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Influence of TBM operational parameters on optimized penetration rate in schistose rocks, a case study: Golab tunnel Lot-1, Iran

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Abstract. TBM penetration rate is a function of intact rock properties, rock mass conditions and TBM operational parameters. Machine rate of penetrationcan be predicted by knowledge of the ground conditions and its effects on machine performance. The variation of TBM operational parameters such as penetration rate and thrust plays an important role in its performance. This study presents the results of the analysis on the TBM penetration rates in schistose rock types present along the alignment of Golab tunnel based on the analysis of a TBM performance database established for every stroke through different schistose rock types. The results of the analysis are compared to the results of some empirical and theoretical predictive models such as NTH and QTBM. Additional analysis was performed to find the optimum thrust and revolution per minute values for different schistose rock types.

Keywords: golab tunnel; penetration rate; tunnel boring machine; TBM operational parameters

1. Introduction

Tunnel Boring Machine (TBM) is one amongst the foremost well liked tunneling instrumentation within the industry. Modern hard rock TBMs are altogether versant what's more have been utilized really favored over different ground states same time setting propel rate records for through 170 m on day.There need been a considerable measure of Analyze on improvement for models to permit exact prediction about machine rate for infiltration in provided for ground conditions. Research works by Graham (1976), Ozdemir (1977), Blindheim (1979), Farmer and Glossop (1980), Cassinelli *et al*. (1982), Sanio (1985), Hughes (1986), Sato (1991), Rostamiand Ozdemir (1993), Nelson *et al*. (1994), Palmstrom (1995), Rostami (1997), Bruland (1999), Barton (1999 and 2000), Yagiz (2002, 2008), Sapigni *et al*. (2002), Ribacchi and Lembo-Fazio (2005), Yagiz (2006), Gong and Zhao (2009), Hassanpour (2009, 2010), Hassanpour *et al*. (2009, 2010, 2011) are some of the notable works on this topic. These models, although successful in calculating machine performance in many cases, are short of accounting for some of the parameters affecting machine performance in a variation of grounds. Furthermore, with more exact predictive capabilitiesabilities and better understanding of operational parameters, accurate planning and cost approximation is possible, which allows for wider area application for TBMs. This explains the initial high monies for the machine and eases increased efficiency by suitable planning of the backup system, matching machine specifications to the jobs site conditions, and lowersthe risks involved in using a machine for a specific project.

2. Influencing parameters

During rock excavation procedures, many factors, containing machine parameters, geological conditions, and site-specific conditions, affect machineperformance level. Table 1 lists the important factors influencing TBM performance (Blindheim 2004). Among these factors, some directly affect TBM penetration rate and some impact utilization and advance rate.

The most main factors which affect TBM penetration rate are rock mass characteristics containing rock material strengths (tensile and compressive strength) and rock fractures and joints (Hassanpour *et al*. 2011). Gong and Zhao (2009) concluded that four parameters, uniaxial compressive strength, brittleness, joint spacing and the angle between direction of tunnel and discontinuity plane, are the main parameters influence on TBM penetration rate.

Some factors directly and some indirectly effect the penetration rate. For example, net penetration is influenced mostly by rock material and rock mass properties and machine parameters such as thrust and cutter spacing. Though, bad ground, logistical issues and lack of tunnel muck haulage and transport capacity surely impacts utilization and thus daily advance rate. In fact sometimes the operator may run the TBM below its nominal capacity to avoid muck haulage issues or excessive maintenance requirements.

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Table 1 Factors influencing TBM performance (Blindheim 2004)

Geological/Geotechnical	Machine & operation	Organization
Rock material properties	**TBM specifications**	**Work arrangements**
1.Strength:compressive, tensile, shear 2. Crushing strength, toughness strength 3. Elasticity, rebound, hardness 4. Anisotropy 5. Porosity 6. Abrasively	1.Thrust, net and total including friction 2. RPM, rolling speed 3. Torque capacity, installed and usable power 4. Number diameter, edge width, material 5. Cutterhead diameter, shape and stiffness 6. Cutter change mode: front or back-loaded 7. Re-gripping principle: thrust on walls/roof or on segmented lining	1. Available hours, work regulations 2. Shift schedule, buffer time 3. Crew organization authority of shift bosses, autonomous groups 4. Crew training and experience 5. Crew remuneration, bonus system
Rock mass features		**Services**
1.Type of weakness planes; joints, fissures, partings, bedding planes 2. Spacing 3. Orientation 4. Persistence		1. Electricity, water etc. 2. Ventilation, cooling
		Safety
		1. Dust control 2. Fire control 3. Light, vibrations, noise
Ground conditions	**Operational parameters**	**Management principles**
1.Mixed face conditions 2. Rock stresses 3. Fault zones 4. Water 5. Gas	1. Thrust and torque 2. utilization 3. Steering, friction 4. Cutter change sequence	1. Authority of TBM manager, foremen 2. Procurement conditions
Ground control	**Backup system**	**Location**
1.Water control measures 2. Rock support measures 3. Lining	Transport system for muck and supplies	1. Tunneling traditions Labor qualifications 2. Supply of goods Local laws, regulations

3. TBM performance prediction models

A great amount of work by many scientists has been carried out that are related to TBM performance prediction in hard rock. These models have been advanced from single factor models to complex models requiring many various input parameters. Among these models, some are based on full scale laboratory cutting tests, and some based on TBM field performance in different ground conditions.

The most important output in most of these models is rate of penetration and the main rock mass factors used to predict the rate of penetration in these models consist the compressive strength and tensile strength of the rock material, and the frequency and orientation of the rock joints. The machine factors applied to predict the penetration rate (PR) in theoretical models include cutter spacing, cutter tip width, cutter diameter, average thrust per cutter and revolution per minute (RPM).

Some writers also related TBM performance to rock mass classification systems (e.g., Cassinelli 1982, Barton 1999, Sapigni *et al*. 2002, Ribbachi and Lembo-Fazio 2005, Bieniawski 2007). In these studies, the rock mass classification systems used to describe rock mass quality generally contain RSR (rock structure rating), RMR and Q systems. These performance estimate models can be mainly classified as theoretical or semi-theoretical that is based on laboratory results, and empirical models that were developed from TBM field performance. Some of the most important methods will be discussed in the following:

3.1 Theoretical/experimental models

The theoretical models are based on the analysis of the forces or the specific energy, which are related to the intact rock and rock mass properties such as rock material compressive, tensile and shear strength, rock quality designation (RQD) or joint spacing and so on. Theoretical studies usually cannot bid correct results due to complex nature of TBM rock fragmentation procedure, specifically in jointed rock, while them make dependable results in more massive rocks. Examples of theoretical and semi-theoretical works can be found in Rox borough and Phillips (1975), Fowell and McFeat-Smith (1976), Ozdemir (1977), Farmer and Glossop (1980), Sanio (1985), Sato *et al*. (1991), Rostami (1997).

3.2 Cutterload approach

The most important parameters in TBM operation contain installed power, cutter head RPM, thrust, and disc spacing. In practice, typical disc spacing is between 60 and 100 mm. Disc rolling velocity and loading capacity determines cutter head RPM and machine thrust, respectively. Also, for a given depth of penetration per revolution, the rolling force can be estimated, which in turn is used for calculation of cutter head torque, and combined with RPM, defines the head power requirements. Spacing to penetration (S/p) ratio is used to determine cutting efficiency since it has been proven that within a certain range of S/p ratios, specific energy of cutting is minimized. This often occurs in S/p ratio of about 10-20 for disc cutting. Since the mid-1950s, significant study has been performed on the evaluation of disc cutter forces. Graham (1976), Farmer and Glossop (1980), Snowdon *et al*. (1983), and Sanio (1985) attained strong correlations between rock compressive strength and the specific energy defined as the amount of energy required to excavate a unit volume of rock. Influence of joints and plane of weakness were studied by Roxborough (1975), Ozdemir and Miller (1978), Sanio (1986), Sato *et al*. (1991), Rostami (1993). All observed "a significant reduction in cutting forces in presence of joints in the rock except for a joint orientated normal to the cutting surface."

3.3 Specific energy approach

Snowdon *et al*. (1982) introduced the relationship between rolling force normal forces and penetration in a comprehensive study of disc cutting in British rocks. Snowdon used a single small diameter (200 mm)V-shape cutter to show that there may be an optimal spacing to penetration (S/P) ratio that gives the lowest specific energy to cut the rocks. They asserted that for each spacing and rock type combination, there is a critical penetration beyond which no further decrease in specific energy of cutting is realized and also showed that the forces upsurge about linearly with spacing until S/P value of 15-20 is reached. Boyd (1986) introduced a model that usages a totally different methodology. The rock mass is assumed to have a specific energy (in kW-h/m3) that is required for disintegration.

3.4 Mathematical/statistical simulation approach

Nero Fuzzy approach is an alternate modeling method to assist in the estimate of the performance of TBMs that is presented by Alvarez Grima *et al*. (2000). The main elements of this modeling approach are Fuzzy sets, fuzzy logic, estimated reasoning, neural networks and data clustering. These are collective into a so-called hybrid modeling structure the Nero-fuzzy modeling provides a powerful tools to usage unclear and inexact (fuzzy) information on the rock or soil present in the subsurface. Additional, it allows us to use large amounts of data, which the physical meaning is not clear (e.g. rebound test data on rock cores or geophysical well logging factors). By using ANN (Artificial Neural Network) analysis, relationships of such data with geotechnical important information can be established and used. Maybe the most fascinating feature of this method is that anyone can cope technically with subjectivity and uncertainty in engineering process, rather than blindly avoiding them (Alvarez Grima 2000). Nelson estimate model is based on large database with information from 630 projects (Nelson *et al*. 1994). The modeling or simulation approach is made possible by modern computer technology. The predicted performance by this model is highly dependent on the user selections in addition to the "facts" of the database, especially with regard to which probability density functions one selects to run the retrieved data through. Each of the input parameters will have some influence on the prediction results, depending on the available information in the database**.**

3.5 Empirical models

Many try have been made to relate laboratory index test results to TBM penetration rate (Delisio and Zhao 2014, Hassanpour 2011, Khademi Hamidi *et al*. 2010, Gong and Zhao 2009, Ramamurthy 2008, etc.) . Prediction reckonings are either empirically stemmed or advanced with a theoretical basis using force balance or energy balance theories. In both cases, simplifications on disc indentation geometry and contact zone stress distribution, leads to deriving coefficients by correlation of sureparameters within the database. Most estimate methods agree on trends, but empirical methods are case-specific in terms of geology and machine characteristics. However, a general reportof attention about the case history databases should be made. Prediction methods that do not consider operating conditions of thrust and torque cannot be applied to project machine performance, since equipment operational parameters vary from time to time. The condition of the cutters can also have a significant effect on performance, since worn or blunted discs present wider contact areas on indentation and require higher force for a given level of penetration. Some databases include performance with single, double, and triple disc cutter, a variation that greatly affects disc edge loading and spacing/penetration ratios. Finally, low thrust and low torque mining through poor ground or alignment curves may result in reduced penetration rates.

3.6 Laboratory studies

Penetration rate of TBM could be calculated using equations, but due to some simplification and lack of accuracy, these equations are rarely used by industry today.

Graham (1976) presented a model in which the penetration rate is calculated as a function of the normal forces per cutter the RPM, and the UCS of the rock. The model considers neither the discontinuities nor the cutter properties. Farmer and Glossop (1980) introduced a model in which the penetration rate is calculated by using the average cutter force and the tensile strength of the rock. The model is based on eight various case histories. This seems to be its major limitation regarding the wide variety of TBMs available. Rock mass properties (i.e., discontinuity) and cutter geometry are not considered in the model. Hughes (1986) presented a model that is similar to the Graham's model described above. The force per cutter, unconfined compressive strength, and RPM are considered in the model. It also includes the number of cutters per kerf (groove) and the radius of the discs. However, the model does not consider the rock discontinuities. Hughes (1986) predicted the rate of performance and power requirement of full-face machines equipped with disc in coal measure strata. His equation incorporates thrust per disc, speed of cutting, average number of discs per kerf, average radius of discs, and UCS of intact rock. Bamford (1984) developed a relationship by correlating TBM performance in two tunnels with wide ranges of rock material properties and indices. The results show that penetration rate is best predicted by a combination of Schmidt hammer rebound hardness, machine propel' thrust force, NCB cone indenter index, and angle of shearing resistance. Nelson *et al.* (1983) have developed a performance prediction model with analysis of construction records documents of TBM performance during the excavation of four tunnels in

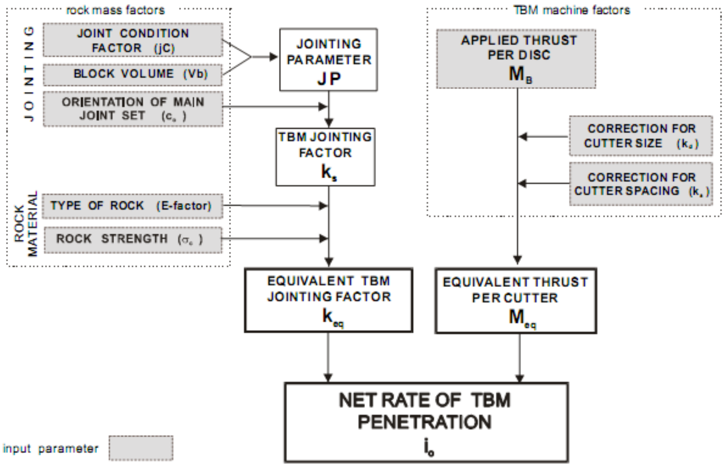

Fig. 1 Layout of a method to predict TBM penetration using RMi parameters based on the NTH model

sedimentary rocks. Innaurato *et al*. (1991) introduced an updated version of the method presented by Cassinelli *et al*. (1982). The method includes the Rock Structure Rating (RSR) of Wickham *et al*. (1974). The major change of the updated method is the incorporation of UCS in rock mass classification. It must be noted that the RSR was originally developed for the determination of the appropriate steel rib tunnel wall support, and that it includes parameters such as rock type, geological structure, joint spacing, dip direction, joint condition, and the water inflow.

4. Field studies and investigations

TBM performance and operational characteristics in the field, and their relationship with geological conditions and the physical and mechanical properties of rock mass has been the subject of extensive research. The main advantage of field studies over research conducted in the laboratory is that they contain the complexity of both machine, and geology, as well as of rock mass properties. This approach is favored method by the tunnel design engineers and project planners since it is practical and based on experiences obtained from actual tunneling operations. Further, the information generated in these studies can be used to confirm and validate related investigations in the laboratory using disc cutters. They provide a basis for extending the results of laboratory researches to field TBM performance by offering the required correction factors to account for the added complexity of the overall excavation system. In following section, some of these models would be discussed.

NTNU model: Bruland *et al.* (2000) offered an updated version of the model presented by Lislerud (1983), which was progressed by the same Norwegian study group. The first version of the model was published in 1976 by Johannessen *et al*. (in Norwegian). The variations in Bruland's model are limited. The intact rock properties are contained in the form of Drilling Rate Index (DRI). Discontinuity direction and spacing, as well as machine characteristics such as thrust per cutter, cutter size and RPM are considered. The model was developed using multivariable regression, and it uses charts to determine working parameters. To obtain the DRI, the brittleness test and the Siever's miniature drill test are performed. The test procedures are described in a paper by Bruland (2000) that also contains DRI values from more than 2000 sample locations, of which about 80% are from Norway. Bruland *et al*. (1988) indicated, that joint orientation of zero and ninety degrees are only extremes values and that between these angles the effects of discontinuities can be more influential. Furthermore, the spacing of the planes of weakness influences the penetration rates considerably, and the difference of scale between point load tester and the actual cutters becomes important.

QTBM model: Barton (2000) developed a model for briefly predicting penetration rate and advance rate of TBM tunneling. This model is based on expanded Q system (rock mass classification) and on average cutter force in relation to appropriate rock mass strength. Orientation of fabric or rock structure together with the compressive strength or point load (tensile) strength of rock is utilized in the model. Also, the abrasiveness of rock is incorporated via University of Trondheim cutter life index (CLI).

RMi model: Palmström (1995) developed another model base on Rock Mass index (RMi). This model is to be considered the closest relation to NTNU model with its parameters. It has been considered the effect of rock mass factors properly, especially jointing properties. The RMi characterization of joints and jointing includes their three dimensional occurrence. It therefore incorporates the effect of more than one joint set. The RMi parameters also include joint characteristics of importance for the shear strength of the joints, which generally has a marked influence on the TBM boring rate. Therefore the RMi should be suitable in assessment of the tunnel boring penetration in hard and moderately hard rock masses. It has always been recognized that the presence of joints improves the boring rate. However, in the interest of conservatism in most analyses, the improvement in boring rate due to jointing has been neglected by testing un-fractured specimens of solid rock and by basing predictions on the strength characteristics of intact rock (Robbins1980).

The system for applying the RMi to evaluate the TBM boring capacity is shown in Fig. 1 Separate parameters have

Table 2 Golab tunnel (lot-1) and double Shield machine characteristics

Specifications TBM	
Machine type	Telescopic shield TB 458 E/TS
Maximum thrust	8300 kN
Maximum torque device	802 kN.m
Power	1120 kW
Rotational speed	0-12
Stroke	65 cm
Number of disc cutter	36
Maximum design load on each disc cutter	500 kN
Maximum working load on each disc cutter	230 kN
Tunnel Characteristic	
Tunnel length	9971 m
Environment during drilling	16.03 m
Diameter tunnel excavation	4.52 m
Finished diameter tunnel	3.78 m
Slope tunnel	0.1%
Tunnel section	Circular
Concrete cover	Hexagonal segment
Volume of Conveyance water	23 m^3

been chosen for:

- The rock material, represented by its compressive strength, σ
- The jointing, represented by the jointing parameter (JP)
- The tunnel /shaft boring machine properties (K), represented by the utilized thrust per disc cutter, and the size of the cutters.

Review of the past research works shows the potentials and weakness points of available models for performance prediction of hard rock TBMs. To overcome the shortcoming of the existing models and develop a more accurate performance prediction model, a combination of field and laboratory based models has to be developed.

5. Project descriptions and geology

Data for TBM-performance analysis have been obtained from Golab Project that is planned to supply water from Zayandeh-Rood River to Kashan city in central Iran. This project consists of three main components including 1) main tunnel 2) pump station cavern 3) access tunnel. Main tunnel, will transfer water from the river to pump station. Transferred water will be sent to a treatment plant through pipe line installed in the access tunnels. Table 2, part of the profile and the tunnel digger machine is presented.

The rock units along the tunnel consist of metamorphic rock masses such as granite genies, amphibolite, schist, phylite, slate and sedimentary rocks such as shale, limestone, argillaceous limestone, conglomerate. Some reaches of the tunnel are in igneous rocks such as diorite, monzonite and monzodioriteic, etc. that are intrusive and are associated with heavily fractured zones. Also different geological structures such as bedding, folding, fractures (faults and joints) and deformation were observed (Fig. 2).

These units include Jurassic-Cretaceous-Tertiary sequence. The tunnel geological profile includes various limestone formations and conglomerate at the north east end of the project site. Tunnel crosses frequent collection of metamorphic Shale, slate, phylites and metamorphosed sandstone in the middle of the alignment that in alternating sequence. Beginning of the tunnel is located to the Chadegan shear zone that consists of metamorphic rocks such as granite genies and various types of schist (Fig.3).

In the facies of green schist with mineralogical complex, the indicator of actinolite+epidote+chlorite+albite and (+) quartz was detected. By the increase of metamorphism degree, the chlorite will become unstable. Also, termolite/actinolite appears in higher heat (The upper level of green schist facies). The geomechanical parameters of rock masses along the alignment of tunnel are summarized in Table 3.

Construction of Golab tunnel was started in summer of 2009. Within 10 month, about five kilometers of the tunnel was been excavated with a monthly average of 500 m. Most frequent formation encountered was schistose rock masses and a small section (about 600 m) was in igneous and meta-volcanic rocks.

In the TBM driven section, machine has had several stops due to adverse geological conditions and operating

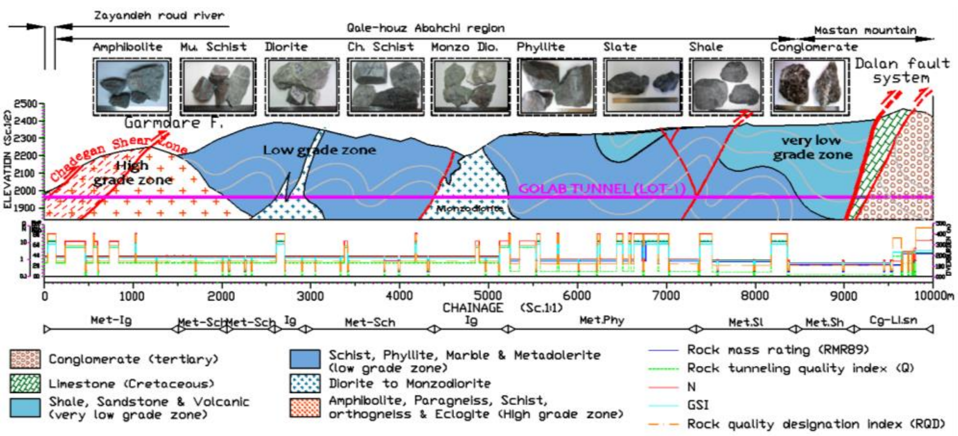

Fig. 2 Golab tunnel (lot-1) geological map & section (Babaahmadi *et al*. 2012)

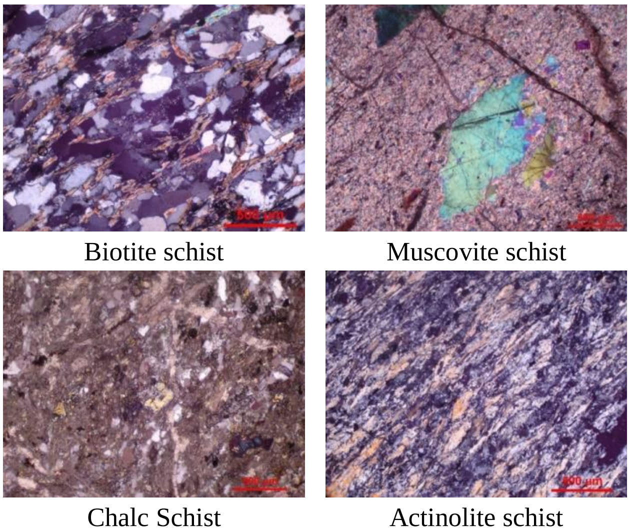

Fig. 3 Petrography of schistose rocks types

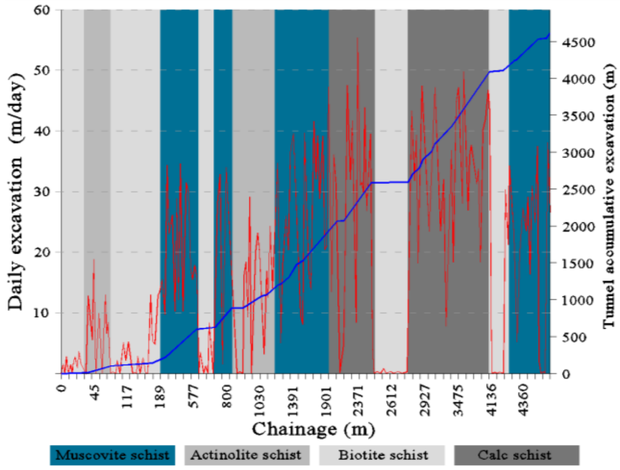

Fig. 4 Daily and accumulative tunnel excavation progress in longitudinal 5 km

system problems. This is in contrast with rather good performances in other sections of tunnel where advances of up to 55 m/day and 900 m/month have been recorded (Fig. 4).

There are various types of rock mass in the tunnel path including massive, weak, and brecciaed units. Tunnel route also included 300 m of Quaternary deposits and Sedimentary rock masses includinglimestone, marly limestone, Shale, Marl, Dolomitic limestone, Sandstone, and Dolomite units. In the middle of tunnel (with 1200 meters overburden) there were Karstic limestone and Dolomitic limestone with spongy texture that are located perpendicular to the tunnel axis. The other units are shales and marly deposits that are composed of organic matters and pyrite (posing risks due to danger of toxic gases such as H2S). It is important to note that the tunnel was excavated below the water level.

The geological structure is problematicalby multiple folding linkedwith shear zones and brittle fault zones, but the general attitude of rock is more or less uniform throughout the tunnel so that the longitudinal axis of the tunnel is almost normal to the schistosity.

Beginning of the tunnelwas composed of massive blocks of granite and genies embedded in a sheared matrix of high-grade metamorphic schist.

Dataset for performance study contains of 411 set of data points featuring TBM parameters (head thrust, net boring time, total boring time, excavated length) and rock mass type, penetration rate and advance rate were calculated by separating the daily excavated length by the net boring time and the total boring time (24 h), respectively. Due to installation of segmental lining, examination and recording of the rock mass was possible only during the daily maintenance of the TBM and cutter inspection when face was accessible for geological mapping. The rock mass surveyed in the short reach between the rock face and the cutterhead (1 m) was assumed to represent the bored section over a working day.

6. Estimation of penetration rate by existing models

Information on the rock strength, rock mass conditions and TBM operating parameters can be used to estimate penetration rate of TBM, and combined with utilization, the advance rate of TBM can be determined. It is clear that penetration rate of a TBM, with specific cutter load in a rock with given strength can be calculated from theoretical models, but the existence of fractures, structural discontinuities, and presence of multiple joint sets in rock mass will cause errors in determining the penetration rate.

Table 3 Geomechanical parameters of intact and rock masses

Unit	Parameters related to rock											
	Rock mass				Intact rock							
	GSI Value	Q Value	Dip & Dip direction of discontinuity	Discontinuities Spacing (cm)	Poisson's ratio	porosity	Abrasiveness index (CLI)	Hardness & drill ability	Friction Angle (Deg.)	Elastic Modulus (GPa)	Tensile strength (MPa)	U.C.S (MPa)
Muscovite schist	30-35	0.4-0.6	75-85/176	10-20	0.36-0.37	7-8.5	65-70	55-60	25-27	1-1.5	1-1.4	12-17
Actinolite schist	35-40	0.5-0.9	75-85/104	20-30	0.32-0.35	5-6	35-40	55-60	27-30	1.5-1.7	1.2-1.6	15-20
Biotite schist	30-35	0.4-0.6	80-90/227	10-20	0.36-0.37	6-7.5	55-60	55-60	25-27	1-1.5	1-1.4	12-17
Chalcschist	40-45	0.8-1.3	35-45/271	30-40	0.27-0.3	4.5-5.5	30-35	60-65	30-33	1.5-2	2-2.5	25-30

Table 4 TBM penetration rate in schistose rocks (Met.Sch) based on different models

No.	Model	PR (m/hr)
1	Barton, 2002	3.15
2	Cassinelli, 1982	0.96
3	Innaurato, 1991	1.02
4	Ghahraman, 2002	6.70
5	NTH	6.10
	Average	3.58
		PR (mm/rev)
6	Graham, 1976	60.4
7	Glossop, 1980	41
8	Hughes, 1986	110.7
	Average	70.7

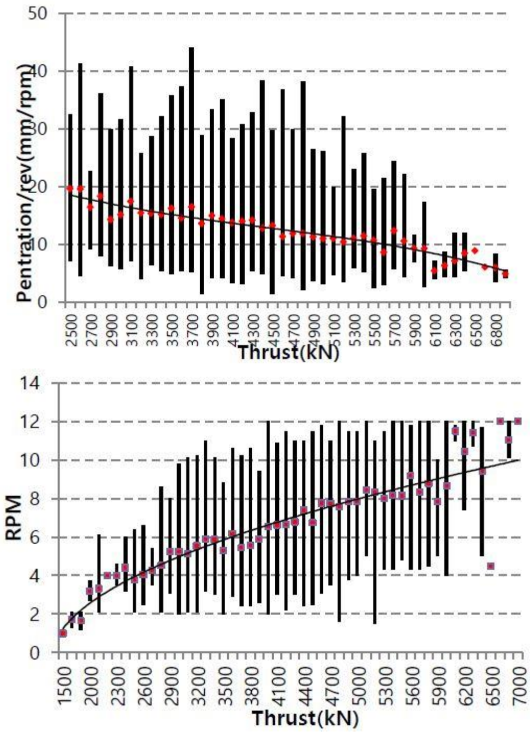

Fig. 5 Changes in penetration rate and RPM in different thrusts in Muscovite schist rock unit

Anticipated penetration rate of the TBM in schistose rocks based on some of the existing methods are presented as Table 4.

In order to estimate the actual penetration rate in various rock formations, while accounting for changesin the TBM operational parameters, the penetration rate in pertinent working conditions has been recorded. Initial studies on the machine parameters, especially cutter load (Fig. 5), shows that increase in cutter load reduces the amount of penetration in the Meta Schist rock units. This apparently odd relationship has a simple explanation and that is in softer rocks, operator uses less thrust to avoid cutter head jamming since due to low strength of rock even lower cutter loads achieves high penetrations.

In order to reduce the effect of increasing thrust in reducing penetration, rotation speed of cutter head (RPM) were increased. The results of this study in the performance of TBM, through 5 km of tunnel excavation in schistose rocks and amount of TBM actual penetration per revolution (PR/rev) in different thrust force and RPM at Figs. 6 to 8 are presented.

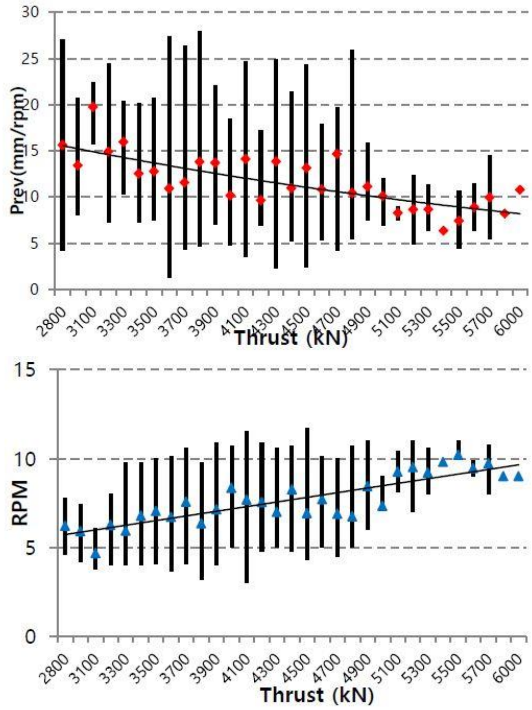

Fig. 6 The relationship between average penetration rate and average RPM with thrust in Actinolite schist rock unit

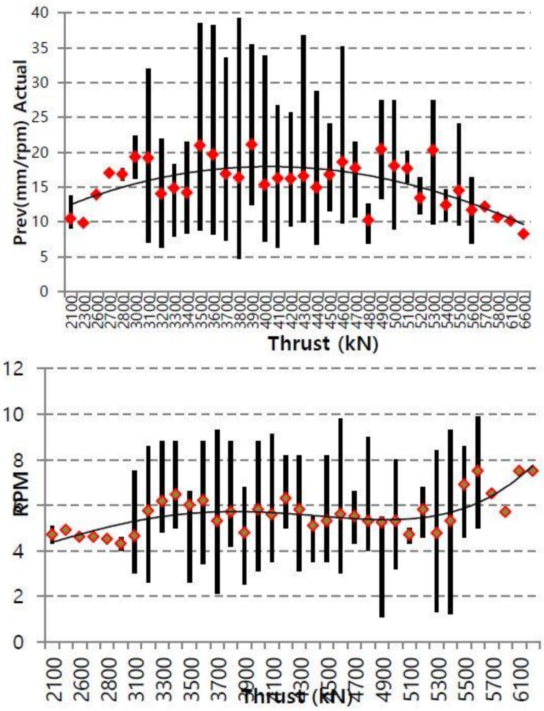

Fig. 7 Changes in penetration rate and RPM in different thrusts in Biotitic schist rock unit

It is illustrated in the figures, increases in RPM did not cause to increase TBM penetration rate in such rocks. Fig. 9

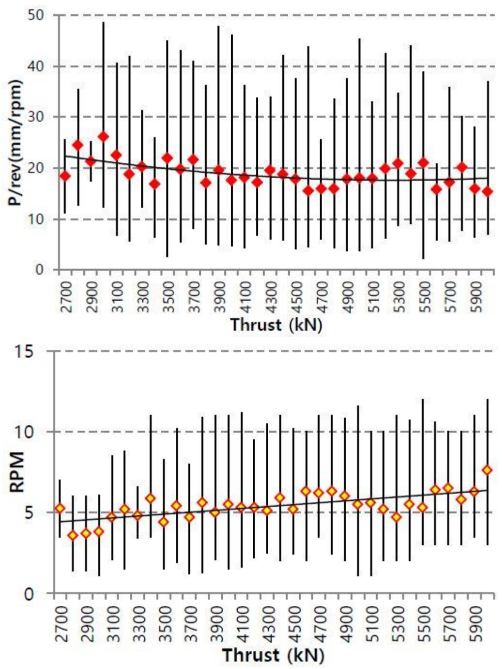

Fig. 8 Changes in penetration rate and RPM in different thrusts in calc-schist rock unit

is illustrated, the relationship between average penetration rate and average RPM with thrust in Chalk schist rock unit.

7. Discussion

Review of the past research works shows the potentials and weakness points of available models for performance prediction of hard rock TBMs. To overcome the shortcoming of the existing models and develop a more accurate performance prediction model, a combination of field and laboratory based models has to be developed, TBM performance prediction in non-uniform rock masses is a very complex process and depends considerably on geological conditions, strength parameters of rock material and rock mass as well as operational and designed parameters of TBM. According to studies by many researchers in order to estimate a correct penetration rate, an appropriate combination of all these factors is necessary and eliminate of each above factors can lead to inaccurate estimation of penetration rate. On the other hand restrictions in the estimation of rock mass property with good accuracy, can lead to creation errors in the presented formula for the penetration rate.

Evaluation of real penetrations with those predicted by the prediction models showed poor agreement. For example as regards the Innaurato model, the disparity is maybe due to the absence of machine-related factors, which limits its

Table 5 Actual penetration rate results of excavation in schistose rocks

	Type	Max	Min	Ave.
Mu.Sch	P/rev (mm/rpm)	43.97	2.17	13.46
	PR (m/hr)	12.94	1.22	4.93
Ac.Sch	P/rev (mm/rpm)	48.57	3.72	18.38
	PR (m/hr)	12.39	1.54	5.17
Bi.Sch	P/rev (mm/rpm)	42.58	4.75	17.26
	PR (m/hr)	10.12	1.32	5.29
Ch.Sch	P/rev (mm/rpm)	28.61	3.50	12.09
	PR (m/hr)	15.37	1.53	4.91
Schistose Rocks	Ave. P/rev (mm/rpm)	40.93	3.53	15.29
	Ave.(m/hr)	12.7	1.4	5.07

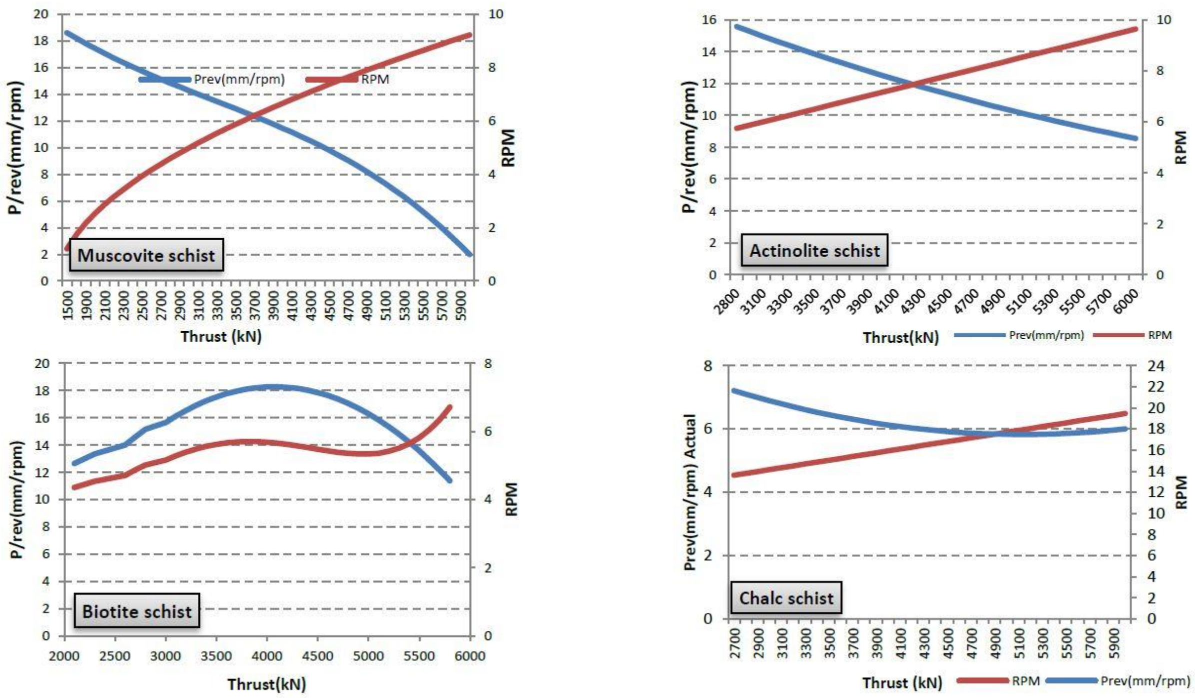

Fig. 9 The relationship between average penetration rate and average RPM With thrust in schistoserocks unit

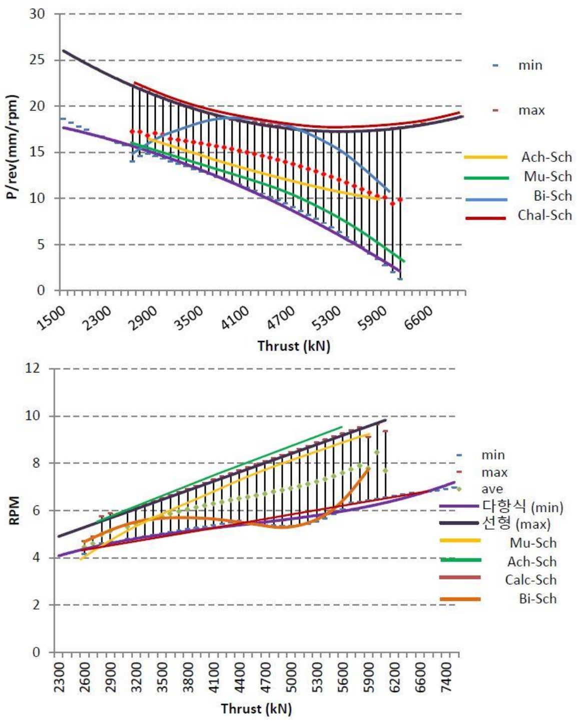

Fig. 10 The relationship between average penetration rate and average RPM with thrust in Mu-Sch, Ach-Sch, Calc-Sch and Bi-Sch units

application to rock-machine combinations. In the case of the Barton model the poor result is much more problematical to describe, as the new term Q_{TBM} has additional rock-machine interaction parameters of special relevance for TBM applications. In particular, Q_{TBM} shows low sensitivity to penetration rate, and the correlation coefficient with recorded data is even worse than conventional Q or other basic parameters like the uniaxial compressive strength of the intact rock. Evidently, the dependability of the Barton model cannot be arbitrated by a specific case, but the incongruity underlines the problems complex in performance prediction when so many parameters (rock mass condition, machine and muck removal system characteristics, human experience) are complicated. Lastly, it is significant to note that empirical relations discussed above are based on rock mass surveying during the excavation that is considering the rock mass conditions at depth. At the design stage instead, especially for deep tunnel, performance prediction mostly deal with geomechanical surveys of outcropping rocks. Purpose of the comparison is to test the predictive capabilities of these models when detailed data, closely surveyed at the excavation face, are available.

Main reason for this difference was in thrust force behind each disc cutter that in these models assumed 230 kN, whereas this amount in operation never be imposed on disk cutter and part of this force spending to overcome friction between the machine and ground or between the shields.In Fig. 10 penetration rate in different schistose rocks is shown during the different thrusts and RPM.

As these Fig. 11, can be seen increasing of machine thrust force in all schistose rock units in the tunnel, cause to

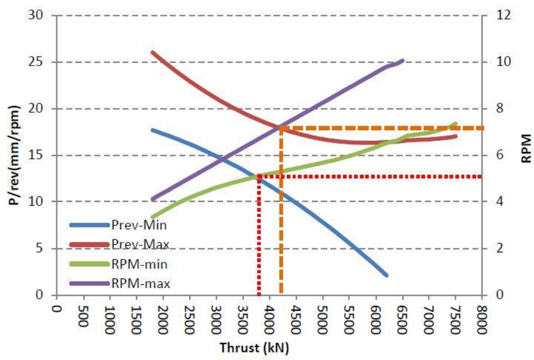

Fig. 11 The relationship between average penetration rate and average RPM with thrust in schistose rocks

reduce penetration rate in these rocks and has been increasing RPM could not increase penetration rate in the higher thrust. Changes in the average penetration rate and average RPM shows the highest penetration rate (17-26 mm/rpm) is derived in the RPM 3.3-4.1 and thrust 2000 KN. While the lowest penetration rate (2-17 mm/rpm) is derived in such rocks with increasing thrust to 6000 KN and RPM 6.5-10.

8. Conclusions

TBM performance depends on several influencing parameters. Most important influencing parameters include intact rock strength and fracturing degree of rock mass as well as machine operation parameters such as thrust and RPM which have been used in developing new prediction models by many researchers.

A collection of estimate models for TBM performance exist. Several have been established by repeated uses, modifications and developments over many years. Most models cover only the penetration rate. A few effort to contain TBM utilization. The models differ widely in complexity.

Increasingin thrust and RPM always cause to increase energy consumption and applied torque to machine. Ifthis problem is not controlled and also is not correctly used, it might cause to device amortization and to spend more time for stopping or changing disk cutters and other machine consuming parts. So that, increasing RPM and thrust force cause to asharp increase in the number of disc cutter replacement. The study of this subject and apply proper thrust and RPM in these rocks decreased the number of disc cutter replacement in the continuous excavation of tunnel and totally has been reduced energy costs, amortization and manpower. Based on the obtained diagrams from machine penetration rate was observed that increasing the amount of thrust more than 3800 KN and RPM up to more than 5 in schistose rocks will reduce the penetration in such rocks.

References

Alvarez Grima, M., Bruines, P.A. and Verhoef, P.N.W. (2000), "Modeling tunnel boring machine performance by neuro-fuzzy

methods", *Tunnel. Underg. Space Technol.*, **15**(3), 259-269.
Babaahmadi, A., Mohajjel, M., Eftekhari, A. and Davoudian, A.R. (2012), "An investigation into the fault patterns in the Chadegan region, west Iran: Evidence for dextral brittle transpressional tectonics in the Sanandaj-Sirjan zone", *J. Asian Earth Sci.*, **43**(1), 77-88.
Barton, N. (1999), "TBM performance estimation in rock using QTBM", *Tunnels Tunnel. Int.*, **31**(9), 41-48.
Barton, N. and Itoh, J. (2000), "TBM performance in rock using QTBM", Fuji Research Institute Corporation.
Bieniawski, Z.T., Celada, B. and Galera, J.M. (2007), "TBM excitability prediction and machine and rock interaction", *RETC*, Toronto.
Bruland, A. (1999), "Hard rock tunnel boring advance rate and cutter wear", Norwegian Istitute Technology, Trondheim, 183.
Cassinelli, F., Cina, S. and Innaurato, N. (1982), "Power consumption and metal wear in tunnel boring machines, analysis of tunnel operation in hard rock", *Proceedings, Tunneling 82*, London, UK.
Delisio, A. and Zhao, J. (2014), "A new model for TBM performance prediction in blocky rock condition", *Tunne. Underg. Space Technol.*, **43**, 440-452.
Ding, W.Q., Peng, Y.C., Yan, Z.G., Shen, B.W., Zhu, H.H. and Wei, X.X. (2013), "Full-scale testing and modeling of the mechanical behavior of shield TBM tunnel joint", *Struct. Eng. Mech.*, **45**(3), 337-354.
Engineering Geological report of Golab Tunnel project (2009), IMN-10054-SUGE-OR-GE-TR-044-1, IMN, Consulting Engineers.
Gong, Q.M. and Zhao, J. (2009), "Development of a rock mass characteristics model for TBM penetration rate prediction", **46**(1), 8-18.
Graham, P.C. (1976), "Rock exploration for machine manufacturers, in exploration for rock engineering", *Proceedings of the Symposium*, Ed. Bieniawski, Z.T., **1**, Johannesburg, Balkema.
Hassanpour, J., Rostami, J. and Zhao, J. (2011), "A new hard rock TBM performance prediction model for project planning", **26**(5), 595-603.
Hassanpour, J., Rostami, J., Khamechian, M., Bruland, A. and Tavakoli, H.R. (2009), "TBM performance analysis in pyroclastic rocks, a case history of Karaj Water Conveyance Tunnel (KWCT)", *Rock Mech. Rock Eng. J.*, **43**(4), 427-445.
Hughes, H.M. (1986), "The relative cuttability of coal measures rock", *Min. Sci. Technol*., **3**, 95-109.
Innaurato, N., Mancini, A., Rondena, E. and Zaninetti, A. (1991), "Forecasting and effective TBM performances in a rapid excavation of a tunnel in Italy", *Proceeding of 7th International Congress on Rock Mechanics*, Aachen, Germany.
Khademi Hamidi, J., Shahriar, K., Rezai, B. and Rostami, J. (2010), "Performance prediction of hard rock TBM using Rock Mass Rating (RMR) system", *Tunnel. Underg. Space Technol.*, **25**(4), 333-345.
Ozdmir, L. (1977), "Development of theoretical equations for predicting tunnel borability", Thesis, Colarado School of Mines: Golden, CO, USA.
Palmstrom, A. (1995), "RMi a rock mass characterization system for rock engineering purposes", PhD Thesis, Olso University, Noreay.
Ramamurthy, T. (2008), "Penetration rate of TBMs", *Proc. Word Tunnel Congress*, India.
Ramezanzadeh, A., Rostami, J. and Kastner, R. (2004), "Performance prediction models for hard rock tunnel boring machines", *6th Iranian Tunnel Conference*, 15.
Rostami, J. and Ozdemir, L. (1993), "A new model for performance prediction of hard rock TBM", *Proceedings of the Rapid Excavation and Tunneling Conference*, Chapter 50, Boston, MA, USA.
Roxborugh, F.F. and Phillips, H.R. (1975), "Rock excavation by disc cutter", *Int. J. Rock Mech. Min. Sci.*, **12**, 361-366.
Sanio, H.P. (1985), "Prediction of the performance of disc cutters in anisotropic rock", *Int. J. Rock Mech. Min. Sci. Geomech. Abs.*, **22**(3), 153-161.
Sapigni, M., Berti, M., Bethaz, E., Busillo, A. and Cardone, G. (2002), "TBM performance estimation using rock mass classifications", *Int. J. Rock Mech. Min. Sci.*, **39**, 771-788.
Sato, K., Gong, F. and Itakura, K. (1991), "Prediction of disc cutter performance using a circular rock cutting ring", *Proceedings 1st International Mine Mechanization and Automation Symposium*, June, Colorado School of Mines, Golden Colorado, USA.
Shin, J.H. (2008), "Numerical modeling of coupled structural and hydraulic interactions in tunnel linings", *Struct. Eng. Mech.*, **29**(1), 1-16.
Taromi, M., Eftekhari, A., Khademi Hamidi, J. and Aalianvari, A. (2017), "A discrepancy between observed and predicted NATM tunnel behaviors and updating: a case study of the Sabzkuh tunnel", *Bull. Eng. Geol. Environ.*, **76**(2), 713-729.
Yagiz, S. (2006), "A model for the prediction of tunnel boring machine performance", *IAEG2006*, 383.
Yagiz, S. (2008), "Utilizing rock mass properties for predicting TBM performance in hard rock condition", Pamukkale University, Turkey, Tunneling and Underground Space Technology.
Zhou, X., Hu, H., Jiang, B., Zhou, Y. and Zhu, Y. (2016), "Numerical analysis on stability of express railway tunnel portal", *Struct. Eng. Mech.*, **57**(1), 1-20.

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