INFLUENCE OF GEOLOGY ON TUNNEL BORING MACHINE PERFORMANCE – A REVIEW

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Abstract

Tunnel boring machines are used for excavating a variety of soils and rocks for circular cross-section tunnels. Several published studies examined the role of rockmass in determining the cutting and advance rate of tunnel boring machines. A comprehensive review of literature was conducted to ascertain the influence of geological conditions on the performance of tunnel boring machines and revealed that different rock characteristics were used to define the tunnel boring machine performance. The progress of the tunnel boring machine was ascribed to the inherent properties of the rockmass, intact rock properties, and surrounding geological conditions. Several authors found that extreme geological conditions strongly influence the advance of the machine. The review revealed that joint spacing, angle between plane of weakness and tunnel axis, rock quality designation, and number of joint sets were the most important variables that influenced the advance rates of the tunnel boring machine. At least 12 intact rock variables were used to define tunnel boring machine performance with one to seven such variables used in combination. The compressive strength, tensile strength, and brittleness index emerged as most crucial intact properties. Rockmass classifications or indices of tunnel boring machine performance were used by different authors to predict their performance and even to define their selection methodology. Use of dynamic properties of rock/rockmass was identified as a grey area for future research by scientists.

Key words: *Tunnel boring machine performance; Rock mass properties; Intact rock properties; Special conditions; Review.*

1.   Introduction

Rapid growth of the world's population increases the demand for energy and that, in turn, accelerates requirements in dependent sectors for tunnelling. The case of the increase in population and a corresponding increase in energy demand in India is presented in Figure 1. The increase in demand for energy, as well as the demand for tunnelling for hydroelectric power generation, is reflected in the annual energy demand in the country, as shown in Fig. 2 [1, 2], consequent electricity production, both in hydropower and gross energy generation.

India is mainly dependent on fossil fuels for electricity generation. Hydroelectric power generation is an alternative competitive renewable source of energy. The shift in the strategy for cleaner production is evidenced by the growth in the contribution of hydroelectric power to total electricity generation from 2012-13 to 2016-17 in India (Figure 2). The growth in

the hydropower sector is a clear indication of the increasing demand for tunnelling.
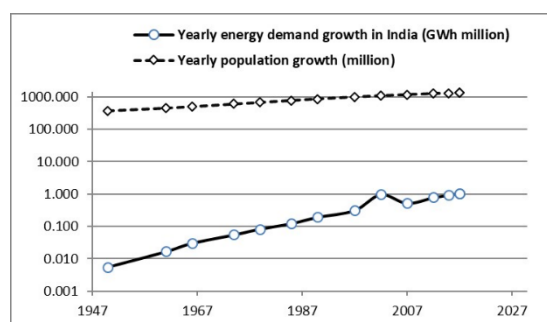

Figure 1 Population growth and energy demand in India [drawn after 3 and 4]

Besides hydroelectric projects, tunnel boring machines are used for other purposes. Tunnels and underground spaces are considered better alternatives for major structures since the available surface land is

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already constrained. Rapid urbanization has also increased the need for tunnelling in various sectors in order to fulfil the demand for power, transport, sewage, and irrigation.
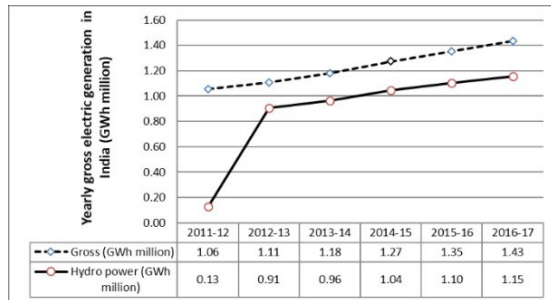

Figure 2 Contribution of hydroelectric power to gross power generation in India [drawn after 3]

Figure 3 shows the sector-wise share of tunnelling. Major tunnelling is currently being deployed in hydroelectric power projects with a share of 49% of total tunnelling. Tunnelling for irrigation projects assumes second rank (20%). All other tunnelling activities constitute the remaining 31% of the total [5].
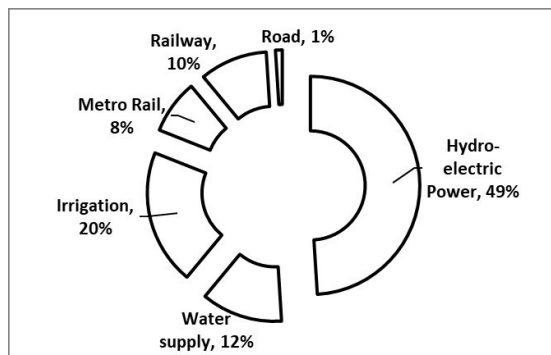

Figure 3 Application of tunnelling for different sectors in India [drawn after 5]

Methods of excavation, tunnelling economics, stability, and safety are major concerns in tunnelling. Besides mechanical devices such as tunnel boring machines and road headers, methods such as drilling and blasting can also be used for creating underground tunnels. As can be seen from Figure 4, about 69% of overall tunnelling is done with drill and blast. However, this method has disadvantages, such as damage to the parent rock and nuisance of noise and vibrations for local populations. Consequently, there are related environmental and legal issues to be overcome.

Although TBM excavation is sensitive to geological formations, it is considered the safest form of tunnelling. Tunnelling with a TBM is also a cost-effective alternative to the drill and blast method. The tunnel boring machine (TBM) has thus found its place as a major method of tunnelling, as is evident from Figure 4.
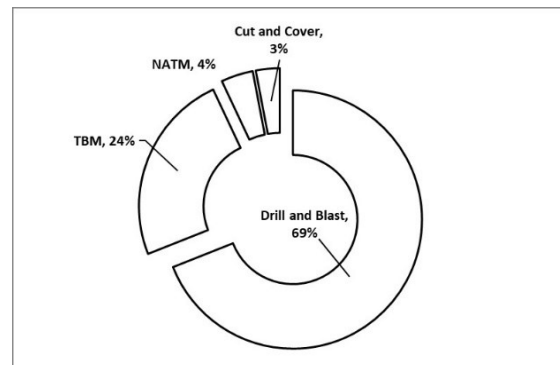

Figure 4 Percentage of different tunnelling techniques [drawn after 5]

TBMs can be used on both soft and hard rock types and can cut rock in varied geological conditions. These advantages make the TBM attractive and, at times, make it the first choice for tunnelling projects especially in urban environments. Advance rates, reliability, low strata disturbance, safety and low labour deployment and simultaneous support erection are some of the advantages of a TBM. Moreover, the TBM produces uniform fragment size and that is an advantage in the removal and transport of mucking. A comparison of the drill and blast method and tunnelling with TBMs is given in Table 1.

Despite being a mechanical method of excavation, the TBM is simple to operate. TBMs do not disturb the surrounding rock mass as they produce minimal vibrations. Since the surrounding rock mass is minimally disturbed during excavation, support requirements are low and safety is enhanced. This is a major advantage of TBMs as roof stability is very important in underground excavations and tunnelling. Moreover, the final excavation surface is quite smooth and energy to meet ventilation requirements reduces considerably [6]. In addition, the overbreak and support costs thereof are reduced.

An added advantage of the TBM is that it can drive exactly on a planned path of excavation by means of a guide system. TBMs may also be used for micro-tunnelling [7] with diameters of less than one meter as

well as in roadway and railway tunnelling with diameters of more than 15 m. They can also be used in trenchless construction. These are probably why the TBM is one of the most suitable options for tunnelling.

Table 1 Comparison of TBM with drilling and blasting methods for underground tunnelling

Sl. No.	Issues	TBM	Drilling and Blasting
1	Ground vibration	Low but continuous	High but transient
2	Noise	Low but continuous	High but transient
3	Accidents	Minimum	High
4	Tunnel profile	Even	Uneven
5	Ventilation requirement	Low	High
6	Rock mass damage	Minimal	Relatively high
7	Fragmentation	Uniform	Uneven
8	Tunnelling rate	Relatively high	Relatively low
9	Operations	Continuous	Cyclic
10	Constraints	Major issues if stuck	Fumes, accidents

TBMs are expensive. It is difficult to transport the machine to tunnelling sites. It tunnels in a unidirectional manner and it is prone to getting stuck in adverse geological conditions. These disadvantages sometimes result in escalating tunnelling costs. However, the cost of tunnelling with a TBM goes down as the length of the tunnel increases [8].

The types of TBMs developed so far include open face, gripper, slurry, earth pressure balance, single and double shield, mixed shield, and convertible shield types [9]. The selection of a TBM depends on the geology of the excavation. Consequently, TBMs are assembled in line with lithology and rock mass conditions. So, an understanding of rock mass and intact rock properties for the deployment of a TBM assume importance. A significant part of the published literature addresses such topics. This analysis in the basis of compilation and critical review of the existing literature. Such findings can help in holistic understanding of role of geology in TBM performance also lay a foundation for future research.

2. Intact rock properties and TBM performance

Intact rock contains neither joints nor cracks. The breakage in case of massive or intact rock is practically defined by its internal granular structure. Intact rock properties can be determined in the laboratory with relative ease and then used for multiple purposes including working out TBM penetration rates.

Uniaxial compressive strength (UCS) and *in situ* stress conditions also influence geomechanical and geotechnical parameters which control the rate of tunnelling [10]. The UCS is considered to be the most influencing variable in TBM penetration and cutter life is strongly affected by joint frequency. However, not only uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS), but also the spacing and orientation of fracture and the brittleness of rock can be more important than intact rock strength in determining TBM performance rate in hard rock conditions [11].

Abrasivity as modelled (abrasivity index) by [12] is an important parameter since it determines cutter wear. The strength of the rock, the abrasivity of the rock and the degree of jointing determine the cutter cost and penetration rate of a TBM [13; Equations 1 and 2].

$$C_c = \frac{d_T}{P_c} + \frac{\sigma_c \times C_l}{J_f} \tag{1}$$

$$R_p = \frac{P_c}{d_T^2 \times S_c \times \alpha_c} + \frac{J_f}{\sigma_c} \tag{2}$$

where, C_c is cutter cost per linear meter of tunnel, d_T is diameter of tunnel, P_c is cutter thrust, σ_c is compressive strength of intact rock, C_l is abrasivity index, J_f is intensity of jointing, α_c is cutter edge angle, and R_p is penetration rate.

The influence of intact rock properties on TBM performance has been modelled by different authors (Table 2).

Though different authors use one to six variables in various combinations (Table 2), a total of 12 intact rock properties have been applied to characterize TBM performance. It is also observed that uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), brittleness index (BI), abrasivity, drilling rate index (DRI), and cohesion of joint plane emerge as major contributing factors in TBM performance (Figure 5). Though empirical and multivariate analysis were the

major methods deployed for such an analysis, more recently, artificial intelligence methods like support vector machines have also been used to predict performance [43].

Table 2 Review of intact rock properties affecting TBM performance

Sl. No.	Author(s)	1	2	3	4	5	6	7	8	9	10	11	12	Total
		Reported intact rock properties influencing TBM performance												
1	Graham, 1976 [14]	√												1
2	Farmer and Glossop, 1980 [15]		√											1
3	Snowdown *et al.* 1983 [16]	√	√									√		3
4	Buchi 1984 [17]	√	√											2
5	Morimoto and Hori 1986 [18]												√	1
6	Hughes 1986 [19]	√												1
7	Rostami and Ozdemir 1993 [20]	√	√											2
8	Nilsen 1993 [21]			√	√									2
9	Rostami *et al.* 1996 [22]	√	√	√	√	√								5
10	Bruland 1998 [23]	√				√								2
11	Barton 1999 [24]						√			√				2
12	Boniface 2000 [25]	√				√					√	√		4
13	Barton 2000 [26]						√			√				2
14	Cigla 2001 [27]	√	√	√	√									4
15	Kahraman 2002 [28]		√					√						2
16	Sapigni 2002 [29]	√	√		√	√	√				√			6
17	Benerdos and Kaliampakos 2004 [30]	√												1
18	Bilgin *et al.* 2005 [31]	√	√											2
19	Yagiz 2006 [11]	√	√	√										3
20	Gong *et al.* 2006 [32]		√						√					2
21	Von Preinl *et al.* 2006 [33]	√			√									2
22	Yagiz *et al.* 2009 [34]	√	√	√										4
23	Hassanpour *et al.* 2010 [35]	√												1
24	Gong and Zhao 2009 [36]	√		√										2
25	Gholamnejed and Tayarani 2010 [37]	√												2
26	Hamidi *et al.* 2010 [38]	√												1
27	Benato and Oreste 2015 [39]	√												1
28	Salimi *et al.* 2016 [40]	√	√											2
29	Liu *et al.* 2017 [41]	√						√				√		3
30	Namli and Bilgin 2017 [42]	√							√					2
	Total	23	12	7	5	4	3	2	2	2	2	2	2	

1 = UCS (Uniaxial Compressive Strength); 2 = BTS (Brazilian Tensile Strength); 3 = BI (Brittleness Index/plasticity of rock); 4 = Abrasivity; 5 = DRI (Drilling Rate Index/drillability of rock); 6 = Dry UCS (Dry Uniaxial Compressive Strength); 7 = CJp (Cohesion of joint plane); 8 = Quartz content; 9 = IBST (Induced Biaxial Stress of Tunnel face); 10 = E (Young's Modulus); 11 = Density of rock; 12 = P-wave velocity
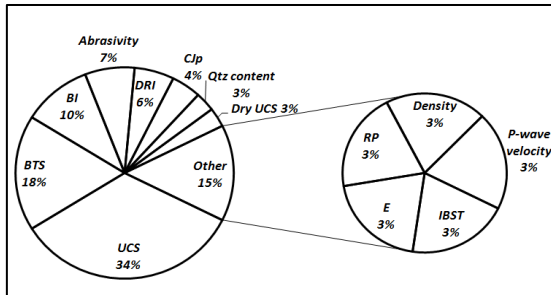
Figure 5 Importance of various intact rock properties in relation to TBM performance

3.   Geology, structures and TBM performance

Though TBMs can achieve an excavation rate of 1000 m/month, in adverse geological conditions, the rate of excavation may be less than 50 m/month [44, 45] or even a few meters in extreme rock mass conditions [24]. In special cases, such as in very hard rock formations, highly fractured and jointed rock mass, large groundwater inflow and high *in situ* stress conditions, using a TBM can lead to excavation stoppage.

If the rock mass bears a high frequency of fracture planes and/or tectonic disturbances, the inherent strength of the rock mass is reduced, thus decreasing wall rock stability. This type of situation reduces the progress of TBM tunnelling, as support systems have to be installed immediately for safe and stable tunnelling [46, 47]. Important publications dealing with the influence of rock mass on TBM performance were therefore compiled and analysed to identify variables impacting TBM progress (Table 3).

Table 3 Review of rock mass properties of TBM performance module

Sl. No.	Author(s)	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
		reported													
1	Buchi 1984 [17]	√													1
2	Bruland 1998 [23]	√			√					√					3
3	Barton 1999 [24]				√	√				√	√	√	√	√	7
4	Barton 2000 [26]				√	√				√	√	√	√	√	7
5	Cigla 2001 [27]	√	√			√									3
6	Benerdos and Kaliampakos 2004 [30]			√					√						2
7	Bilgin *et al.* 2005 [31]	√		√											2
8	Gong et al. 2006 [32]	√													1
9	Yagiz 2006 [11]	√	√												2
10	Von Preinl *et al.* 2006 [33]				√	√									2
11	Yagiz *et al.* 2009 [34]		√												1
12	Hassanpour *et al.* 2010 [35]	√	√	√											3
13	Gong and Zhao 2009 [36]		√		√										2
14	Hamidi *et al.,* 2010 [38]	√	√	√											3
15	Gholamnejed and Tayarani 2010 [37]			√											1
16	Benato and Oreste 2015 [39]						√	√							2
17	Salimi *et al.* 2016 [40]	√	√	√			√	√	√						6
18	Salimi *et al.* 2017 [48]		√	√			√	√	√						5
19	Liu *et al.* 2017 [41]		√			√	√	√	√						5
20	Namli and Bilgin 2017 [42]			√			√	√							3
	Total	9	9	8	5	5	5	5	4	3	2	2	2	2	

1 = Joint spacing; 2 = Alpha (Angle between plane of weakness and tunnel axis); 3 = RQD (Rock Quality Designation); 4 = Jn (No. of joint sets); 5 = Jw (Joint water condition); 6 = GSI (Geological Strength Index); 7 = Q-Index; 8 = RMR (Rock Mass Rating); 9 = Mohs' hardness; 10 = RQD0 (Conventional RQD interpreted in the tunnelling degree); 11 = Rock mass strength; 12 = Porosity; 13 = Jr (Roughness of the most unfavourable joint or discontinuity)

Various authors have applied one to seven variables in combinations to characterize TBM performance based on rock mass characteristics, thus identifying a total of 13 rock mass properties (Table 3). Joint spacing, angle between plane of weakness and tunnel axis, Rock Quality Designation (RQD), Rock mass strength (RMS), number of joint sets, joint water condition, Geological Strength Index (GSI), Q-index, and Rock Mass Rating (RMR) emerge as major factors that can be used to model TBM performance (Figure 6). The properties that have been used range from individual to groups (as classifications).
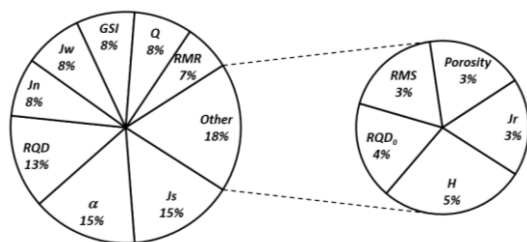

Figure 6 Importance of various rock mass properties in relation to TBM performance

It is also clear from Table 3 that initial attempts to correlate TBM performance were driven by independent rockmass variables. However, later attempts have focused on classifications like GSI, QTBM, and RMR to define TBM performance as these can accommodate several variables.

3.1. Influence of Joint Sets and Joint Spacing

Joint spacing appears to have a major influence on the normal force on TBM cutters. When schistosity, joints, fractures, folds, faults and shear-zones, and groundwater inflow do not manifest in rock mass, the rock may be intact or massive. If the rock mass is too fractured and jointed, it can reduce tunnelling rate and increase the risk of roof collapse. This would call for roof supports, such as ring beams, rock/roof bolts, shotcrete, steel straps, ring steel, wire mesh, and concrete segments [49]. When there is less joint spacing, the normal force for the jointed rock mass is much lower than that of the intact rock mass. In case of rock mass with 400 mm of joint spacing, the normal force dramatically decreases and the cutting surface appears 280 mm away from the joint plane [50].

The effect of joint spacing is minimal when joint spacing is around 500 mm and the effect is highly significant if joint spacing is around 10 mm. When joint spacing is less than 200 mm, chipping stress increases rapidly and, when it is >200 mm, chipping stress increases mildly [32]. With decrease in joint spacing, the TBM penetration rate increases distinctly [23]. If joint spacing is 20-100 mm and the angle of attack varies from 30° to 90° with tunnel axis, then less force is required for maximum penetration [51]. This way, the strata into which the tunnel is driven and the angle and orientation of the joint of the strata play an important role in defining the excavation rate of TBMs.

RQD also finds a place in most used factor, probably because it has a relationship with joint spacing, [52] established correlation between field penetration index (FPI), rock mass cuttability index (RMCI), and RQD (Eq. 1 and 2).

$$FPI=10.52e^{0.011RMCI} \qquad (3)$$

$$RMCI= \frac{\sigma_c}{100}RQD^{\frac{2}{3}} \qquad (4)$$

where *FPI* is field penetration index, *RMCI* is rock mass cuttability index, and *RQD* is rock quality designation.

Table 4 Review of some geological conditions that impact TBM efficiency

Author	Geological condition	Effect on TBM efficiency
Yin *et al.* 2016 [50]	Joint spacing and fracture	Cutting rate increases with less joint spacing and vice-versa
Paltrinieri 2016 [54]	Fault and shear zone, high *in situ* stress and groundwater inflow	Each reduces TBM performance independently
Rostami 1996 [22]	Brittleness of rock	Low – Increases TBM penetration High – Decreases TBM penetration
Howarth1981 [51]	Alpha (Angle between plane of weakness and tunnel axis*)*	When angle of attack varies from 30° to 90°, less force is required for maximum penetration depth
Bilgin *et al.* 2005 [31]	Uniaxial Compressive Strength, Brazilian Tensile Strength	Low – increases TBM cutting rate High – decreases TBM cutting rate
Stack 1995 [49]	If rock mass is too jointed, fractured, folded, faulted and squished	Reduce the advance rate as roof support is required

The influence of various geological variables impacting TBM performance, as reported by different authors, is summarized in Table 4. It is obvious that in soft rocks the penetration rates can be quite high but the support erection consumes significant time, thus hampering the advance rate. However, in the case of very hard rocks, the penetration rates are quite low, whereas the time and effort required to erect support structures are quite low [53].

4. Influence of in-situ stress and fault zones

Some major problems occur during tunnelling at fault-zones such as high ground pressure and subsequent loads on TBMs. *In situ* stresses such as degree of fracturing, weathering, influence of water, and depth of tunnel affect TBM performance during tunnelling in fault zone conditions (Table 5). Due to high

and sudden inflows of groundwater, jamming of TBMs has been reported [55]. Tunnelling under fault-zone, heterogeneous structural disturbance and underground water inflow conditions are always dangerous and can lead to accidents and collapses [54]. Such conditions and extreme water inflows have even resulted in the abandoning of the TBM [56]. Between relatively weak and hard rock in a fault zone, the possibility of breaking more of the tunnel wall boundary increases when stress is homogeneous over the zone. In areas of fault-zones and where rock overburden is low, the use of ribs of reinforced shotcrete has normally been sufficient [57]. High vertical stresses due to large overburden can lead to major displacements during the course of tunnelling and may demand stiff supports. Such instances result in cost overrun and extended time for the completion of such projects.

Table 5 Various mining conditions involved in tunnel construction and their influence on progress

Sl. No.	Condition	Sub-condition	Impact on tunnel progress	References
1	Rock mass condition	Hard rock massive Hard rock fractured	High - disadvantage Less - advantage	Bruland (1998) [23]
		Soft rock with high/ Less fractures	High - disadvantage Less - advantage	Barton (1999) [24]
2	Ground water condition	High water pressure Less/no water pressure	Disadvantage Advantage	Paltrinieri *et al.* (2016) [54] Paltrinieri *et al.* (2016) [54]
3	Depth, shape, diameter and appropriate risk management of tunnel	*In situ* stress condition Roof stability problem	High - disadvantage Less - advantage Disadvantage	Swannell *et al.* (2016) [10] Hoek *et al.* (1998) [58]

In addition, while developing a prediction model for the performance of the machine, [59] classified and determined clogging, swelling, abrasion, unstable tunnel face, and probable water flow as factors that impact the performance of a hard rock TBM deployed in soft rock conditions. Mostafaei et al. [60] determined the impact of variables such as moisture, lithology, grain size and foam of drilling on TBM performance. They highlighted the variations in TBM behaviour in different types of rock.

4.1. Classification of fault-zones

Paltrinieri et al. [54] dwelled on the degree of fracturing and weathering of the rock mass to define a fault-zone. They considered water inflows and depth of faulted or fractured zones as additional factors while developing a classification for such zones (Figure 7) and

they concluded that these factors contribute to the reduction of TBM performance.
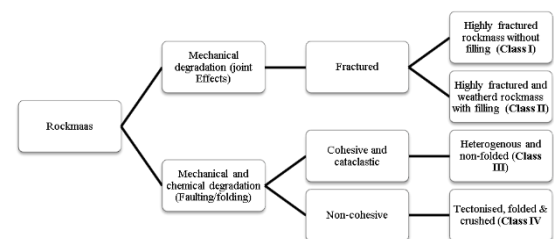

Figure 7 Fault-zone rock mass classification for underground tunnelling [54]

Mechanically degraded rocks with fractured nature were thus designated as Class I and II. Class III and IV fault-zones consist of low-strength rocks with high deformability index, as well as foliated/ overlaid/ sheared

rock masses of non-blocky structures and a predominant set of discontinuities and slickenside surfaces. In such classes, deformation is controlled by shear strength and displacement along foliation planes [58].

5. Rock mass classifications and modelling of penetration rate for TBM

Rock mass classification is made to systematize on-site rock mass assessment and to categorize, on a common basis, analytical studies, measurements and field observations. The major objective of classification is to divide a particular rock mass formation into groups and to assess the parameters that influence rock mass behaviour during excavation. To model TBM progress, many authors have developed empirical relationships with different rock variables. A compilation of such relationships is summarised in Table 6.

Table 6 Penetration rate of TBM as correlated with rock properties or classifications by various authors

Sl. No.	Citations	Equation
1	Cassinelli *et al.* 1982 [61]	$PR = -0.0059 \times RSR + 1.59$
2	Nelson *et al.* 1983 [62]	$PR = 10.45 - 1.19 \times H_A$
3	Boyd 1986 [63]	$PR = \dfrac{HP \times \eta}{SE \times A}$
4	Innaurato *et al.* 1991 [64]	$PR = \sigma_c^{-0.437} - 0.047 RSR + 3.15$
5	Ramezanzadeh *et al.* 2008 [65]	$PR = \dfrac{CSM\ ROP^{0.453}}{Exp(0.001 \times JS - 0.002 \times PTI - 0.687)}$ $PR = \dfrac{CSM\ ROP^{0.407}}{Exp(0.001 \times JS - 0.002 \times \propto - 0.002 \times PTI - 0.632)}; \alpha < 45$
6	Rostami *et al.* 1996 [22]	$PR = R \times (1 - cos\phi)$
7	Barton 2000 [26]	$PR = 5 \times Q_{TBM}^{-0.2}$ $Q_{TBM} = \dfrac{RQD_o}{J_n} \times \dfrac{J_r}{J_a} \times \dfrac{J_w}{SRF} \dfrac{20^9 \times SIGMA}{F^{10}} \dfrac{20}{CLI} \dfrac{q}{20} \dfrac{\sigma_0}{5}$
8	Bruland 1998 [23]	$I_0 = \left(\dfrac{M_{ekv}}{M_1}\right)^b$
9	Ribacchi and Lembo-Fazio 2005 [66]	$SP = 250 \times \sigma_{cm}^{-0.66}, \sigma_{cm} = \sigma_c \times e^{\left(\frac{RMR-100}{18}\right)}$
10	Mahdevari *et al.* 2014 [67]	$ARA = 0.56 \times (RME - 26)$ (*For RME > 75*) $ARA = 0.213 \times RME$ (*For RMR < 75*)
11	Bieniawski and Grandori 2007 [68]	$ARA = -0.422 \times RME_{07} - 11061$
12	Hassanpour *et al.* 2010 [35]	$FPI = 0.222 \times RMR + 2.755$ $FPI = 9.273 e^{0.008 GSI}$ $FPI = 11.718 Q^{0.098}$
13	Salimi *et al.* 2017 [48]	$PR = \dfrac{L_b}{t_b}, P = \dfrac{ROP \times 1000}{RPM \times 60}, FPI = \dfrac{F_n}{P}$

Where PR = penetration rate; σ_c = uniaxial compressive strength of rock; σ_{cm} = uniaxial compressive strength of rock mass; ARA = average rate of advance; FPI = field penetration index; J_n, J_r, J_a, J_w and SRF are original parameters of Q-system; RQD_0 is orientated-RQD in tunnelling direction; SIGMA = rock mass strength; F = average cutter load; CLI = cutter life index; q = quartz content; σ_0 = average biaxial stress on tunnel face; Adj ROP = adjusted rate of penetration; CSMROP = calculated rate of penetration; JS = Joint spacing; α = angle between tunnel axis and plane of weakness; ROP = rate of penetration; L_b = boring length; t_b = boring time; P = penetration per cutterhead revolution; RPM = cutterhead rotational speed; F_n = cutter load; p = penetration rate; H_A = Taber abrasion hardness; Φ = angle of shearing resistance; HP = installed cutterhead power; η = mechanical efficiency factor; SE = specific energy; A = tunnel; RSR = rock structure rating; R = cutter radius; GSI= geological strength index; RMR= rock mass rating; I_o= penetration per cutterhead revolution; M_{ekv}=equivalent thrust; M_1=critical thrust; RME= Rock mass excavatability; PTI=punch test index

An examination of Tables 2 and 3 reveals that several properties have been used to model the penetration rate of TBMs (Table 6). While some researchers focus on rock mass characteristics, others have employed combinations of rock mass and intact properties. However, the degree and orientation of jointing, as well as the compressive strength and abrasivity of the intact rock have been used invariably to

define penetration rates.

Two classification systems viz. Bieniawski's RMR and Barton's Q have found a special place in such relationships and deserve mention. The penetration rate of TBMs was found to correlate well with modified RMR [66], but joint spacing also had a major influence. [26] Expanded his Q system to QTBM that is a function of 20 variables and includes average cutter force, abrasive nature of the rock and stress levels in addition to normal Q. QTBM uses a relationship between penetration rate (PR) and QTBM to estimate TBM performance. If QTBM is greater than 1, it represents bad rock mass condition and, due to this, would usually decrease the value of PR and, the lower the QTBM the higher the PR.

6.   Selection of TBM on the basis of different geological conditions

TBM selection methodology is a formal process to gather information to make an informed decision to match a particular rock mass condition and lithology with an appropriate TBM. Modern TBMs [5] mainly consist of a rotating cutting wheel, i.e. a cutter head, a thrust system, and support mechanisms. However, as seen earlier, the type of machine that can be used for tunnelling is primarily dictated by the inherent properties of the geology including groundwater and other complex conditions as well as by the geomechanical properties of the rock. Hence, the selection of a TBM is a complex process. However, an attempt has been made here (Table 7) to present an overview of TBM deployment along with possible cutter types.

Despite the guidelines, a large tunnel project should start with a comprehensive investigation of geology and geological conditions. The project calls for a complete information database of the geology along the tunnel alignment, including minor details of sections and 3D models. It is important to have prior knowledge of the available TBMs and their specifications and features, to select the best TBM configuration for deployment.

Table 7 Use of TBMs and type of cutters in different type of ground conditions [after 69]

Ground condition	Rock type	Lithology	Types of TBM used	Types of cutters used
Hard ground condition	Igneous and metamorphic rock	Granite, gabbro, syenite andesite, charnokite, gneiss, peridotite, slate	Shield (single/double) or open type TBM	Disc cutter
Soft ground condition	Sedimentary rock	Clay, silt, sand and gravels	Earth pressure balance (EPB), slurry shield (SS) and open face type TBMs	Carbide disc cutter and hard rock disc cutter
Soft ground with ground water pressure condition	Sedimentary and metamorphic condition	Sandstone, shale	Slurry shield (SS)TBM	Pressurized slurry cutter
Urban and near (shallow) surface tunnelling conditions	Mixed condition	Clay, gravel, hard rock	Earth pressure balance (EPB) and Slurry shield (SS) TBMs	Carbide disc cutter and hard rock disc cutter

While defining the type of wear, it has been observed [70] that the choice of ideal tools can be made with an understanding of the interaction between rock and cutters. Once deployed, the analysis of the performance continues and enormous data gets generated during the process. This leads to issues like big data handling and can be taken care of by methods like balanced iterative reducing and clustering using hierarchies [71].

Although significant research has been conducted on defining rock mass and intact properties that define the progress of a TBM, dynamic properties have scantly used to model the same. Such a study is necessitated by the fact that breakage is a dynamic process. Moreover, modern day geophysics allows us to determine the dynamic properties of in-situ rock and hence can present a viable alternative to eliminate human bias in empirical and laboratory studies of intact rocks.

7.   Conclusion

The geology of an area plays a vital role in determining the performance of a tunnel boring

machine. A comprehensive review of published literature indicated that the factors that influence the performance of a TBM can be categorised into nature of rock mass, intact rock properties, and special conditions such as the presence of faults, shear zone, or water content in the formation. Various models have been developed by different authors that have been summarised to predict TBM performance in the field. These models include rock mass or intact rock properties viz. joint spacing, angle between plane of weakness and tunnel axis, Rock Quality Designation, Rock Mass Rating, Geological Strength Index, Q-Index, Uniaxial Compressive Strength, Brazilian Tensile Strength, Brittleness Index/ plasticity of rock, abrasivity, and drillability of rock. Machine variables such as machine power, torque, RPM, cutter geometry, cutter spacing, tip width, and cutter type are dictated by rock type and lithology along with other laboratory properties of the rock. There are 13 rock mass properties and 12 intact rock properties or rock classification systems that have been applied to characterize TBM performance. Joint spacing, joint angle and RQD and UCS, BTS, and brittleness index emerge as major contributing factors in TBM performance. While intact rock properties affect cutting rate and define disc-cutter configurations, geological variables influence the overall productivity of the TBM. Tectonically disturbed formations are associated with overbreak and roof instability and reduce TBM cutting rate.

Systematic appraisal of the geology and geological conditions along the alignment of the proposed tunnel is indispensable. Every detail of the rock mass, geotechnical and intact rock properties determined in the laboratory can be useful at any stage of the project and should be acquired well before the onset of the excavation.

There is a significant gap in literature in terms of determining the dynamic properties of rock masses during tunnelling. Once the performance of the TBM is correlated with the dynamic properties, the relevant properties can be easily identified using geophysical surveys. This will avoid bias introduced due to empirical and lab-based assessment of rock properties.

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UTICAJ GEOLOGIJE NA UČINAK MAŠINE ZA PROBIJANJE TUNELA – PREGLED

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Izvod

Mašine za probijanje tunela se koriste za iskopavanje raznih vrsta tla i stena za tunele sa kružnim presekom. Nekoliko objavljenih studija se bavilo ispitivanjem uloge stenske mase u određivanju brzine iskopavanja i napredovanja mašine za probijanje tunela. Izvršen je sveobuhvatni pregled literature kako bi se odredio uticaj geoloških uslova na učinak mašine za probijanje tunela prilikom kojeg je utvrđeno da se različite karakteristike stena koriste za utvrđivanje učinka ove mašine. Napredak mašine za probijanje tunela je povezan sa inherentnim osobinama stenske mase, nepromenljivim osobinama stena, kao i sa okolnim geološkim uslovima. Nekoliko autora je utvrdilo da ekstremni geološki uslovi imaju veliki uticaj na napredak mašine. Pregledom literature je takođe utvrđeno da raspored pukotina, ugao između slabe ravni i ose tunela, kvalitet stene i broj pukotina predstavljaju najvažnije parametre koji utiču na brzinu napredovanja mašine za probijanje tunela. Najmanje 12 varijabli nedirnutih stena je korišćeno za određivanje učinka mašine za probijanje tunela, gde je kombinovano od jedne do sedam ovih varijabli. Utvrđeno je da čvrstoća na pritisak, čvrstoća na istezanje i indeks krtosti predstavljaju najvažnije osobine za ispitivanje. Različiti autori su koristili klasifikaciju stenske mase ili indeks učinka mašine za probijanje tunela za predviđanje učinka mašine, a isto tako i za definisanje metodologije odabira. Upotreba dinamičkih osobina stene/stenske mase je identifikovana kao siva zona za buduća istraživanja.

Ključne reči: *Učinak mašine za probijanje tunela; Osobine stenske mase; Nepromenljive osobine stena; Posebni uslovi; Pregled.*