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Tunnelling Using Hard Rock Tunnel Boring Machines – Some Design and Performance Aspects

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Abstract

Hard rock TBMs (Tunnel Boring Machines) are being increasingly used in hydro-power projects to excavate small to large diameter water conveyance tunnels in different countries. These projects are favoured due to their eco-friendly nature. In India, a good number of water tunnels are being planned to be excavated by TBMs in different projects, namely, Loharinag Pala, Tapovan-Vishnugad of NTPC Limited and Kishanganga of NHPC Limited apart from the existing projects namely, Parbati Stage II (NHPC), Srisailam (APGENCO) where the head race tunnels are being driven by imported TBMs. These projects have created a high demand for rapid tunneling which can only be met by hard rock TBMs as other conventional and semi-mechanized tunneling techniques are plagued by low development rates. Thus, there is a need to develop a system/method to select accurately the correct TBM configuration according to the geological conditions existing en-route the tunnel to achieve the desired rate of penetration.

Determination of design parameters and performance prediction of a tunnel boring machine are carried out by various rock cutting tests. Cutter forces i.e. thrust force, rolling force and specific energy values are estimated for each rock type to be encountered in tunneling using laboratory studies and test data. The results of the tests are first used to calculate TBM design specification and performance. Further, the performance of the TBM recorded in the field is compared with that of predicted based on laboratory tests. It is believed that the results will serve as a guide for efficient and economical selection and use of TBMs. There are two widely used methods to predict TBM performance, namely, the NTH (of NTNU) model and CSM (Colorado School of Mines) Model. The former is based on the achieved performance of the machine in the field as a whole system while later is based on the cutting forces acting on the individual cutters. A successful system must incorporate intact rock/ rock mass properties to predict TBM specification and also once the system is formulated it must be tested/calibrated with field data to ensure its accuracy and usefulness.

This paper discusses the applicability of these two models in the performance prediction of hard rock TBM in Indian conditions i.e., for Parbati hydroelectric project, Stage II works, located in Himachal Pradesh (India) where TBM tunneling is in progress. This paper presents, initially, the laboratory studies done (Brittleness test, Siever's J value test, Cerchar Abrasivity Index) concerning boreability prediction of tunnel boring machines (TBMs) for the rock type, namely, quartzite. Subsequently, a comparison of the lab based performance prediction with the actual field performance has been made. It was found that the NTH model fits in well while the CSM model can be used for its validation. There is a need to develop a database relating the different rock tests data and TBM performance data so that a suitable performance prediction model can be developed covering various rock suits for Indian conditions.

Introduction

Tunnel Boring Machines, popularly known as TBM's, are currently being utilized in underground construction and tunneling both in civil and mining industries the world over. Since, the first successful use of tunnel boring machine in hard rock as early as 1950s, they have been continuously transformed by improving their installed cutter head power, size of machines, cutter

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loading capacity, and designs for application in various ground conditions, even in some adverse grounds. During the past three decades, numerous TBM performance prediction models have been introduced based on theoretical, empirical, and semi-empirical investigations. The TBM performance prediction involves understanding the rock fragmentation process in a wide range from micro-scale (i.e. the interaction of surface contact of rock material and cutter tip) to macro-scale (including the interaction of rock mass and TBM). In spite of many advances, there seems to be a lack of complete understanding of the rock cutting process due to the very complex nature of the problem. This was described by Robbins (1980) as "nothing has been more difficult than evaluating the rock mass characteristics and applying the evaluation to a formula predicting penetration rate". Penetration rate, however, is a result of interaction between rock mass properties and TBM operational parameters (Zhao, 2007). A large number of parameters affecting the rock cuttability and hence machine performance in the field are identified. This has generated a need for accurate identification of different common parameters among the various models to suit specific rock conditions.

TBM Performance Prediction Models

The demonstrated capabilities of Tunnel Boring Machine in attaining higher rates of advance have forced the planners to go for such proven options wherever time and cost overruns need to be minimized. TBM performance prediction is based on rock failure mechanism and involves development of theoretical models to analyze cutting force acting on the disc (Crow, 1975; Roxborough et al., 1975; Ozdemir et al., 1978; Snowdon et al., 1982; Sato et al., 1991; Rostami and Ozdemir, 1993; Rostami, 1997)

These models are primarily developed by using indentation tests or full-scale laboratory cutting tests providing an estimate of cutting forces based on cutter, cutting geometry, spacing and penetration of the cut. The empirical models are developed using various rock/ rock mass parameters, namely, uniaxial compressive strength, tensile strength, joint condition , drilling rate index (DRI), cerchar abrasivity index, bit wear index, cutter life index, Q_{TBM}, RMR, RMi, Siever's J value along with machine parameters (Tarkoy, 1973; Graham, P.C. 1976; Farmer and Glossop, 1980; Blindheim, 1979; Bruland, 1998; Barton, 1999; Palmström, 1995; Innaurato et al., 1991; Nelson, 1993; Yagiz, 2008).

There are various prediction models available but the Colorado School of Mines Model (CSM model), the NTH Model and the Q_{TBM} system are the most commonly used performance prediction models. A brief description of these models is given below.

The Colorado School of Mines Model (Sato et al., 1991)

The basic idea behind this method is to begin from the individual cutter forces, and then determine the overall thrust, torque and power requirement of the entire cutter head. The values estimated are compared to the actual field data. The full scale test is most reliable as the miniature cutting tests can be short of representing/ simulating field variables accurately. The parameters used in this model are as follows:

Cutter radius	Tip width	Spacing	Penetration
Rock UCS	Tensile strength	TBM diameter	TBM RPM
Number of Cutters	Thrust	Torque	Power

The NTH Model

Bruland et al. (1998) presented an updated version of the model presented by Lislerud (1988), which was developed by the same Norwegian research group. The Empirical Prediction Models are based on the database acquired during a long period of time and it has a set of graphs correlating various input parameters with output parameters. These models rely on past data, therefore, with speedy growth of tunneling technology and capability, the predicting ability of these models is limited. The NTH model employs a group of rock parameters and indices, which were originally developed for estimating the Drillability of hard Scandinavian Rocks. The various parameters used by NTH model are as follows:

Fracturing/ Jointing condition	Drilling Rate Index	Siever's J value	Brittleness Index, S_{20}
Cutter thrust	Porosity	Cutter spacing	Cutter diameter
Machine's diameter	Abrasiveness		

The Rock Mass Index –NTH (RMi-NTH) Model

The RMi-NTH model (Palmström, 1995) employs a group of rock parameters and indices, which were originally developed for estimating Rock-Mass Index (RMi). The various parameters used by NTH model are as follows:

Jointing condition	Type of Rock	Block Volume	Abrasiveness
Rock strength	Cutter Diameter	Cutter Load	Spacing
Machine's diameter	Orientation of Main Joint Set		

The Q_{TBM} System (Barton, 1999)

The Q-system came into existence in 1974 from the database of drill and basted tunnels case histories, but was not sufficient for tunneling purposes. The new Q_{TBM} system is strongly based on the old Q-system, but it also has additional rock-machine-rock mass interaction parameters. This system has evolved into one of the most successful and practiced system. The parameters used in Q_{TBM} system are as follows:

RQD (Rock Quality Designation)	J_N (Joint Number), J_R (Joint Roughness), Ja and J_W	SRF (Support Requirement)
Average Cutter Load	Rock Mass Strength	

Performance Prediction for Parbati Stage II TBM Project

The Parbati Hydroelectric Project (Stage-II) is a run-of-the-river scheme proposed to harness hydro potential of the lower reaches of the river Parbati (Fig.1). The proposed scheme is 'inter basin transfer' type. The river is proposed to be diverted at Village Pulga in Parbati valley and the Power House shall be located at village Suind in Sainj valley. Thus

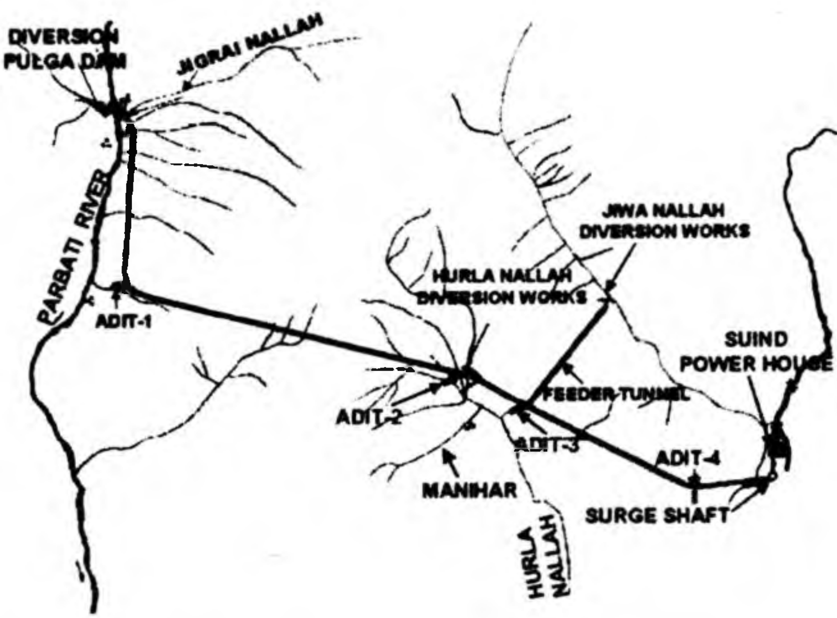


Fig. 1: Layout of the Parbati Stage II hydel project (Madaan and Kumar, 2004)

a gross head of 862 m between Pulga and Suind will be utilized for generating 800 MW power. The HRT of the project is being driven by TBM for faster and safe completion of the tunnel. The head race tunnel is of 6 m dia and 31.52 km long. The salient details of the TBM in use are given in Table 1 (Madaan and Kumar, 2004)

Table 1: Tunnel boring machine parameters, Parbati Stage II Project, NHPC Ltd.[21]

MACHINE PARAMETERS	VALUE
Model	Robbins TBM MK-27
Machine Diameter	6.8 m
No. of Discs	49
Disc Cutter Spacing	65 mm
Cutter diameter	432 mm
Cutter Head Capacity	3150 kW
Average RPM	5.77
Applied Thrust per Disc	267 kN

The authors have decided to use the NTH model (Bruland et al., 1995) scheme to predict the performance. According to NTH model the penetration rate can be estimated by combining the rock material's drilling properties with the jointing of the rock mass and the representative machine factors. The parameters used are given in Table 2.

The values of Drilling Rate Index (DRI) were determined using a nomogram as shown in Fig. 2. The DRI values determined are presented in Table 4.

Table 4: Determination of drilling rate index(DRI)

Rock Type	Mean Brittleness index (S_{20})	Mean Siever's J Value (S_j)	Drilling Rate Index (DRI)
Quartzite	70	7.1	72

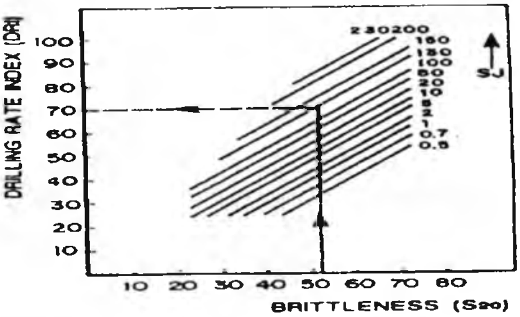


Fig. 2: Nomogram for estimation of DRI

Different facilities available at ISM, Dhanbad for rock characterization to facilitate TBM selection are shown in Fig.3. The same have been used for generating the needed data for Parbati Stage II Project.

Table 2: Rock mass and machine parameters used in the study

ROCK MASS PARAMETERS	MACHINE PARAMETERS
- Fracturing, Joints, etc	- Cutter thrust
- Drilling rate index (DRI)	- Cutterhead RPM
- Abrasivity(CAI)	- Cutter Spacing
- Porosity	- Cutter Diameter
- Brittleness Index (S_{20})	
- Siever's –J Value	

Tests on the cored samples were performed in the laboratory as per the standard ISRM test procedures. The rock/ rock mass properties determined are presented in Table 3.

3.1 Estimation of Penetration Rate

According to the NTH Model, the instantaneous penetration rate is given by the following relation, and the unit is mm per revolution.

Table 3: NTH model parameters for Parbati Stage II Project, NHPC Limited (Murthy et al., 2002)

PROPERTIES OF ROCK	VALUE
Siever's –J Value	7.1
S_{20} Value (Brittleness Index)	70
Uniaxial compressive strength(UCS)	136 MPa
Cerchar Abrasivity Index (CAI)	4.12
Joint Class	Class 0-I
Porosity	2.0%
Angle of joints with tunnel axis	20^0

$$I_o = (M_{EQ}/M_1)^b \qquad (1)$$

where M_{EQ} represents the TBM properties and 'M_1' and 'b' depends on the rock mass properties. The rock mass properties are in turn represented by the factor 'K_{EQ}'. The value of 'M_{EQ}' and 'K_{EQ}' can be determined by the relations (2 & 3) given below:

$$M_{EQ} = M_B \times K_D \times K_A = 267*1.15*1.03 = 316 \text{ kN} \qquad (2)$$

$$K_{EQ} = K_S \times K_{DRI} \times K_{POR} = 0.67*1.2*1.01 = 0.812 \qquad (3)$$

Where:

M_B is applied thrust per disc (in kN),

K_D *is the correction factor for cutter diameter (*refer Fig.4*)*

K_A *is the correction factor for cutter spacing (*refer Fig.5*)*

K_{DRI} *is the correction factor for DRI (*refer Fig.6*)*

K_{POR} *is the correction factor for Porosity (*refer Fig.7*)*

K_S *is the correction factor for jointing/ fractures (*refer Fig.8*)*

These correction factors are given by following figures:

The values of all the parameters are used to determine the rock mass factor K_{EQ} using relation (3). Once the rock mass parameter 'K_{EQ}' is known, values of 'M_1' and 'b' can be calculated from Fig. 9 and Fig. 10 respectively, as given below:

Cerchar Abrasivity index

Uniaxial compressive strength

Brittleness index apparatus

Siever's J value apparatus

Fig. 3: Rock characterization facilities at ISM, Dhanbad for TBM selection (Murthy et al., 2002)

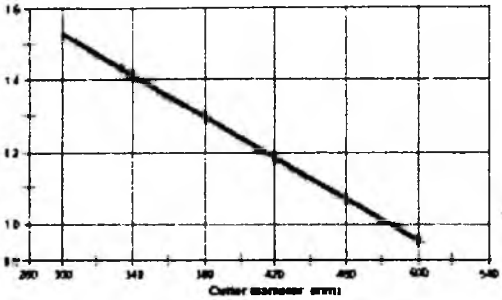


Fig.4: Correction factor KD for cutter size

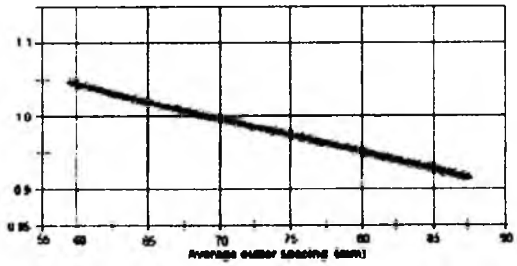


Fig. 5: Correction factor KA for cutter spacing

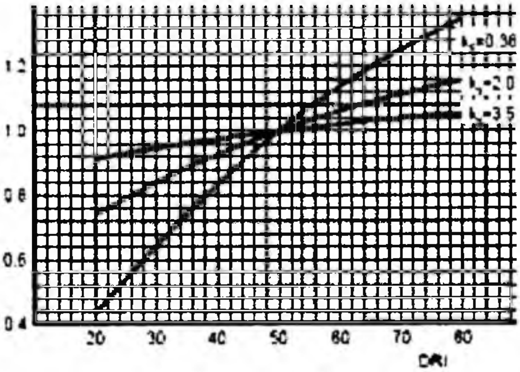


Fig. 6: Correcticon factor, KDRI

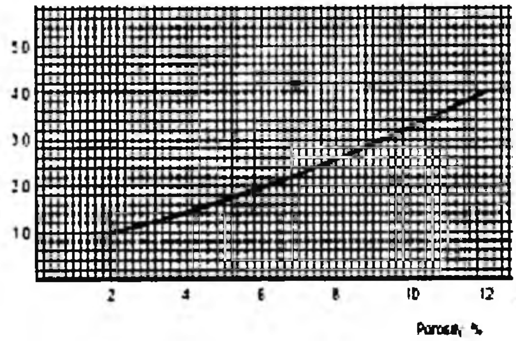
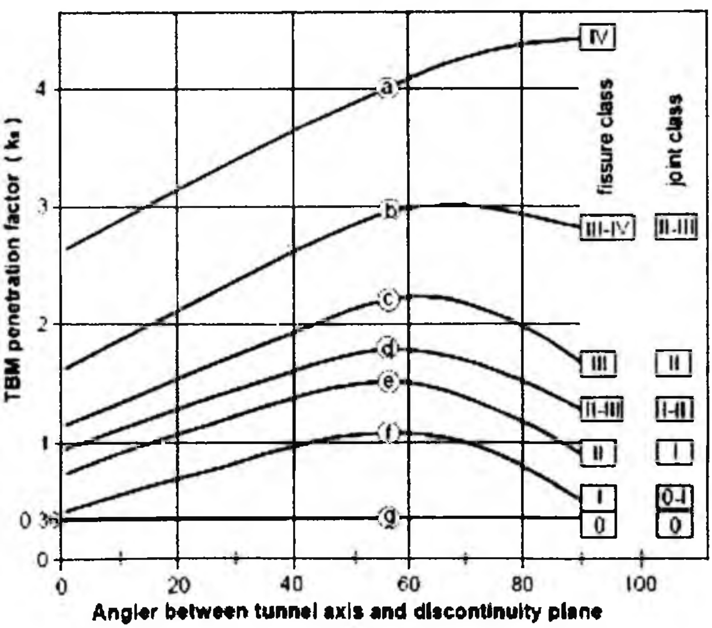


Fig.7: Rating of the factor KPOR



NTH class	Joint/fissure spacings
0	-
0-I	1.6 m
I-	0.8 m
I	0.4 m
I-II	0.3 m
II	0.2 m
II-III	0.15 m
III	0.1 m
IV	0.05 m

Fig. 8: Rating of the jointing factor KS

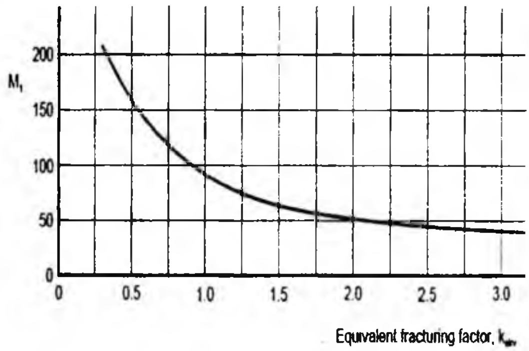


Fig. 9: Parameters 'M1' Vs. 'KEQ'

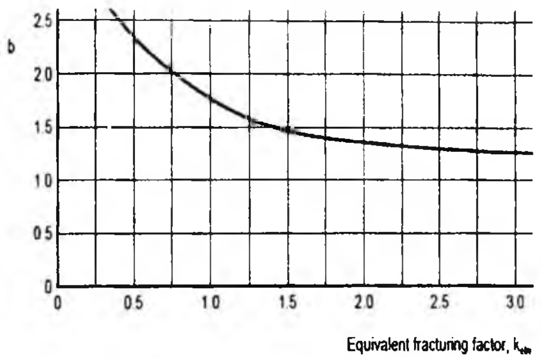


Fig. 10: Parameters 'b' Vs. 'KEQ'

The penetration rate is calculated using the relation (1) as follows:

$I_o = (M_{EQ}/M_1)^{b} = (316/115)^{1.9} = 6.82$ mm/rev

The net advance rate (m/h) is found from relation (4):

$I = (I_O) \times (RPM) \times 60/1000 = 6.82*5.77*60/1000 = 2.36$ m/h (4)

Daily Advance $(D_A) = (I) \times (W) \times (U) = 2.36*14*0.4 = 13.2$ (5)

Where

I_O is the instantaneous penetration rate (mm/rev).

RPM is rotation per minute.

W is working hours available per day

U is the utilization factor (%)

D_A is advance per day (m/day)

Table 5: Performance prediction in quartizite, Parbati Stage II Hydel Project, NHPC Limited

PARAMETERS	CALCULATED VALUE
M_{EQ}	316 kN
K_{DRI}	1.2
K_S	0.67
K_{POR}	1.01
K_{EQ}	0.812
i_O	6.82 mm/rev
I	2.36 m/hour
Utilization Factor	40%
Working Hours/day	14 hr
Advance per day	13.2 m

Results of Performance Prediction

Based on the above relations and calculation, the typical performance parameters for the Parbati TBM Project are presented in Table 5. It may be observed that the predicted advance (13.2 m/day) using NTH model closely matches with that of the actual advance achieved (10 m/day).

Conclusion

Considering the increased application of TBMs for meeting the tunnelling needs in underground construction sector in India, an attempt has been made to predict the performance of Tunnel Boring Machine using the popular NTH model for Parbati Stage II hydel project for its HRT drivage through quartzite formation. Required laboratory data was generated at Indian School of Mines, Dhanbad. The actual average advance rate achieved in quartzite rock suit at Parbati Project is 10 m/day (Madaan and Kumar, 2004). This value is in good agreement with the predicted value of 13.2 m/day. The rock conditions were favorable for tunneling with high value of Drilling Rate Index (DRI) as 72. However, the relations used above are developed for European conditions and there is a need for further improvement considering varied rock suits and recorded TBM performance as they become available in due course of time for accurate and reliable TBM performance assessment in Indian conditions. When developing or using performance prediction systems and other tools to evaluate the penetration rate, it is of crucial importance to keep in mind the innumerable variations that occur in rock masses and the uncertainties involved in observing and recording the different parameters.

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