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Geological controls on the breakthrough of tunnel boring machines in hard rock crystalline terrains

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ABSTRACT: Geological factors including the orientation, condition and frequency of discontinuities in rock mass, and also intact rock properties such as strength and brittleness are crucial parameters for performance analysis of hard rock TBMs. These data along with machine specifications such as thrust and power allow the appraisal and prediction of machine penetration rates. Recently completed projects include the Queens freshwater, Manapouri Second tailrace hydropower and the Milyang hydropower tunnels are assessed to investigate the effect of geological and rock mass conditions on the penetrability of utilized full face tunneling machines. Compilation of the experiences and datasets obtained from these projects indicates that even though intact rock properties including mineralogy, texture, metamorphic grade, hardness, strength and brittleness have an effect on the breakthrough of the machines, the most significant and controlling geological parameters are the orientation, condition and frequency of discontinuities in rock mass encountered along the tunnel. Thus, the geological conditions of the site should be investigated in early stage of the constructed tunnel and continuously updated until projects are completed.

1 INTRODUCTION

Performance of tunnel boring machines (TBM) depends on both geological conditions and rock mass characterizations encountered at the site as well as utilized machine specifications such as thrust and power. Geotechnical site investigation and TBM performance analysis are essential to develop construction schedules and cost analysis for any tunnel project. TBM performance prediction refers to the estimation of the rate of penetration (ROP), [the excavated distance as machine is actively mining or boring the face], and the advanced rate (AR), [the distance mined on a daily basis while including machine maintenance and other support activities].

Various researches have been conducted to investigate the affect of intact rock properties, geological and rock mass condition on TBM performance to estimate the rate of penetration (Ozdemir, 1977; Aeberli and Wanner, 1978; Nelson and O'Rourke, 1983; Lislerud, 1988; Rostami and Ozdemir, 1993; Bruland, 1999; Barton, 2000; Cigla et al., 2001; Yagiz and Ozdemir, 2001; Yagiz, 2002, 2006a, 2008; Gong and Zhao, 2009; Yagiz et al., 2009). Even though numerous researches have been performed on this issue, there is no universally acceptable approach to generalize the effect of intact rock properties, geological and rock mass conditions on the performance of tunnel boring machine and to estimate the rate of penetration.

In our study, geological controls on the breakthrough of tunnel boring machine in hard rock terrains are analyzed using laboratory and field data obtained from various tunneling projects around the world.

2 PROJECTS

The dataset established for this study consists of intact rock properties such as strength and brittleness; full-face machine data i.e., thrust and power and also quantified geological parameters including conditions, frequency and orientation of discontinuities encountered in rock mass along the excavated tunnels including Queens, Manapouri and Milyang projects.

2.1 *Queens freshwater tunnel*

The tunnel was constructed to improve distribution of freshwater throughout the City of New York, especially in county of Queens. 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

Table 1. Averaged rock properties with rock types for tunnels; Queens, Manapouri and Milyang respectively.

Rock type	UCS MPa	BTS MPa	BI kN/mm	DPW m	α deg	ROP m/hr
Rhyodacite	151	8.9	34	0.10	43	2.42
Granitoid gniess	158	9.3	34	1.02	46	2.02
Amphibolite	161	9.9	43	0.56	28	2.35
Orthogneiss	137	9.4	35	1.11	46	2.05
Gneiss/schist	148	9.7	33	1.10	47	1.99
Calc-silicate	162	7.7	36	1.32	37	1.04
Granitic gneiss	97	7.1	32	1.16	34	1.26
Meta dolorite	124	12	29	1.63	25	0.94
Meta-andesite	147	11	33	1.34	36	1.32
Paragneiss	111	10	31	3.33	27	1.11
Fine granite	375	17	37	1.3	n/a	0.48
Medium granite	176	11	36	1.3	n/a	0.99

the Appalachian mountain belt by utilizing an open-beam TBM (Robbins, Model 235–282). The machine bored through hard, poorly foliated and jointed formations of various metamorphic and meta-igneous rocks, i.e., gneiss and schist mixture, granitoid gneiss, amphibolite, orthogneiss and also swarm of rhyodacite dikes. (Merguerian, 2001; Brock et al., 2001; Yagiz, 2002; Merguerian and Ozdemir, 2003). The ranges of quantified geological and rock properties with actual penetration rate obtained from tunnel project are illustrated in Table 1.

2.2 *Manapouri Second tailrace hydropower tunnel*

The Second tailrace tunnel of the Manapouri hydropower station was excavated along the various rocks including calcslicate, metadolorite, meta-andesite, paragneiss, and granitic gneiss in the Southwestern New Zealand. The objective of 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 10m diameter and was excavated with open type TBM (Robbins, Model 323–288). Excavated rock type and properties are illustrated in Table 1 together with field penetration rate.

2.3 *Milyang hydropower tunnel*

The Milyang tunnel project about 5.4-km long was excavated along the igneous rock mass ranging from fine to medium textured granite to deliver clean water from Milyang dam to Yangsan area through 2.6 m-diameter hydro-tunnel in South Korea (Kim, 2004) using open type TBM (WIRTH, Model TB 260E). The ranges of UCS of rock are various from 176 to more than 370 MPa. Thus, obtained penetration rate can be quite different from fine grained through medium grained granite along the excavated tunnel as shown in Table 1.

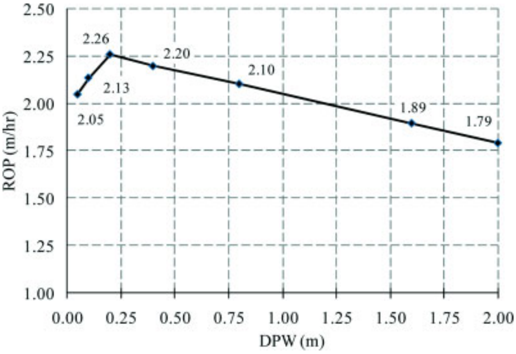

Figure 1. Generalized relationships between the DPW and ROP.

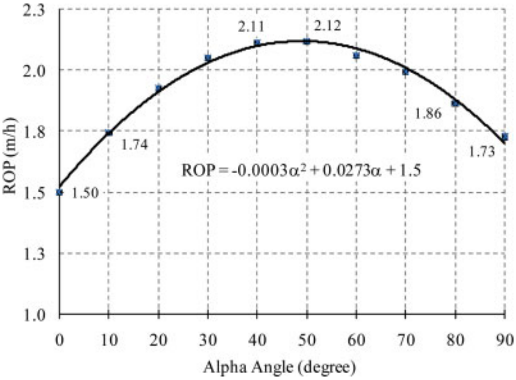

Figure 2. Generalized relationships between the α and ROP.

3 GEOLOGICAL CONDTIONS

Geological condition can be quantified as frequency and orientation of discontinuity in rock mass as well as main regional/global geological structures such as faults and shear zones encountered in the field. Further, intact rock properties including strength and brittleness should also be considered for performance analysis in mechanical tunnels.

3.1 *Orientation and frequency of discontinuities*

Geological condition including frequency, condition and orientation of discontinuities such as joints, faults and foliations have great effect on the TBM performance (Yagiz, 2002; Merguerian, 2008). Discontinuity frequency can be quantified via distance between planes of weakness (DPW), as orientation of discontinuities may be quantified via alpha angle (α), the angle between the TBM driven direction and the plane of weakness. These parameters have been used for quantifying the geological properties of rock mass in various performance models (Bruland, 1999; Barton, 2000; Yagiz, 2002; 2006b, 2008; Yagiz et al., 2008). It is found that both DPW and alpha angle have a affect on the ROP in fractured hard rock mass as shown in Figure 1 and 2 respectively.

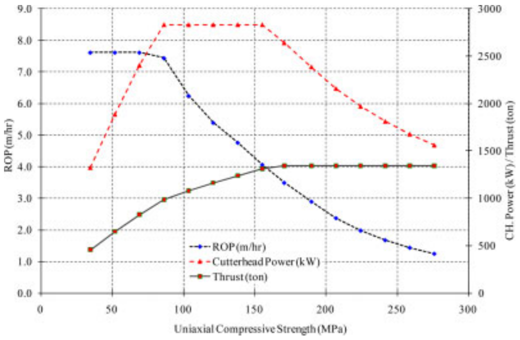

Figure 3. Generalized relationships between the UCS, thrust and cutter head power with the ROP (Yagiz et al., 2009a).

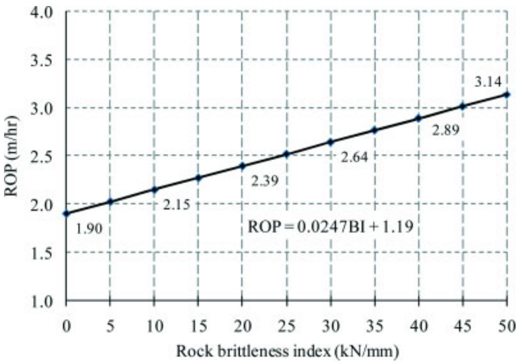

Figure 4. Generalized relationships between the BI and ROP.

So, geological parameters including frequency, condition and orientation of discontinuities in rock mass encountered along the tunnel should also be assessed with care. The alpha angle [the angle between plane of weakness and the TBM driven direction] has major control on the rate of penetration. ROP increases with the alpha angle in between 0° to 65°. After 65° of it, the ROP decreases gradually. So, the rate of penetration has been found the highest as the alpha angle ranges from about 50° to 65°. Consequently, the highest ROP is obtained as DPW ranges from about 20 to 40 cm. More than 2 m away from the machine, TBM is not much affected from a weakness plane or discontinuity. Conversely, as the DPW is around less than 20 cm, then the machine utilization decreases and so does the ROP due to increment of the down time.

3.2 *Intact rock properties*

Intact rock strength both uniaxial compression and Brazilian tensile strength (UCS and BTS), are commonly used for estimation of cost, time to be complete the project and machine performance in mechanical tunneling (Rostami and Ozdemir, 1993; Yagiz et al., 2008; Gong and Zhao, 2009). Even though intact rock strengths are usually used for estimating the TBM penetration in hard rock mass, those properties are not enough to estimate and analyze the TBM performance in fractured hard rock mass. Although the BTS of rock has little effect on TBM performance in fractured rock mass, the UCS of rock is an important parameter for evaluating the ROP (Figure 3). There is no universally accepted test to quantitative measurement of rock brittleness; however, several indices have been introduced (Hucka and Das, 1974; Bruland, 1999; Yagiz, 2009; Yagiz and Gokceoglu, 2010). The brittleness index (BI) introduced by Yagiz, (2009) has been used for assessing the brittleness affect on the rate of penetration herein (Figure 4). So, the rate of penetration increases with rock brittleness as decreases with the UCS in general.

Table 2. Specifications of TBMs utilized for excavated tunnels.

Project Name	Thrust Ton	Torque Ton-m	Power Hp	RPM	Disc #	Dia* cm	U %
Queens	1575	1170	3800	8.3	50	43.2	38
Manapouri	1634	873	3120	5.07	68	48.3	34
Milyang	395	267	760	13	22	43.2	32

*Dia refers to disc diameter.

4 MACHINE SPECIFICATIONS

The machine specifications and in particular operational parameters including the ranges of applied thrust and power, diameter and number of disc cutters, conducted rotation per minutes (RPM) have effect on the rate of penetration. The effect of the TBM thrust and power on ROP together with rock strength is depicted in Figure 3. So, machine specification, condition and operation should be also considered to obtain the ultimate benefit from the operated machine. Further, utilization (U) that is the percentage of the shift time during boring activity occurs is one of the main parameters to be given careful consideration (Yagiz, 2010). U depends more on geological condition, contractor capabilities and maintenance plans. TBM specifications with around 90% efficiency and averaged U for excavated tunnels are given in Table 2.

5 RESULTS

Geological conditions and discontinuity properties of rock mass have a great affect on both breakthrough of machines, cost scheduling and time to complete purposed projects. Where the rock mass have high strength and low brittleness, then, obtained ROP is relatively lower than expected. Maximum ROP are achieved as the alpha angle ranges from 50 to 65 degrees. As DPW ranges from about 20 to 40 cm, the obtained ROP is also rather high.

Geological condition and rock mass characterization in the field should be investigated before selecting the TBM, since the machine specification including thrust, cutter-head power and both diameter and number of disc have also influence on the ROP. Concluding is that geology and rock properties including orientation, condition and frequency of discontinuities together with rock strength and brittleness provide the major control on the penetrability of tunnel boring machine.

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