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Factors influencing performance of hard rock tunnel boring machines

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ABSTRACT: Intact rock properties together with rock mass characteristics should be well investigated for selection of proper tunnel boring machine (TBM) for tunneling in various ground conditions. This is due to the significant impact of rock mass characteristics on machine performance. TBMs are site specific and designed for optimal performance in given ground conditions. When selected and put to work at a specific site, TBM parameters including thrust and power are the controlling factors for excavation rate. These two parameters along with rock properties and rock mass characteristics converge to define the operating point of a machine. To investigate the factors influence on TBM performance in rock mass, a database including two tunnel projects, the Queens Water Tunnel in the City of New York, USA and the Second Manapouri Tailrace Tunnel in New Zealand, have been compiled and studied. The relationship between the penetration rate, rock mass properties, and thrust and power consumption of the machine was examined. The obtained relationships together with the Colorado School of Mines TBM performance prediction model are discussed herein.

1 INTRODUCTION

Prediction of TBM performance depends on machine specifications and both rock properties and rock mass characterizations encountered at the site. Accurate TBM performance estimation is necessary in estimation of construction schedule and cost for any mechanical tunneling. Performance prediction refers to the estimation of the rate of penetration (ROP) that is the excavated distance when machine is actively mining or boring the face, and advanced rate (AR) which is the distance mined on a daily basis while including machine maintenance and other support activities (Yagiz, 2008). Many models and equations have been introduced where machine and rock properties are used to the estimation of TBM performance in terms of ROP and AR (Ozdemir, 1977; Nelson and O'Rourke 1983; Snowdon et al., 1983, Lislerud, 1988; Rostami and Ozdemir, 1993; Rostami 97; Bruland, 1999; Barton, 2000; Yagiz, 2002, 2006a, 2006b; Yagiz et al., 2009). Further, numerous researches have conducted investigation on quantifying the rock mass properties that affects on machine performance (Bruland, 1999; Yagiz and Ozdemir, 2001; Cigla et al., 2001; Merguerian and Ozdemir, 2003; Merguerian, 2001, 2008a, 2008b; Yagiz, 2008, 2009).

In this paper, TBM performance parameters, including machine specifications, rock properties and encountered ground conditions, have been investigated by using a database of TBM field performance. This database was established using information from two tunnel projects, the Queens Water tunnel in New York City, USA and the Second Tailrace Tunnel of the Manapouri Hydro-Power Station in New Zealand. The data includes machine performance, detailed information on machine thrust and power consumption, and geological information from tunnel back mapping and laboratory physical property testing on rock samples. Analysis of available data has been the basis for development of new performance prediction models of related adjustment factors.

2 TUNNEL PROJECTS

The Queens Water Tunnel # 3 was constructed to improve distribution of fresh water throughout the City of New York, especially in borough of Queens. The excess capacity offered by the new tunnel allows for the maintenance of two existing tunnels that have been operating since 1917 and 1936 and will be an important connecting link for operation of the New York City water tunnel system (Yagiz, 2002). Here, beneath Brooklyn and Queens, an 8 km long concrete-lined pressure tunnel was excavated at an average depth of 200 m below sea level through hard, Proterozoic metamorphic rocks of the Appalachian mountain belt by utilizing an open-beam TBM (Robbins, Model 235-282). The machine bored through hard jointed formations of varying metamorphic and igneous rock types, including diorite gneiss, tonalite, pyroxene-garnet gneiss, and biotite-hornblende gneiss, intermixed with granite gneiss, amphibolite, pegmatite, biotite schist as well as mafic and rhyodacite dikes. (Yagiz, 2002, 2008; Brock, et al., 2001; Merguerian and Ozdemir, 2003).

The Second Tailrace Tunnel of the Manapouri hydro-power station was excavated along the calcslicate, metadolorite, meta-andesite, paragneiss, and granitic gneiss type of rock mass in the Southwestern New Zealand. The objective of adding the tailrace tunnel was to increase the overall cross-sectional area of flow, thereby reducing the flow velocities and associated frictional head losses (Kim, 2004; Macfarlane, et al., 2008). The tunnel is about 9.8 km long with 10 m diameter and was excavated with open type TBM (Robbins, Model 323-288).

Table 1. Averaged thrust and rock properties in the Queens Water Tunnel.

Rock type	UCS (MPa)	BTS (MPa)	PS kN (mm)	DPW (cm)	Alpha (degree)	Thrust (Tonne)
Rhyodacite dike	151	8.9	34	10	42.5	1300
Granitoid gneiss	158	9.3	34	102	46.1	1650
Amphibolite	161	9.9	43	56	28.3	1460
Orthogneiss	137	9.4	35	111	45.8	1625
Gneiss/schist	148	9.7	33	110	46.7	1610

Table 2. Averaged thrust and rock properties in the Second Manapouri Tailrace Tunnel.

Rock type	UCS (MPa)	BTS (MPa)	PS KN (mm)	DPW (cm)	Alpha (degree)	Thrust (Tonne)
Calc-silicate	162	7.7	36	132	37	1564
Granitic gneiss	97	7.1	32	116	34	1537
Meta dolorite	124	12.2	29	163	25	1571
Meta-andesite	147	10.5	33	134	36	1435
Paragneiss	111	10.0	31	333	27	1550

3 PERFORMANCE FACTORS FOR HARD ROCK TBM

TBM parameters including thrust and power together with rock material properties and rock mass characteristics are main parameters used for TBM performance estimation. Therefore, these key parameters should be quantified carefully for any type of hard rock TBM projects. The impact of these factors on TBM performance and the basis of the existing TBM performance prediction models such as the Colorado School of Mines (CSM) model are discussed herein.

3.1 *Machine specifications*

The machine specifications and in particular operational parameters including applied thrust and power represent the amount of forces and torque delivered to the rock via cutterhead and disc cutters to initiate fracture propagation in rock. Therefore, the cutting geometry/wear characteristics of the cutters installed on the cutterhead have a significant effect on the efficiency of energy transfer to the rock and the attainable rate of penetration. Single disc cutters are the most commonly used roller cutters for hard rock TBMs. The cut spacing and the depth of penetration per cutter head revolution define the efficiency of rock cutting by disc cutters. As would be expected, the spacing of cutters has a significant impact on the chipping mechanism and the efficiency of boring. Geometry of disc cutters, thrust, and power are the main machine parameters utilized in the CSM model together with intact rock properties; UCS and BTS. Figure 1 is an example of performance prediction by the CSM hard rock TBM performance prediction model, where machine ROP and operational parameters are estimated for a given rock strength. It is important to note that this graph does not represent the effects of rock mass or joints present at the face.

3.2 *Rock material properties*

The UCS and BTS are frequently measured intact rock properties to be utilized for TBM performance

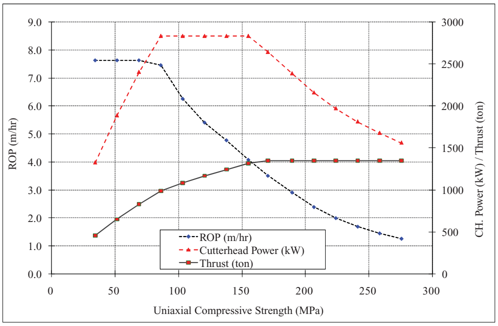

Figure 1. Typical TBM performance curve in the existing CSM model.

prediction (Ozdemir, 1977; Rostami, 1997; Cigla, et al., 2001; Yagiz et al., 2008). Furthermore, the ease or difficulty of crack propagation in rock, which is often referred to as brittleness has significant effect on rock boreability. There is no universal test accepted quantitative measurement for rock brittleness; however, several different indices have been introduced, including UCS/BTS ratio (Hucka and Das, 1974), Sievers' J value and S_{20} by the NTNU (Bruland, 1999) rock brittleness index obtained via punch penetration test (Yagiz, 2009). Dollinger, et al., (1998) stated that the punch penetration test is a useful tool for studying various machine parameters including the effect of cutter tip width, cutter spacing and depth of penetration on the force required for rock excavation. Nevertheless, these concepts have not been accepted by the extended rock mechanics testing community as yet. Reference intact rock properties, including UCS and BTS, have been usually measured in rock mechanic laboratories by following relevant standards. These rock properties are then used as input intact rock variables to estimate the rate of penetration in many TBM performance prediction methods (i.e. the CSM model). But these tests, although have some indication of rock brittleness behavior, the need an adjustment for rock brittleness to represent this specific intrinsic property of the rock. Hence an adjustment factor has been introduced as one of the input parameters for use in the Modified CSM model (MCSM) for predicting the ROP. Figure 2 shows the variation of the Brittleness Index (BI) as a function of peak slope which is measured by the punch test. The use of this adjustment factor allows for more accurate prediction TBM performance based on intact rock properties, thus more reasonable predictions are possible in massive rock conditions.

3.3. *Rock mass characteristics*

Rock mass properties including distance between the planes of weakness (DPW), orientation of these planes, as well as presence, frequency, and orientation of faults, joints, and foliations play a significant role in TBM performance. Orientation of weakness zone with respect to the direction of machine advance can control on TBM performance (Bruland, 1999; Yagiz, 2002). Therefore, both orientation of joints and faults together with direction of machine advancement needs to be quantified for estimation of TBM performance. Since 1980's (Lislerud, 1988; Bruland, 1999), Norwegian University of Science and Technology (NTNU) has developed a hard rock TBM prognosis model that count orientation of joint and direction of machine advancement via alpha angle that is the angle measured between the plane of weakness and tunnel axis.

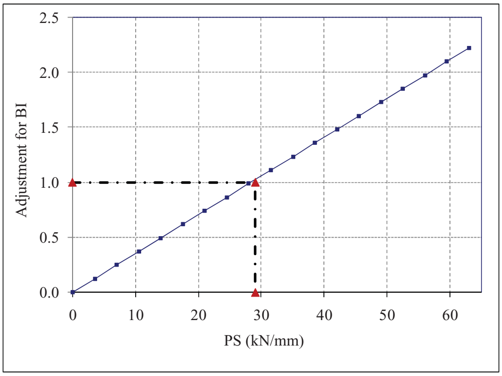

Figure 2. Adjustment factor for rock brittleness in the MCSM model (Yagiz, 2002).

Likewise, the joint/fissure system could be quantified by using fracture class designation introduced by the NTNU. As a result, orientation of discontinuities via alpha angle and distance between the planes of weakness have been quantified and used to make correlation between geological condition and the rate of penetration for investigated projects. Further, those rock mass properties are utilized as in put variables into the MCSM model (Yagiz, 2002). Therefore, rock fracture index (RFI) has been introduced and used as an adjustment factor that especially significant for fractured rock mass condition (Figure 3).

It should be noted that direct use of the NTNU fracture and joint classes in other modeling systems are fairly difficult and needs a deep understanding of both systems to allow their efficient and accurate use in adjustment of estimated rates by the existing models such as CSM model. This is because of the inherently different approaches used in each system to estimate the penetration rate and thus each seem to be most effective in a certain ground conditions. This refers to CSM model to be

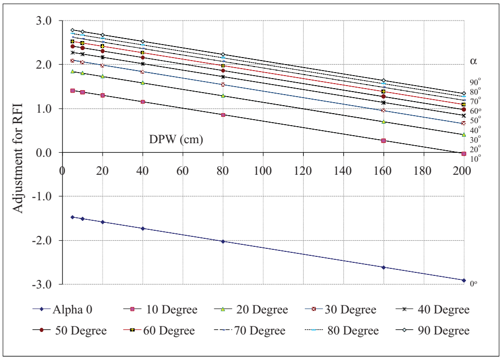

Figure 3. Adjustment factor for rock mass properties in the MCSM model (Yagiz, 2002).

more efficient in massive rock types and sedimentary rock while the NTNU system is more suitable in jointed rock masses and metamorphic rock with known fissures and related features.

Each model can predict machine performance when all the conforming input parameters of pertinent model are used in the process. Meanwhile, many attempts has been made to use other rock mass characterization methods including joint systems, RQD, and rock mass classification for adjustment of ROP from the CSM models (Yagiz, 2006b; Ramezanzadeh et al., 2008). A recent study by Hassanzadeh et al. (2009) has offered a new model for adjustment of ROP predicted by CSM model based on Geological Strength Index (GSI) which was introduced by Hoek et al. (1995). This adjustment factor seems to be reasonable in prediction of the anticipated penetration rate. Same study has offered a new relationship between Field Penetration Index (FPI) and GSI for various sedimentary rocks that allows machine performance prediction using the applied cutterload.

4 DISCUSSION AND RESULTS

The CSM model has been developed by Ozdemir, (1977) and it is updated as field and laboratory data became available to increase its accuracy for various rock types (Rostami and Ozdemir, 1993; Rostami, 1997; Cheema, 1999; Yagiz, 2002). The model gives promising result for predicting ROP for massive rock mass; however, rock behavior is often controlled by the structural features such as joins and planes of discontinuities and weaknesses. Since most of the geological conditions encountered in the tunneling operation involve rock mass with fractures and discontinuities that makes rock weaker than expected, the model may provide inaccurate result. Therefore, it requires relevant adjustments to account for rock mass behavior.

As result, developed adjustment factors for RFI, BI, and similar approaches explained in this paper should be used in conjunction with the actual model to achieve better accuracies in performance prediction. For this purpose, one can estimate the ROP from the CSM model as function of the UCS, BTS, cutter and cutting geometry, and thrust and power of TBM, then use adjustment factors such as RFI and BI to fine tune the estimated rates for given rock mass characteristics. An example of such equations for adjustment of the estimated ROP is provided below. In this formula the ROP could be estimated from the base CSM model and adjusted for fractured/rock mass conditions.

$$\mathrm{ROP\ (m/h)} = 0.097 \times \mathrm{ROP(CSM)} + \mathrm{RFI} + \mathrm{BI}$$

$$\mathrm{ROP\ (m/hr)} = 0.097 \times \mathrm{ROP\ (CSM)} + \mathrm{RFI} + \mathrm{BI} \quad (1)$$

In this formula, ROP (CSM) is the basic penetration rate obtained from the CSM model as in m/hr; both RFI and BI can be estimated from the charts given in this paper. Obtained ROP (m/hr) reported as the result of Modified CSM model.

The Modified model offers better result for case study of tunnels in the described database where the tunnel has passed through fractured rock masses (Tables 3 and 4). As excavated rock mass is highly fractured and faulted, the ROP mainly depends on the rock mass fractures properties including orientation, spacing and brittleness rather than rock strength (UCS and BTS) that are used as inputs for the CSM model.

Even though introduced models (i.e., CSM and MCSM) are acceptable for predicting TBM performance, further improvement of these models is needed.

Various research groups are dealing with machine-rock interaction and performance prediction of hard rock TBMs and have been focusing on improvement of models especially in jointed rock masses. This effort is underway by expanding and sharing database as well as developing new models

Table 3. Actual and predicted TBM performance for the Queens Water Tunnel.

Rock type	Cutter Load (kNf)	ROP (Field) (m/hr)	ROP (CSM) (m/hr)	ROP (MCSM) (m/hr)
Rhyodacite dike	260	2.42	4.07	2.27
Granitoid gneiss	330	2.02	3.86	2.06
Amphibolite	292	2.35	3.71	2.30
Orthogneiss	325	2.05	4.31	2.11
Gneiss/schist	322	1.99	4.00	2.03

Table 4. Actual and predicted TBM performance for the Second Manapouri Tailrace Tunnel.

Rock type	Cutter Load (kNf)	ROP (Field) (m/hr)	ROP (CSM) (m/hr)	ROP (MCSM) (m/hr)
Calc-silicate	230	1.04	2.31	1.86
Granitic gneiss	226	1.26	3.66	1.90
Meta dolorite	231	0.94	2.43	1.55
Meta-andesite	211	1.32	2.28	1.77
Paragneiss	228	1.11	2.85	1.27

and adjustment factors to allow for more accurate representation of the rock mass parameters and ground conditions.

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