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Mechanical wear of cutters in tunnel boring machines – a comprehensive review

Factors that determine the selection of method to excavate a tunnel depend upon the geology, economy and site conditions,but when it comes to the economics of tunnelling then it has to be chosen correctly as per the methodology. Cutters are an integral part of a tunnel boring machine and its performance depends largely on these. In order to ascertain various factors of cutters that influence the performance of the machine, a comprehensive study of literature was carried out. The method involved referencing the citations to a particular publication from which the importance of factors responsible for cutter wear in TBM were decided. In order to categorise the impact of different variables on cutter wear, the references were divided into wear, mechanical, geological and engineering categories based on citations reviewed and observed. Cutting conditions of disc cutters has been reviewed and evaluated based on findings of different authors.

Keywords: *Mechanical excavation, TBM, disc cutter wear, crack propagation, failure inspection*

Introduction

India is one of the fastest growing venues for tunnel construction. Tunnelling with tunnel boring machines (TBM) has proved to be cost-effective and a faster alternative to the drilling and blast method (DBM). TBM gives a variety of advantageous factors to make TBM more favourable for any type of rock formations or geological strata. It also works smoothly and faster as well without disturbing the surrounding rock mass. Although it has dimensional and directional constraints, large numbers of such machines are deployed for tunnelling throughout the world. The fact stands despite possibilities of getting stuck in adverse geological conditions like shear and thrust zones. Nowaday's different types of TBM are assembled as per the different geological conditions such as open face, gripper, slurry, earth pressure balance, single and double shield, mixed shield and convertible shield are designed (Zhao et al., 2006).

TBM is quite sensitive to changing rocky strata to soft formations. Conditions like squeezing, swelling, rock bursting, spalling and high-water inflow (Delisio et al., 2013) have a bearing on the functioning of a TBM. Tunnel projects are characterised by high risk, complexities, uncertainties, repetitive construction task, large budgets and uncertain durations owing to actual site conditions. The performance of TBM is measured in terms of advance rate, penetration rate and utilization index. The performance rate depends mainly on local geology, type of rockmass and hydrological conditions. Such conditions thus determine the machine design, engineering and operational factors of a TBM (Rostamiet al., 1997 and Gong et al., 2009). The machine related factors are thrust, torque, disc geometry, disc wear and disc diameter, cutter arrangement and cutterhead revolutions per minute (RPM).

All mechanical excavation tools share the same principles of cutting and the mechanical force exerted is considered to be the main parameter. A lot of effort has gone into development of TBM performance prediction models in this direction (e.g. Cook et al. 1984, Sanio 1985, Snowdon et al. 1983 and Peng et al. 1989). A comparison of TBM application in different formations is given in Table 1.

Table 1 shows that rock characteristics and mechanical parameters of TBM are very important for tunnelling in adverse geological strata as well as design and construction of tunnelling. It can be noted that the performance of TBM is least in mixed geology conditions.

Table 2 is a comparison of two major types of TBM deployed in various projects.

Cutter head

Cutterhead is the main component of the TBM and to a major extent defines the success of a project where TBM is deployed. The design of the cutterhead impacts the efficiency of cutting, the balance of the head, the life of the cutters, the maintenance of the main bearing/seal/gearbox, and the effectiveness of the mucking along with its effects on the wear of the face and gauge cutters/muck buckets. Since cutterhead

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Table 1: Rock and respective TBM characteristics in known cases (adopted from published literature)

Rock characteristics			Mechanical parameters					
Rock Nature	Rock type	Lithology	TBM type	Thrust (kN)	Torque (kNm)	RPM max	Advance rate (m/day)	Cutterhead/ diameter
Hard rock	Igneous and metamorphic rocks	Granite, gabbro, syenite, and esite, charnockite, gneiss, peridotite, slate	Gripper, single shield, double shield	Single shield 16418-40, 225 double shield 5692-27, 038	Single shield 1348-3218 double shield 822-3442	Single shield 6.25 double shield 10	Single shield 8.6 double shield 20.09	Simple twin disc[1] single shield dia-5.05 double shield dia-5.57
Soft soil rock	Sedimentary rock	Clay, silt, sand gravels	EPB, Slurry	EPB 22613-55403 slurry 26591-74850	EPB 1822-7631 slurry 2726-6859	EPB 3 slurry 2	EPB5.6 slurry 6.4	Shield, screw conveyor[2] EPB dia-6.5 slurry dia-7.85
Mixed and changing ground	Mixed condition	Clay, gravels, marble, hard rock upto 180 Mpa	Multimode, hybrid	Multimode 22619, hydraulically supported hybrid 16882	Multimode 17,344 hybrid-5516	Multimode-6.4 hybrid-1.99	8.8	Convertible 17" disc cutter[3] dia-8

1 - Bilgin et al., 2012b; Ocak and bilgin 2009; 2 - Ocak and bilgin 2009; Bilgin et al., 2012b; 3 - Sandell and Stypulkawski 2019

Table 2: Main types of TBMs deployed for excavation

	Shield type TBM	Open type TBM
1	Machine body is wrapped in cylindrical skin plate	Machine body is open
2	Pressing force is from segments	Pressing force is from surrounding rock mass through main gripper
3	Water tight lining by segments	Permeable lining
4	Construction cost is higher	Economical
5	Segments are installed for permanent support within excavation cycle	No permanent support, shotcrete as a temporary support, concentric lining is necessary

directly affects the TBM performance the layout of cutters plays a major role in determining its performance. The machine performance can be evaluated in terms of noise, vibration, main bearing of the cutter and the service life of cutter head and main bearing that plays the role of supporting and making the cutter to rotate. Table 3 shows the main components of cutterhead along with their functions.

Table 3: Functions of cutterhead components

	Cutter head components	Function
1.	Cutter head jacket	Rolled steel plates act as a protective jacket of cutter head which is situated at the outer most part of cutter head
2.	Inner/outer kelly with gripping	The cylindrical or box shaped mechanical structure situated on the slipways of outer kelly is called as inner kelly, which gives an advantage of transmission of forces from outer to inner.
3.	Thrusting component	Thrusting components are the mechanical partsin form of two pressure cylinders that provide thrusting force. The force exerted is equally distributed to both the inner/outer kelly

The cutter head acts as a holder for the cutting tools. The cutterhead is conical in shape with an optimum thickness and composed of a proven material. The internal stresses generated with the cutterhead are responsible for crack formations and breakage. An important component of the cutterhead is the stiffener plate which allows fall of loose material on external scrapper. The exterior scraper is arranged in radial pattern on the cutterhead. The stiffener plates direct the material into the middle of the centre-free supported cutterhead. There, the muck is fed into the machine's muck conveyor collection hopper and dispatched to the respective collection bank. The drives responsible for cutterhead rotation are as follows.

- Friction coupling electric drive
- Frequency controlled electric drive
- Hydraulic drive
- Electrohydraulic drive

Types of cutters

Cutters are the main component of cutterhead which are mounted on it in a predetermined fashion. There are mainly three types of cutters viz. drag cutter, roller cutter and disc cutter. Drag cutters are mainly favourable for soft ground conditions and are available in a different range and sizes. Cutting modes are generally breaking out relatively large lumps of ground, this promotes efficient cutting and great ease in excavating weak and plastic beds.

Owing to the fact that in mixed geology the drag cutters damage rapidly, roller cutters are used to overcome the difficulty. There are mainly two types of roller cutters viz. milled tooth and tungsten carbide inserted cutters. On attack roller cutters create shear and tensile failure in the adjacent rock formation that results in formation of chips.

Disc cutter is a disc possessing a replaceable leading cutting edge. The cutters may be single double or triple in number on a single disc. The disc cutters make grooves in the rock and generate shear forces to break such ridges created in rock. Disc cutter work on grinding and pulverise action that cause disintegration of rock. Rocks with UCS of 175 MPa can be easily excavated by disc cutters. Table 4 shows the different types of disc cutters with their respective sizes. Range of the load bearing capacity of the cutters gives an idea of the selection of the disc cutters in varied geological formations. The ring tip width was main focus initially. However, continuing metallurgical research eventually resulted in rings made from tool steel. The rings have higher hardness as well as better fracture toughness as compared to the previous materials.

TABLE 4: TYPES OF DISC CUTTERS, THEIR SIZE AND LOADING CAPACITY

	Types of disc cutters	Size in inches	Load capacity range in tonnes
1	Single disc	12,14,17,18,19,20	12 to 35 d”
2	Twin disc	17,18,19	25 to 35
3	Double disc	12,14,17,18,19	12 to 35
4	Mono block single disc	10,11,12,14,17,18,19	d”12 to 35
5	Mono block double disc	8,10,11,12,17,18,19	d”12 to 35

Followings are the theories of the cutter penetration that are fundamental to design of the TBM cutter layout (Sun et al., 2011). The theories are mainly used when there is an occurrence of highly stressed and crushed zone.

- Shear crushing theory
- Radial tension crack crossing theory [Source]
- Hybrid crushing theory

The work done by crushing is the surface expose by the operation of cutting by TBM. Above given three theories analyse the cutterhead force distribution. The disc cutters layout design ensures that cutting force are exerted on the tip of the disc cutter during excavation in terms of normal force, rolling force and side force to ensure effective breakage.

Mechanism of breakage by TBM cutter

The cutters and rocks are characterised by their own physical properties. The disc cutter behaves like an elastic cylinder, rock as a brittle material (Wang et al., 2017) and the joint plane in rock can be considered to be a circle with an infinite radius. The transmission of energy from cutters to sub-surface area of rock mass under their mechanical action results in rock fragmentation and damage. Fractures take place due to mechanical force acting on the rock surface that creates a powered zone. The disc cutter is of V-shape with elliptical contact between disc cutter and rock. A simple breaking mechanism by disc cutter is explained in Fig.1. In order to achieve optimum rate of penetration, it is important to analyse the effect of geometry and wear characteristics of cutterhead on the transformation of efficiency of the energy transfer to the rock.

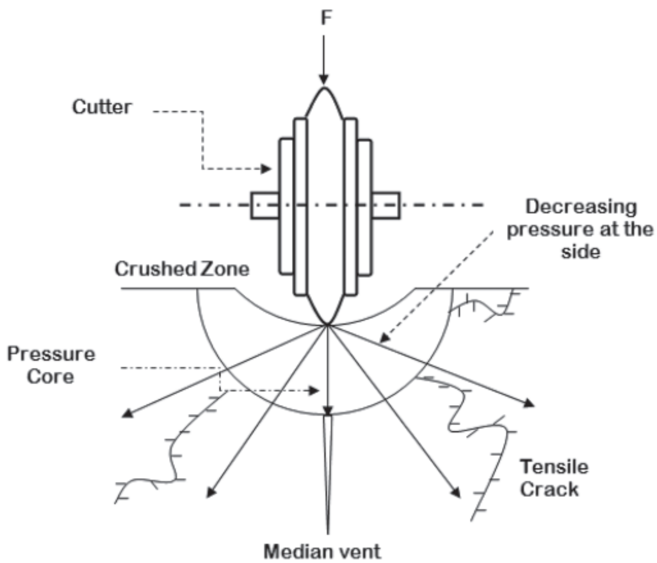

Fig.1 Crack propagation by cutter penetration (modified after Medel and Botello, 2013)

Suh (1973) states that when the normal load of cutter impacts the sub-surface by four times of its critical shear stress the rate of crack propagation by loading cycle is used to determine the wear rate of the cutter. The impact of disc cutter on the surface area shows major fractural characteristics on the face of rock mass. TBM equipped with disc cutters is pressed against the tunnel face or surface, thus the impact force released through crushed zone to pressure core which experienced tensile crack also which refers to the brittle deformation without displacement at the discontinuous surface and median vent crack at some depth as well. When the force impacts, the rock undergoes tensile cracking with respect to the pressure core, stress field forms about the plastic zone and it has been demonstrated that the residual stress field exerts an opening force on the median vents which is open at the face and narrow towards the bottom as shown in Fig.2 that explains the formation of chips by a combination of the cutters.

Line spacing of the adjacent cutters is the main parameter governing the interaction of ground/rock with the cutters and the forces applied. The interaction become more complex by

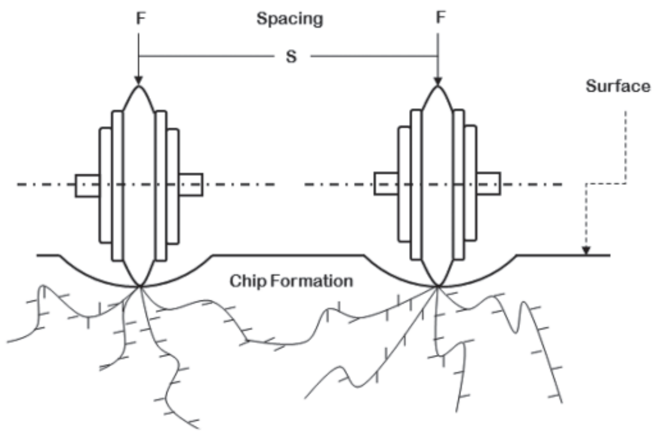

Fig.2 Chip formation by multiple cutters

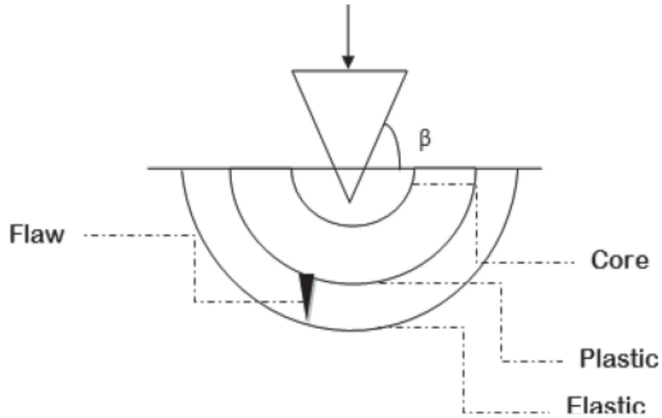

Fig.3 Disc cutter working in crushed zone

the presence of joints and discontinuities in rock. Chip formation is the part of process of cutting material by mechanical means, using disc cutters. Cracks are initiated from the crushed zone and propagated downward and sideward. One or more cracks under the action of the rolling cutter may reach the free surface or propagate to meet the cracks of the neighbouring cuts. Interaction and subsequent chip generation process are directly relevant to the design of the TBM cutterhead. Ratios such as uniaxial compressive strength to shear strength is equal to the ratio of cutter spacing to penetration (Roxborough et al., 1975).

Fig.3 shows the schematic diagram of disc cutter application in crushed zone where the impact of mechanical force towards the surface results in considerable deformation of the surface and the formation of core zone as well.

The rock surface under impact of cutter undergoes two main deformations i.e. plastic and elastic. Plastic deformation created due to fracture in the subsurface of the rock mass which tends to create flaws. The flaws are extended up to the elastic limit due to which it tends to complete deformation of the subsurface during rock mass breakage.

TBM

Performance evaluation of TBM

Physico-mechanical tests for TBM

There are a number of tests used for determination of various physico-mechanical properties for deployment of tunnel boring machine in a rock formation. These tests are of varied nature and a summary of such tests used by different authors are given in Table 5. These tests range from compressive strength to determination of drilling rate while providing information on hardness of rock, disc cutter force, cutter life, wear rate and rolling distance etc.

Among the 8 documented tests given in Table 5, compressive strength is the predominant method followed by Seiver's J value and Cerchar abrasivity index. The tensile strength, brittleness, point load and abrasivity can be assumed to have taken a secondary ranking in this scheme.

Analytical methods of TBM performance determination

To evaluate the performance of tunnel boring machine, artificial intelligence, numerical as well as statistical analysis has been usedby various authors. Such methods can be used to evaluate the cutter wear and related analysis as explained in Fig 4.

Fig.4 shows the broad differentiation of TBM performance prediction methods with their respective models. A brief review of such techniques used in practice is given in Table 6.

Intelligence analysis involves neuro fuzzy model, fuzzy logic model, artificial neural network, particle swarm optimization, applied fuzzy logic as well which collection and processing of the data and information of every aspects of machine with respect to the parts, links, hydraulic systems, cutter penetration rate etc.

Disc cutter wear

During the process of cutting, the cutters get damaged and exhibit wear in several ways. Different damage categories of cutter due to the attack are listed in Table 7.

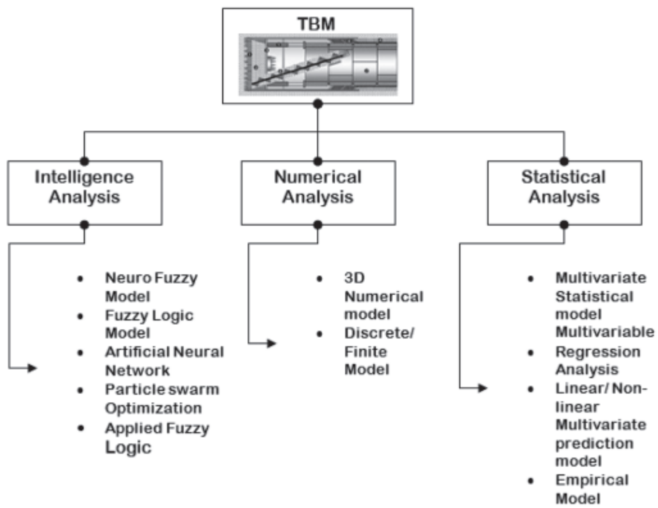

Fig.4 Performance prediction models

Table 5: Physico-mechanical tests to estimate TBM disc cutter wear prediction and machine parameters (Modified after Liu et al., 2017)

	Authors	UCS	Tensile strength	Cerchar abrasivity	Brittleness (S20)	Sievers' J	point load	Abrasivity	drilling rate	Total	Outputtest result
1	Sievers, 1950					√				1	Hardness
2	Matern and Hjelmer, 1963				√					1	Disc cutter strength
3	Graham, 1976	√	√							2	Cutter force
4	Farmer and Glossop, 1980	√	√							2	Cutter force
5	Büchi, 1984		√			√				2	Cutter spacing, rpm, cutter force
6	Hughes, 1986	√								1	Cutter dia, cutter force
7	Ewendt, 1992						√			1	Wear rate
8	Wijk, 1992	√		√			√			3	Rolling distance
9	Rostami and Ozdemir, 1993	√	√							2	Cutter spacing, cutter tip Width, cutter radius
10	Gehring, 1995	√		√						2	Cutter ring life avg
11	Rostami et al., 1996				√	√		√		3	Avg cutter ring life, avg cutter life
12	Rostami, 1997			√						1	Rolling distance and No. of cutter change
13	Bruland, 1998					√		√	√	3	No. of cutter changed, avg cutter life
14	Barton, 2000	√				√				2	Cutter force
15	Preinlet al., 2006	√				√		√		3	Tbm thrust, dia, rpm
16	Dahl et al., 2007					√	√			2	Cutter life index
17	Maidlet al., 2008	√		√						2	Rolling distance avg
18	Gong and Zhao, 2009	√			√	√				3	Cutter force
19	Bieniawskiet al., 2009	√		√	√	√				4	Cutter consumption
20	Hassanpouret al., 2009	√								1	Cutter force
21	Khademi Hamidi et al., 2010	√				√				2	Rpm, cutter force
22	Frenzel, 2011			√						1	Cost, cutter life index
23	Hassanpouret al., 2014	√								1	Avg. Cutter ring life
24	Yang et al., 2015	√								1	Wear rate of disc cutters
25	Benato and Oreste, 2015	√								1	Cutter force
	Total	16	4	6	4	10	3	3	1	47	

Rock mass damage assessment is required for many applications in rock engineering practice including support design, contamination transport control and stope design. Table 6 shows the damage category with respect to its degree of severity, how a crack developed by the attack of TBM to the surface grows initially is directly related to the impact of load. The table also shows the rock destruction characterization of crack rise to fracture of the rock mass. The wear in disc cutters in TBM as documented by different authors has been given in Table 8 that includes adhesive, micro, energy, delaminating, contact surface and alloy surface wear types.

Table 8 points to the fact that adhesive wear is the predominant type of wear in TBM cutters while as other types are equally predominant. Most of the authors have identified one or two types of wear in cutters.

Similarly, the mechanical parameters impacting the performance of the TBM are shown in Table 9.

Table 9 points to the fact that one to two factors have been used by different authors to identify their role on performance of the TBM.

Table 10 shows the geological parameters which are responsible for the wear in disc cutters.

It is evident from Table 10 that rock abrasion is the main rock factor influencing the performance of the cutters.

Foliation plays a role in rock fracture propagation between cuts in foliated and bedded rocks. Fig.5 shows the application of disc cutter in foliated/bedded rock and the direction to which the attack has to be done on the face of the tunnel.

Two distinct cases of foliation can be identified from Fig.5. These cases are discussed below.

- Case-1: In this case of foliated/bedded rock, when machine advances, the cutters are parallel to the foliation planes, crack propagation are forced to occur across the foliation plane. This reduces cutter penetration rate due to increase in difficulty in breaking the rock.

Table 6: TBM performance prediction models and relevant methods used by various authors

Citations	Method used for TBM performance prediction
Alvarez et al.,2000	Neuro-fuzzy employing fuzzy sets, fuzzy logic, approximate reasoning, and data clustering
Wang, 2000	Artificial intelligence expert system and intelligence control system for drilling engineering
Benardos et al.,2004	Artiûcial neural networks by dividing the data sets in two sub-sets
Ruvanpura,2004	Algorithms to predict the soil strata in tunnel path
Kim,2004	Fuzzy logic using geological and geotechnical site conditions
Zertsalov and Deineko,2005	Fuzzy sets, numerical modelling
Miranda et al.,2007	Artificial intelligence for geomechanical parameters evaluation in rock mass
He et al.,2007	Fuzzy evaluation to optimize main TBM parameters
Benardos,2008	Feed forward ANN for forecasting
Acaroglu et al.,2008	Fuzzy logic model to predict speciûc energy requirement
Tiryaki et al.,2008; Yagiz et al.,2009	Artiûcial neural networks
Javad and Narges,2010	ANN technique for modelling the penetration rate of TBM
Eftekhariet al.,2010	Artificial Neural network for the prediction of penetration rate of TBM
Yagiz et al., 2010	ANN, fuzzy logic and neuro fuzzy using database of rock mass and intact-rock properties
Hamidi et al., 2010	Fuzzy set theory for all rock engineering classification system
Yagiz,2011	Particle swarm optimization on rock properties data to predict TBM penetration rates
Jiang et al.,2011	Support vector machine and particle swarm optimization for feedback control system
Iphar,2012	Adaptive neuro fuzzy inference system for prediction of breaking rate of impact hammer
Mahdevari and Torabi,2012	ANN for the analysis of the convergence in tunnels.
Mahdevari et al.,2012	Artificial neural network and support vector regression for ground squeezing
Zhang et al.,2013	Multivariable regression analysis
Salimi and Esmaeili, 2013	Linear and non-linear regression and ANN
Adoko et al.,2013	Multivariable adaptive regression and artificial neural network for convergence
Ninic and Meschke,2015	ANN and particle swarm optimization to optimize machine parameters
Salimiet al., 2015	ANN, neuro fuzzy and support vector regression
Fattahi and Babanouri,2017	Non-linear and multivariable regression analysis with evolution algorithm, artificial bee colony algorithm and gravitational search algorithm
Minh et al.,2017	Linear, non-linear regression analysisincluding BTS, UCS, BI and distance plane weakness
Salimi et al.,2017	The regression tree to evaluate the RMR system by clustering number of parameters

- Case-II: When foliation is perpendicular to the direction of machine advance, the rock failure occurs along the foliation planes and the penetration rate increases.

Above given cases generally represents the most favourable boreability as the foliation assist crack initiation and growth in adjacent cuts. Penetration rate of the machine is greater in case of small distance between fractures (Cigla et al., 2001).

Table 7: Damage categorisation of cutters

Damage category	Degree of severity	Description of typical damage
0	Negligible	Hairline crack
1	Very light	Fine crack easily treated during normal treatment
2	Slight	Cracks are easily filled redecoration probably required
3	Moderate	Cracks can be patched by an engineer re pointing and possibly refilling material
4	severe	Extensive repair work involving replacement
5	Very sever	Major repairs required including partial or complete rebuilding

Table 11 also shows the engineering parameters which influence the wear in disc cutter.

Engineering parameters to describe the influence of wear in disc cutters as shows in Table 11 which lead to effectively working on engineering parameters which influence wear in cutter. The applicability of such parameters make ease while working controlling wear in disc cutter. Besides wear of the cutter ring tip, wear takes place on other parts of disc cutters as well. This is referred to as secondary wear which is caused by muck and loose rock. Especially, when operating an EPB or mix shield TBM in abrasive ground conditions, secondary wear may determine the overall lifetime of disc cutters. Factors responsible to eliminate secondary wear in disc cutters are as follows:

1. Conditioning of muck should be proper, although the observed decrease in torque due to muck conditioning with foams, water or slurry suggests an elimination of secondary wear.

Table 8: Types of cutter wear in TBM

	Wear parameters citations	Adhesive wear	Micro wear	Energy wear	Delaminating wear	Contact surface wear	Alloy surface wear	Total
1	Archard, 1953	√	√					2
2	Fleisher,1973			√				1
3	Suh, 1973				√			1
4	Evans and Marshall, 1981	√						1
5	Rabinowicz, 1995	√				√		2
6	Petrica et al., 2013						√	1
	Total	3	1	1	1	1	1	

Table 9: Mechanical factors influencing the TBM performance

	Parameters Citations	Friction	Load	Wheel profile	Rail profile	Cutter head thrust	Total
1	Fleisher, 1973	√					1
2	Evans and Marshall, 1981		√				1
3	Rabinowicz,1995			√			1
4	Ignesti et al.,2012				√	√	2
5	Alber, 2008						1
6	Wijk, 1992						2
	Total	1	1	1	1	1	

Table 10: Geological factors influencing the cutter wear

	Parameters Citations	Rock abrasion	Rock strength index	Total
1.	Oparin and Tanaino, 2015	√		1
2.	West, 1989	√		1
3.	Rostami, 1997	√		1
4.	Frenzel et al., 2008	√		1
5.	Gong et al., 2012	√		1
6.	Wijk, 1992		√	1
	Total	5	1	

2. Optimisation of muck flow is critical for mix shields since the abrasiveness of the slurry itself is very low.
3. Regular maintenance of wear protection on the cutterhead is applicable to all types of TBM (Frenzel et al.,2008).

Due to the above given conditions the cost initiated within cutter maintenance and inspection has become a barrier in the way of machining. Changing worn out cutters is costly when changing in the middle of the tunnel, cost associated with the cutter is categorised in three main conditions that is cost of downtime that may be due to technical failure, machine adjustment, maintenance, or non-availability of inputs such as power, labour etc. Cost of cutter replacement is another condition which is due to the over consumption of disc cutter, worn out cutter etc. The cost of refurbishing is associated with the servicing or renovation of older or damaged cutter to bring it to a workable condition. Project can be stopped for a longer period and the cost rises rapidly while tunnel production is at a standstill. If a cutter fails, there is a tendency of failure of cutters in the path next to the failed cutter. A case of 10 cutters approximately failing in a group was reported by Roby et al., 2008. The hard rock disc cutter generally fails in a group and is known as wipe-out phenomenon.This may also be due to operator failing to stop the machine in time that can further result in severe damage to cutterhead, also. When cutters are worn out then there are two treatments given to the cutters before being returned to the TBM.

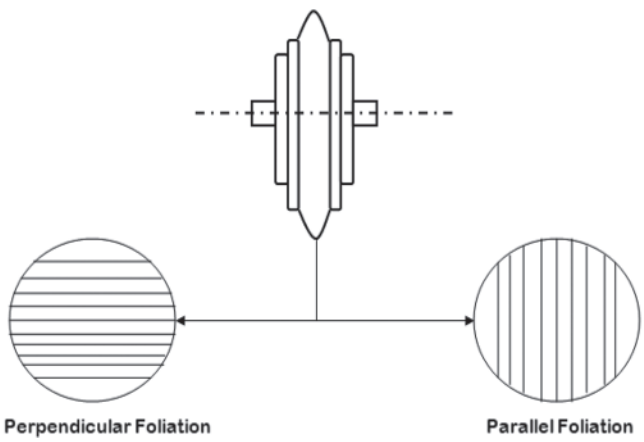

Fig.5 Cutter impact direction in case of foliated/bedded rock

1. Re-ring – Remove and replace as well as change the lubricant
2. Rebuild – Disassemble and replace cutters rings, bearing, seals, other small parts and lubricant.

Table 11: Engineering parameters of cutters defining cutter wear

	Parameters Citations	Energy consumption	Contacting surface	Arc length	Shaft contact	Bushing contact	Elastic cylinder	Total
1	Fleisher, 1973	√						1
2	Rabinowicz, 1995		√					1
3	Goryacheva and Goryachev, 2006		√	√	√	√	√	5
4	Goryacheva and Mezrin, 2011		√	√	√	√	√	5
5	Zhang et al., 2014			√				1
	Total	1	3	3	2	2	2	

Failure Inspection

Inspection is an examination of the mechanical parts and evaluation of the working machine. The activities involve in engineering inspection tests, measurement and gauges applied for the specific object or an activity as well. Fig.6 describes failure of seal and bearing inspection of disc cutterin detail with respect to the modes of failure and the cause due to which failure takes place.

Seal failure can lead to a potential consequence in a mechanical system, mainly that of cutters of TBM in an underground environment. During the failed cutter assembly analysis, it is seen that the most commonly needed first part to be removed is failed mechanical seal. Once the failure mode is isolated then it complicates the things which reflects in failure of inspection. One of the most significant developments in the disc cutter technology came with the application of metal face seals. This type of seal uses two metal rings that are loaded axially such that they ride against each other with a film of lubricant between them, creating a dynamic face-seal interface. Most rolling disc cutters use two tapered rollers bearing that are arranged in indirect mounting. There are two types of damage responsible for the failure of disc cutter. Bearing and seal, due to this the question arises that did the bearing failure misalignment and let the muck pass the seals or the seals fails and allow contamination to the bearing. So, for that the inspection is carried out. Modes of failure in seal such as damage toric which is mainly an O-ring used in seal to make a bond for resisting dirt into the seal, also the damage due to the impact of abrasive rock particles into which come in contact with seal. Similarly, in case of bearing spalled or grooved race ways which defines the flaking or loss of small spalls of material on a bearing rolling element and also brinelling and false brinelling is the occurrence of hollow spots that resemble brinell dents and are due to wear caused by vibration at the contact points between the rolling elements and raceway. The prevention of cutter from damage is very essential for TBM as per different geological conditions to get the best balance of cost and risk. Usually, the following types of bearings and drives are used in TBM such as central shaft bearing, circumferential bearing and centre-free compact bearing.

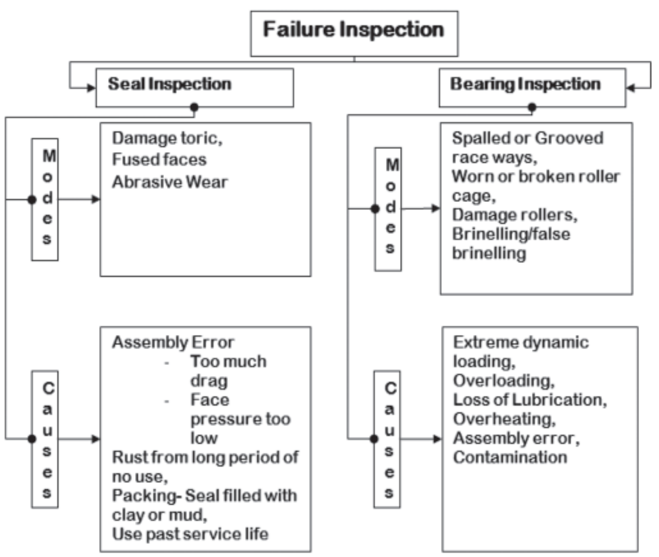

Fig.6 Failure inspection protocol

Conclusion

A comprehensive review of various aspects of tunnel boring machine based on the literature in published domain has been conducted with a focus on cutter wear. The review revealed that while efforts have been on to maximise the production of the TBM in varied geological formations, researchers have entered into the domain of intelligent systems to predict the performance of such machine. The cutter as the case should be has received a significant attention with a thrust on improving their life and defining a proper arrangement on the cutter head using statistical and intelligent methods. The alignment of the machine has also received a significant attention. The most used properties of the rock are the compressive strength and Siever's J value with a moderate use of Cerchar abrasivity index for determination of performance of the machine and cutter life and many other such variables of the machine.

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