tot}) is the parameter predicted by 4 different models: CSM model (1993), in particular the work proposed by Frenzel (2010, 2011, *et al.*, 2008); Gehring model (1995); NTNU model by Bruland (1998), the correlation proposed by Alber (1996).

As said before, lithology abrasiveness and σ_c are the parameters that have a higher influence on cutter consumption, as well as CAI.

The results of laboratory tests on rock samples (tab. 15) highlight how marble has a low abrasiveness in comparison with schist and gneiss,

Wear analysis is highly focused on mica-schist and gneiss-schist lithology, representing the most common geology formation in Koralm Tunnel.

As discussed in Section 4.2, L_{tot}

Tab. 15. CAI and quartz content from laboratory tests on Koralm Tunnel rock samples.
CAI e contenuto in quarzo nei test di laboratorio sui campioni di roccia del Koralm tunnel.

Rock	CAI		q	
	μ	σ	min	max
Mica- and gneiss-schist	3.51	0.83	3	45
Fine grain gneiss	4.03	0.71	3	90
Marble	2.19	0.92	0	21

variability is taken into account by assuming a range of acceptability equal to ± 25% of the mean value.

What emerges from the analysis on the whole database (tab. 14, 17, and 18) is that CSM (1993) and NTNU (1998) models allow a better prediction of disc wear in a long-term perspective, while the approaches proposed by Gehring (1995) and by Alber (1996) are not able to give a reliable answer to cutter consumption prediction; these models underestimate L_{tot} recorded along the alignment.

Detailed prediction is capital in cutter wear analysis: the number of accepted cases is remarkable just in CSM (1993) and NTNU (1998) models.

Prediction from all models, except from NTNU model (1998), produce an underestimation of disc wear. NTNU prediction entails an underestimation at lower σ_c and an overestimation at medium-high σ_c. Furthermore, the wear prediction distribution as a function of uniaxial compressive strength for this model shows a higher variability than other models.

Best models in terms of error and correct evaluation, grouped by their range of compressive strength, are:
- CSM (1993) and NTNU (1998) models, if $50 < \sigma_c < 100$ MPa;
- NTNU model (1998), if $100 < \sigma_c < 150$ MPa;
- CSM (1993) and NTNU (1998) models, if $\sigma_c > 150$ MPa.

Prediction is acceptable in 18 cases, over a total number of 37 sections, corresponding to 48.7 % of the sections analysed, a result not completely satisfactory if compared with PR and UF estimation. Prediction for low level of compressive strength present frequently underestimation, and a quite high value of TME, if compared with other groups; better results can be seen in rock with medium-high/very high values of σ_c (100-150 MPa).

Sections that present marble lithology are characterized by predicted values constantly minor in consumption. As widely explained in Section 2.2.2, NTNU (1998) prediction of cutter wear is the most complete, because it is sensible to rock abrasiveness, drillability, quartz content, in addition to machine and performance parameter (Bruland, 1998). In these cases, best assessment is provided by NTNU model (1998), while in other cases, where abrasiveness is higher, also other models provide good outcomes.

Total mean error of "σ_c-based" filter is 0.50, and error threshold can be even reduced by applying NTNU model (1998) to rock sections composed of lithology that presents high CLI value (corresponding to low abrasiveness), as marble or limestone.

Tab. 16. L_{tot} prediction by the filter "σ_c-based", 100-150 MPa group.
Previsione di L_{tot} con il filtro "σ_c-based", gruppo 100-150 MPa.

Model	Acc.	Under	Over	TME
CSM mod.(Frenzel), 1993, 2006, 2010	2	11	0	0.52
Gehring, 1995	0	13	0	0.76
NTNU, 1998	7	3	3	0.39
Alber, 1996	0	13	0	0.79
Av. 100 – 150 MPa	7	3	3	0.39

Tab. 17. L_{tot} prediction by the filter "σ_c-based", > 150 MPa group.
Previsione di L_{tot} con il filtro "σ_c-based", gruppo > 150 MPa.

Model	Acc.	Under	Over	TME
CSM mod.(Frenzel), 1993, 2006, 2010	0	5	0	0.52
Gehring, 1995	0	5	0	0.79
NTNU, 1998	3	0	2	0.34
Alber, 1996	0	5	0	0.74
Av. > 150 MPa	4	1	0	0.24

Tab. 18. Summary, L_{tot} prediction by the filter "σ_c-based.
Riassunto, previsione di L_{tot} con il filtro "σ_c-based".

Model	Acc.	Under	Over	TME
Av 50 – 100 MPa	7	12	0	0.65
Av. 100 – 150 MPa	7	3	3	0.39
Av. > 150 MPa	4	1	0	0.24
Filter "σ_c-based"	18	16	3	0.50

4. Conclusions

The analysis about application of prediction models in the 1000-m-long portion of alignment of the Koralm tunnel project provides satisfactory results, 21/37 sections (56.8 %) were correctly predicted with the methodology proposed, i.e. by grouping sections starting from a geological parameter. Results can be summarized as follows:
- at medium-low compressive strength ($50 < \sigma_c < 100$ MPa), best models are the ones where the database includes similar rocks, with outstanding results in terms of accepted values (79 % of sections correctly predicted);
- medium-high compressive strength ($100 < \sigma_c < 150$ MPa) is the range with worst outcomes,

just 31 % of accepted results, and best models are a mix of empirical and analytical models;
- at high compressive strength (σ_c > 150 MPa), empirical models are the ones that provide best results, but just 40 % of performance are correctly predicted;
- if DRI is high (marble sections), predictions can be performed by averaging models that take into account drillability, as NTNU (Bruland, 1998) and Q-TBM (Barton, 2000) models, and eventually models whose dataset is while composed of these rocks (Hamidi *et al.*'s equation, 2010).

Same philosophy was applied in order to predict the utilization factor. UF predicted is within the range of values recorded in 29 cases, over a total number of 37 sections, corresponding to 78.4 % of sections analysed. NTNU model by Bruland (1998), the correlation proposed by Alber (1996), and Q-TBM model by Barton (2000) have good results in UF estimation.

Cutter wear prediction was investigated too, even if results are less satisfactory.

Models allow a correct prediction in 49.7 % of the cases, with better results in the range medium-high/very high values of σ_c. CSM (1993) model, in particular Frenzel's equation (2010, 2011), and NTNU model by Bruland (1998) guarantee better results; in particular, the Norwegian model is able to predict with success also the wear in case of low abrasiveness (marble deposits).

The study proves how the choice of the correct prediction model can have a severe impact on TBM performance prediction, in particular it highlights the influence of the geology.

Since this analysis regards only 1000 m of the tunnel, a wider database is needed in order to compare TBM performance and investigations in a suitable way. In the future, correlations could be improved by additional analyses regarding the entire length of the tunnel, providing most reliable numerical results that can integrate the outcomes here presented, integrating the system of TBM data analysis and prediction at the construction stage proposed in this work. Furthermore, prediction should be enhanced strongly by applying a distribution of thrust as a function of rock mass classifications, in particular GA and GSI. These results will allow a more accurate prediction of TBM performance, utilization factor and cutter wear: outcomes can have a remarkable impact both on technical side and on economic side.

The results can be used, in this case, as a prediction method to evaluate performance and cutter consumption for the excavation of the residual part of Koralm tunnel, but the methodology can be applied in any other project. The system is particularly useful in long tunnels, in which a continuous improvement of the ability of prediction, and of the goodness of correlations found too, can have an effective impact on time and costs.

Bibliography

Alber, M., 1996. *Prediction of penetration and utilization for hard rock TBMs*, in *Proceedings ISRM International Symposium Eurock '96*, Turin, Italy, Balkema, pp. 721-725.

Alvarez Grima, M., Bruines, P.A., and Verhoeh, P.N.W., 2000. *Modeling Tunnel Boring Machine Performance by Neuro-Fuzzy Methods*. Tunnelling and Underground Space Technology, 15(3), pp. 259-269.

Barla, G. e Pelizza, S., 2000. *TBM tunnelling in difficult ground conditions*, in: *GeoEngineering 2000, International Conference on Geotechnical and Geological Engineering*. Melbourne, Australia.

Barton, N., 2000. *TBM Tunnelling in Jointed and Faulted Rock*. Balkema, Brookfield, Rotterdam.

BGG Consult ZT GmbH, ÖBB-Infrastrucktur AG, 3G Gruppe Geotechnik Graz ZT GmbH. *Ausschreibungsprojekt Koralmtunnel Baulos KAT 2; Geologie, Hydrogeologie und Geotechnik*. Unpublished, 2009.

Bottero M. e Peila D. (2005) *The use of the Analytic Hierarchy Process for the comparison between microtunnelling and trench excavation*. Tunnelling and Underground Space Technology, 20 (6), pp. 501-513.

Brino, G., 2015. *Prediction of performance and cutter wear in rock TBM: application to Koralm tunnel project*. MSc thesis, Politecnico di Torino.

Bruland, A., 1998. *Hard Rock Tunnel Boring*. PhD thesis, NTNU Trondheim Norwegian University of Sciences and Technology, Vol. 1-10.

Cassinelli, F., Cina, S., Innaurato, N., Mancini, R. e Sampaolo, A., 1982. *Power consumption and metal wear in tunnel-boring machines: analysis of tunnel-boring operation in hard rock*, in: *Tunnelling '82*, London, pp. 73-81.

Cheda, J., Schuerch, R., Perazzelli, P. e Mezger, F., 2013. *Performance of penetration models for hard rock TBMs in the case of the Gotthard Base Tunnel*, in: *World Tunnel Congress 2013 Geneva. Underground – the way to the future*. Geneva, Switzerland. Anagnostou, G. e Ehrbar, H. (Eds), International Tunnelling Association ITA-AITES, pp. 1-8.

Farrokh, E., Rostami, J. e Laughton, C., 2012. *Study of various models for estimation of penetration rate of hard rock TBMs*. Tunnelling and Underground Space Technology, 30, pp. 110-123.

Frenzel, C., Käsling, H., and Thuro, K., 2008, *Factors Influencing Disc Cutter Wear*. Geomechanik und Tunnelbau, 1(1), pp. 55-60.

Frenzel, C., 2010. *Verschleisskostenprognose für Schneidrollen bei maschinellen Tunnelvortrieben in Festgesteinen*. Technical report, TU Munich. Ingenieurgeologie Hydrogeologie Geothermie. Dr. Friedrich Pfeil (Münchner Geowissenschaftliche Abhandlungen, Reihe B).

Frenzel, C., 2011, *Leistungs- und Verschleissprognose in der Praxis am Beispiel des CSM Modells,* in: *Penetrations- und Verschleissprognose beim TBM-Vortrieb im Fels*, ETH Kolloquium.

Gehring, K., 1995. *Leistungs- und Verschleissprognosen im maschinellen Tunnelbau*. Felsbau, 13, pp. 439-448.

Gong, Q.M. e Zhao, J., 2007. *Influence of rock brittleness on TBM penetration rate in Singapore Granite*. Tunnelling and Underground Space Technology, 22, pp. 17-24.

Gong, Q.M. e Zhao, J., 2009. *Development of a rock mass characteristics model for TBM penetration rate prediction*. International Journal of Rock Mechanics and Mining Sciences, 46, pp. 8-18.

Hamidi, J.K., Shahriar, K., Rezai, B. e Rostami, J., 2010. *Performance prediction of hard rock TBM using Rock Mass Rating (RMR) system*. Tunnelling and Underground Space Technology, 25, pp. 333-345.

Harer, G. e Koinig, J., 2010. *Current state of design, investigation and construction works at the Koralm Tunnel.* Geomechanics and Tunnelling, 3(2), pp. 155-162.

Hassanpour, J. , Rostami, J. e Zhao, J, 2011. *A new hard rock TBM performance prediction model for project planning.* Tunnelling and Underground Space Technology, 26, pp. 595-603.

Innaurato, N., Mancini, R., Rondena, R. e Zaninelli, A., 1991. *Forecasting and effective TBM performances in a rapid excavation of a tunnel in Italy*, in: *Proceedings of the Seventh International Congress ISRM*, Aachen, pp. 1009-1014.

Moritz, B., Wagner, H., Mussger, K., Handke, D., and Harer, G., 2011. *Criteria for the selection of tunnelling method through the example of the Koralm Tunnel*. Geomechanics and Tunnelling, 4(4), pp. 305-315.

Oggeri, C. e Oreste, P., 2012. *The Wear of Tunnel Boring Machine Excavation Tools in Rock*. American Journal of Applied Sciences, 9(10), pp. 1606-1617.

Peila D. e Pelizza S. (2009). *Ground probing and treatments in rock TBM tunnel to overcome limiting conditions.* Journal of Mining Science, 45(6), pp. 602-619.

Peila D. (2009). *Indagini Preliminari nella Costruzione di Gallerie: Analisi della Letteratura Tecnica.* Geoingegneria Ambientale e Mineraria, 128(3), pp. 23-44.

Ramezanzadeh, A., Rostami, J. e Kastner, R., 2003. *Performance Prediction Models for Hard Rock Tunnel Boring Machines*, in: *6th Iranian Tunneling Conference*.

Ramezanzadeh, A., 2006. *Performance Analysis and Development of New Model for Performance Prediction of Hard Rock TBMs in Rock Mass*. PhD thesis, Institut national des sciences appliqués de Lyon, France.

Ribacchi, R. e Lembo Fazio, A., 2005. *Influence of Rock Mass Parameters on the Performance of a TBM in a Gneissic Formation (Varzo Tunnel)*. Rock Mechanics and Rock Engineering, 38(2), pp. 105-127.

Rostami, J. e Ozdemir, L., 1993. *A new model for performance prediction of hard rock TBM*, in: *Rapid Excavation and Tunnelling Conference 1993*. Boston, U.S.A., pp. 793 – 809.

Rostami, J., 2008. *Hard rock TBM cutterhead modelling for design and performance prediction*, Geomechanik und Tunnelbau, 1(1), pp. 18-28.

Yagiz, S., 2008. *Utilizing rock mass properties for predicting TBM performance in hard rock condition*. Tunnelling and Underground Space Technology, 23, pp. 326-339.

Wagner, H., Handke, D., Matter, J., Fabbri, D. e Keiper, K., 2009. *Concepts to overcome squeezing geological conditions at the Koralm tunnel.* Geomechanics and Tunnelling, 2(5), pp. 601-611.

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