A model for the prediction of tunnel boring machine performance

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Abstract: A key factor in the successful application of a Tunnel Boring Machine (TBM) in tunnelling is the ability to develop accurate penetration rate estimates for determining project schedule and costs. Rate of penetration (ROP), defined as the distance the machine advances in a given time in rock, is a complex process that not only depends upon intact and rock mass properties (strength, fractures, and texture of rock) but also machine specifications including thrust and torque requirement. The Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM) has developed a model to predict the performance of TBM in hard rock conditions. The model is primarily based on intact rock properties and machine specification. Although the model has proven reliable in massive rock conditions, its accuracy has been limited in brittle rocks exhibiting a high degree of fracturing. Therefore, this research was conducted to investigate the effect of rock mass fracture and brittleness on TBM performance. In order to accomplish the goal, extensive mapping of the tunnel was conducted to make a record of the joints and fractures along the 16-kilometer long Queens Water Tunnel in New York City. A large number of cores were taken from inside the tunnel where rock exhibited varying degrees of fracturing to conduct geomechanical tests including uniaxial compressive strength, tensile strength, and punch penetration tests. Additionally, the field TBM data from the tunnel was analysed in detail. Consequently, the data collected for the machine, rock properties and geology were then subjected to a multiple regression analysis together with the basic penetration rate derived from the existing model. As a result of this research, a new model was proposed for TBM performance prediction.

Résumé: Un facteur principal dans l'utilisation réussie d'une aléseuse de tunnel (TBM) dans le perçage d'un tunnel est la capacité de développer des évaluations précises de taux de pénétration pour déterminer le programme et les coûts de projet. Le taux de pénétration définissant comme une distance que la machine avance dans un temps donné dans la roche est un processus complexe qui dépend non seulement au moment intact et les propriétés de masse de roche (force, ruptures, et la texture de la roche) mais usinent également des caractéristiques comprenant la condition de poussée et de couple. L'institut de mécanique de la terre (EMI) de l'école du Colorado des mines (CSM) a développé un modèle pour prévoir l'exécution de TBM en état dur de roche. Le modèle est principalement basé sur les propriétés de roche et les spécifications intactes de machine. Bien que le modèle ait prouvé fiable en états massifs de roche, son exactitude a été limitée dans les roches fragiles montrant un degré élevé de rupture. Par conséquent, cette recherche a été conduite pour étudier l'affectation de la rupture et de la fragilité de la masse de roche sur l'exécution de TBM. Afin d'accomplir le mais tracer étendu du tunnel a été conduit pour noter les joints et les ruptures le long du 16-kilometer longtemps les Reines arrosent le tunnel à New York. Un grand nombre de noyaux ont été pris de l'intérieur du tunnel où la roche a montré des degrés variables de rupture pour effectuer les essais geomechanical comprenant la résistance à la pression uniaxiale, résistance à la traction, et essais de pénétration de poinçon. En plus, les données du champ TBM du tunnel ont été analysées en détail. En conséquence, la machine rassemblée, la roche et les données géologiques ont été alors soumises à une analyse de régression multiple ainsi que le taux de pénétration dérivé du modèle existant. En raison de la recherche, un nouveau modèle est purposed pour la prévision d'exécution de TBM.

Keywords: Excavations, rock mechanics and tunnels

INTRODUCTION

The key parameters for the TBM tunnel project are intact and rock mass properties and also machine specifications. The Colorado School of Mines (CSM), Earth Mechanics Institute (EMI), developed the CSM model for TBM performance prediction over the course of 25 years. To establish the detailed database for the development of the model, EMI has collected extensive field data and conducted full-scale laboratory cutting tests to serve as a basis for model development and validation. This data collection effort was complemented by extensive theoretical analysis of rock failure under the action of TBM cutters. All these efforts successfully led to the development of the initial formulation of the CSM model in late 1970s by Ozdemir. Subsequently, Rostami and Ozdemir (1993) modified the model in the early 1990s. At the CSM, an empirical modified CSM model has been developed for describing rock fractures and brittleness and quantifying their effect on TBM performance. Incorporating these adjustment factors into the existing CSM model basic penetration rate has led to more accurate TBM performance prediction for given rock conditions (Yagiz, 2002). This paper is based on the geotechnical study that was performed at the CSM and the field data gathered from 16-kilometer Queens water tunnel, which was excavated in fractured hard rock by using High Power TBM in the City of New York.

BACKGROUND

Several models have been introduced over the years for prediction of TBM performance. The TBM performance prediction models are mostly based on an empirical or a semi-theoretical approach. The interrelationship between cutter wear, machine operation, continuous mucking, and support installations requires an evaluation of many factors affecting TBM performance. Tunnel boring is a complex process and it is difficult to account for all rock properties in a single formula. The rock cutting process involves the indentation of a rock surface by a cutting tool as it is driven forward, leaving behind it a groove and fractured and crushed rock.

All mechanical rock-cutting tools share the same principles and, consequently, many efforts have been made to develop performance prediction models and theories offering explanations into the force-penetration behavior of rocks (Roxborough (1975), Ozdemir (1977), Cook *et al.* (1984), Sanio (1985), Snowdon *et al.* (1983), Peng *et al.* (1989)). The analytical solution for indentation of mechanical tools into the rock begins with an analysis of stress in an elastic media under the point load. Swain and Lawn (1975) provided the most comprehensive description of indentation fracture in rock to express the fracture phenomenon in rock cutting. Paul and Sikarski (1965) proposed a theoretical model for wedge penetration, omitting the crushed zone occurrence phase and emphasizing the brittle chip occurrence phase for brittle isotropic rock. Wijk (1982) modified Paul and Sikarski's proposal to account for the interaction between penetrations. Cook *et al.* (1984) performed a series of acoustic emission tests to observe crack growth in hard rock loaded by an indentor. Graham (1976), Farmer and Glossop (1980), Snowdon *et al.* (1983), and Sanio (1985) achieved strong correlations between rock compressive strength and the specific energy defined as the amount of energy needed to excavate a unit volume of rock. The influence of joints and planes of weakness were examined by Roxborough (1975), Ozdemir and Miller (1978), Sanio (1985), and Sato *et al.* (1991). 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."

Tarkoy (1987) developed an empirical relationship between total hardness and TBM rate of penetration. Cassinelli *et al*. (1982) used a rock structure rating (RSR) system for correlation with TBM performance. Nelson (1983) studied TBM performance at several tunnelling projects mainly in sedimentary rock formations by comparing the instantaneous penetration rate achieved with different rock properties. Aeberli and Wanner (1978) studied effects of schistosity on TBM performance. Barton (1999, 2000) reviewed a wide range of TBM tunnels to establish the database for estimating rate of penetration, utilization and advance rate of TBM. In order to estimate the TBM penetration rate, Barton slightly modified the existing Q rock classification system and produced a new equation, defined as Q_{TBM} that was used for estimating rate of penetration.

The Norwegian Institute of Technology (NTNU) has developed a comprehensive empirical performance prediction model that considers intact rock and rock mass properties as well as machine parameters (Lislerud, 1988; Bruland, 1999). In the model, the machine specifications (including cutter size, type and number, machine thrust and torque requirements) along with laboratory measured indices, (drilling rate index, brittleness index, and cutter life index), and rock fracture data, are used to estimate the rate of penetration (Norwegian Institute of Technology, 1995).

CSM has developed a semi-theoretical model, based on the measurement and evaluation of the cutting forces on an individual cutter (Ozdemir, 1977). Rostami and Ozdemir (1993b, 1993c). They improved this model theoretically by estimating cutting forces as a function of intact rock properties, including uniaxial compressive and tensile strength of rock, and the cutter geometry. The shortcoming of this model was that it did not quantitatively consider rock mass properties, including planes of weakness, fracture orientations and rock brittleness. Yagiz (2001, 2002) modified the CSM model by adding brittleness of intact rock and fracture properties of rock masses as indices into the model.

DATABASE DEVELOPMENT FOR THE MODELLING

As mentioned previously, the semi-theoretical model developed by CSM is mostly based on intact rock strength, expressed as uniaxial compressive and tensile strength. In order to render the CSM predictor model more accurate in predicting TBM performance, particularly in fractured rock mass conditions, the model was modified and developed by accommodating the rock mass fracture properties and orientations, and the rock brittleness as additional quantitative indices into it. In order to obtain these objectives, extensive geotechnical and mechanical field data from a 16-kilometer hard rock tunnel in New York City was collected and analysed in detail to examine the influence of various rock mass properties and brittleness on TBM performance. The following are the main results from the geotechnical and mechanical investigations, which were used as input parameters for the model development.

Geotechnical investigation

In order to investigate engineering rock properties that affect TBM performance and to establish a database, an intensive rock coring, sampling, and testing programme was conducted both in the field and in the laboratory. Intense rock sampling was undertaken at 151 points along the tunnel where fractures comprising faults, shear zones, and joint sets were encountered. Using these data, correlations between rock mass and intact rock properties and TBM penetration rate could be developed. After rock cores were retrieved and logged in detail, rock samples were prepared for testing according to ASTM and industrial standards. Uniaxial compressive strength (UCS), Brazilian tensile strength (BTS) tests were conducted for each station along the tunnel where fractures were encountered according to ASTM (American Society for Testing and Materials, 1995) D3967 and D4543 respectively. Punch penetration tests as used for investigation of intact rock brittleness, were performed according to recommended industrial standards (Dollinger, et al. 1998; Atlas-Copco-Robbins, 1995).

Along the tunnel alignment, fractures, faults and shear zones were observed and orientation and fracture conditions were quantified for use in the database. The alpha angle that fractures make with tunnel axis, expressed as a function of fracture orientation and tunnel direction was calculated as follows:

$\alpha = \arcsin(\sin \alpha_f - \sin(\alpha_t - \alpha_s)$

Where α_s is the strike and α_f is the dip of the fracture; and α_t is the bearing of the tunnel axis. Fracture class designation has been used for fracture classification in terms of spacing for database development in Table 1. Developed intact and mass rock properties part of the database was given in Table 2.

Table 1. Fracture class designation with corresponding spacing of fracture (modified from Bruland, 1999)

Rock class	Fracture spacing	Description
O	Greater than 1.60 m	Totally massive rock interval with few joints or fissures. Seldom found in complexly deformed terranes except for granoblastic metamorphic rocks and equiangular, crosscutting igneous rocks. Fracture spacing must be greater than 1.60m
O - I	1.60 m	Massive rock interval with fracture spacing of 1.60m
I-	0.80 m	Relatively massive rock interval with fracture spacing of 0.80m
I	0.40 m	Fractured rock interval with fracture spacing of 0.40m
II	0.20 m	Well fractured rock mass with fracture spacing of 0.20m
III	0.10 m	Highly fractured rock mass with fracture spacing of 0.10m
IV	0.05 m or less	Highly brecciated with closely spaced anastomosing fractures exhibiting spacing of 0.05m or less. Commonly associated with zones of stress relief, fault breccia, and fault gouge.

Table 2. An example of intact and mass rock data collected along the tunnel

Stations (m)	Tunnel Bearing (deg)	UCS (MPa)	BTS (MPa)	Brittleness Index -	Orientation		Fracture Class Designation	Fracture Spacing (m)	Alpha Angle (degree)
					Strike (deg)	Dip (deg)			
269	N47E	200	9.3	4.95	N20E	68SE	I-	0.80	25
280	N47E	199	9.3	4.95	N22E	58SE	O-I	1.60	21
301	N47E	199	9.1	4.95	N25E	68SE	O	>1.60	20
473	N47E	190	9.0	5.02	N48W	42SW	II	0.20	42
600	N47E	189	9.0	5.02	N05W	54NE	O	>1.60	40
929	N47E	168	9.8	5.17	N57W	34SW	O-I	1.60	41
989	N47E	174	9.9	5.20	N88W	55NE	O	>1.60	35
1021	N47E	178	10.1	5.17	N19W	74NE	I	0.40	61
1026	N47E	181	10.1	5.15	N08W	86NE	II	0.20	55
1045	N47E	184	10.2	5.12	N23W	54SW	I	0.40	49

TBM field data analysis

The TBM operational data for the Queens Tunnel was analysed and evaluated for the entire length of the tunnel where the fractured rock mass was encountered. All data derived from the control system of the machine was recorded on a standard personal computer (PC), which was connected to the control system via modems, or via a local connection; logging was done automatically. The data was stored on the PC hard drive, which could then be printed in text or graphical form. The data was easily accessible for analysis by another program, such as a spreadsheet or a database program. Separate daily files, in which the pertinent variables were stored, were created on the hard drive. In order to analyse the TBM field data, an Excel macro program was written to open the two daily raw data files and retrieve the data according to the shift schedule. As a result of data evaluation, the average of penetration rate, total thrust, cutterhead power, cutterhead torque, and cutter load was calculated (Table 3).

Table 3. An example of TBM field data for Queens Water Tunnel

Stations (m)	TBM Field Performance and Power				TBM Field Penetration Rate	
	Thrust (ton)	Cutter Load (ton)	Torque (ton-m)	Cutterhead Power (HP)	(m/hr)	(mm/rev)
269	1511	30	99	1150	2.19	0.43
280	1535	30	102	1187	2.12	0.41
301	1512	30	95	1106	1.88	0.37
473	1587	32	136	1580	2.81	0.55
600	1685	34	149	1728	2.20	0.43
929	1725	35	132	1533	2.37	0.47
989	1783	36	162	1884	2.34	0.46
1021	1429	29	140	1628	2.90	0.57
1026	1737	35	172	1998	3.04	0.60
1045	1586	32	181	2098	3.07	0.60

Evaluation of the existing CSM model

The CSM Earth Mechanics Institute (EMI) developed the CSM model for TBM performance prediction over the course of 25 years. To establish the detailed database for the development of model, EMI has collected extensive field data and conducted full-scale laboratory cutting tests to serve as a basis for model development and validation. This data collection effort was complemented by extensive theoretical analysis of rock failure under the action of a TBM cutter.

A database of measured cutting forces using disc cutters in different rock types has been developed and continuously updated at the EMI (Rostami, 1991). The Linear Cutting Machine (LCM) full-scale test was used for establishing this database for a variety of rock types. LCM tests were accompanied by physical property testing of the same rocks to measure the uniaxial compressive and Brazilian tensile strength of the samples.

The database was initially used to derive formulas for cutting forces. The data was collected including spacing between cuts, penetration rate, cutter diameter and tip width, compressive, and tensile strength of rock to calculate individual cutter load so that the normal force acting on the rock surface could be calculated. Multiple variable regression analysis was performed to find the best combination of parameters to develop a relationship between the cutter load and the input parameters. As a result of findings, formulas of TBM performance prediction in the model are as follow.

$$F_n=8.76.T^{0.8}.R^{0.79}.\phi^{0.6}.S^{0.28}.\sigma_c^{0.63}.\sigma_t^{0.2}$$

$$\phi=Cos^{-1}((R-p)/R)$$

$$P^o=C.T^{-1/6}.R^{-1/6}.\phi^{-1/3}.S^{1/3}.\sigma_c^{2/3}.\sigma_t^{1/3}$$

$$F_n= (T.R.P^o/\phi).(1-Cos\phi)$$

$$F_r=(T.R.P^o/\phi).(1-Sin\phi)$$

$$T_h=\Sigma F_n.n$$

$$T_r = \Sigma F_r.R=0.3.D_c.F_r$$

where; F_n is the normal force in pounds, S is the spacing between the cuts in inches, p is the penetration in inches, P^o is the base pressure in the crushed zone at the point underneath cutter, σ_t and σ_c is the Brazilian tensile strength and the uniaxial compressive strength in pounds per square inches respectively, T is the cutter tip width, D_c is the cutter diameter and R is the cutter radius in inches.

After that, calculating the maximum rotational speed (RPM) is governed by the diameter of the cutter and the power (P_c) requirement of the cutter head as follows:

$$RPM=(V_{max}/\pi.D_c)$$

$$P_c=T_r.RPM$$

With all these parameters fixed in a certain rock type using a specific TBM, penetration (p) is the only unknown variable that can be increased until maximum thrust, torque or power is reached. Obviously, maximum thrust (T_h), torque (T_r) and power (P_c) of the machine for rock cutting are known. Therefore; from known parameters and formulas, rate of penetration can be calculated by using iteration method.

In the model, all the input parameters and result output can be either in English or SI units. However, the best results can be achieved using the English unit system since the original equation of the model was based on English units, which can be converted to SI units as required. Typical existing TBM performance prediction model output is given in Table 4.

Table 4. An example of the existing CSM performance prediction model output

Stations (m)	TBM Field Performance and Power				CSM-Model Penetration Rate	
	Thrust (ton)	Cutter Load (ton)	Torque (ton-m)	Cutterhead Power (HP)	(m/hr)	(mm/rev)
269	1511	30	99	1150	2.98	0.58
280	1535	30	102	1187	3.12	0.61
301	1512	30	95	1106	2.98	0.58
473	1587	32	136	1580	3.34	0.65
600	1685	34	149	1728	3.34	0.65
929	1725	35	132	1533	3.34	0.65
989	1783	36	162	1884	3.34	0.65
1021	1429	29	140	1628	2.50	0.49
1026	1737	35	172	1998	3.34	0.65
1045	1586	32	181	2098	3.34	0.65

Database establishment and statistical approach

In order to modify the existing TBM performance prediction model, intensive field and laboratory research was conducted at the EMI for analysing the affect of fractures and brittleness of the rock on TBM performance. In the

USA, the Queens Water tunnel in New York City was investigated from both a mechanical and geotechnical point of view to identify the influence of the rock fractures and brittleness feature of rocks on the TBM performance.

After completing the geotechnical site investigation, geomechanical laboratory testing and TBM field data analysis was undertaken in order to obtain the relationship between the parameters (including spacing of fractures, alpha angle that fractures makes with tunnel axis and rock brittleness). These, taken together with TBM field penetration rate and the existing CSM predictor model basic penetration rate allowed the establishment of the database. This database was used for developing a modified penetration rate equation and adjustment factors including fracture and brittleness indices to improve the accuracy of the model specifically for fractured rock conditions. As mentioned previously, the existing model could not accept input parameters appropriate to the rock fractures and brittleness properties that are two of the main effects on TBM performance in the field.

One of the• commercial software packages for standard statistical analysis was used to perform the multiple variable regressions among the rock and machine parameters in the database. Actually, the relationship achieved between the variables is a linear function. In other words, the program finds the best-fit regression between the parameters in a linear combination, as follows:

$$F = f(x_1, x_2, \ldots) = a_1.x_1 + a_2.x_2 + \ldots$$

where:
F = Objective parameter
$x_1, x_2, \ldots$ = Independent variables
$a_1, a_2, \ldots$ = Calculated coefficients

The non-linear relationships between the parameters can be determined by defining a new set of variables (new columns) in the program from the original set of variables. For example, a new variable x_j can be empirically defined as a function of the original parameter x_i ($x_j = f(x_i)$). This allows defining other parameters in various forms, such as polynomials, exponential, and logarithmic functions of the original parameters. In order to determine the correct power or constant coefficients to be used for each variable in an equation, the new variables can be set to different powers of the original parameters (*e.g.* instead of using x_i, its square or square root is used). An alternative to this method is logarithmic analysis, using the logarithm of each parameter in a linear relationship. This allows for obtaining the correct power for each parameter using the characteristics of logarithmic function. Altogether, use of the logarithmic method allows the development of several combinations of parameters in different mathematical forms. In order to develop the best linear relationship between the parameters and the objective parameters, input parameters need to be defined as they are or as functions of logarithms. Using the regression analysis, the following equation was developed, relating the field penetration rate to rock mass properties, rock brittleness and the basic penetration rate provided by the CSM model. Thus, the predictor equation is:

$$ROP = 0.859-0.0187.F_s+1.44.Log(\alpha)+0.0157.P_s+0.0969.CSM_{(b\text{-}rop)}$$

where, F_s is the spacing between the fractures in inches, Ps is dimensionless, $CSM_{(b\text{-}rop)}$ is the CSM model basic rate of penetration in ft/hr, and α is the alpha angle in degree.

In the equation, the variables were then grouped according to their representative parameters. Spacing of fracture and alpha angle that tunnel axis makes with plane of weakness or fractures was taken as rock fracture index (RFI) since both of them are rock fracture properties. Peak slope (P_s) calculated from punch penetration tests was named as brittleness index (BI) with a constant coefficient so that the adjustment could be made in the model according to these indices. The regression coefficient achieved for this equation is 82%. As a result, RFI and BI are formulated as follows:

$$ROP = 0.859-RFI+BI+0.0969.CSM_{(b\text{-}rop)}$$

where 0.859 is a constant coefficient, $RFI = 1.44.Log(\alpha)- 0.0187.F_s$ and $BI = 0.0157.P_s$.

The achieved equation was introduced as a function of TBM specification including machine thrust and torque, machine power, cutter diameter, cutter tip width, depth and spacing between the cuts; intact rock properties including uniaxial compressive and Brazilian tensile strength, brittleness index; and also rock mass properties including spacing of fractures and fracture orientation.

Influence of rock properties on TBM performance

It is widely considered that the uniaxial compressive strength of the rock is the most significant parameter for TBM performance estimation. However, if the rock mass is heavily fractured and has significant shear zones, intact rock strength alone is insufficient for reliable performance estimation since it is not representative of rock mass properties. Thus, machine performance prediction on this basis would differ significantly from observed performance. In this research, special attention was given to rock mass properties and their influence on the performance of TBM since the machine performance could be influenced by rock mass strength, fractures properties of rock mass and rock brittleness with machine specification.

As a result of the statistical analysis among the variables that were evaluated for performance prediction, it is observed that the rock fracture properties and brittleness behaviour of the rock are two main parameters that control TBM performance in rock masses. Correlation and effect of RFI and BI on TBM performance are shown in Figure 1 and 2 below respectively. After the formula was adjusted with these two indices, achieved regression coefficient (r) between field TBM performance and predicted ROP that achieved from the modified model was 0.82 (Figure 3).

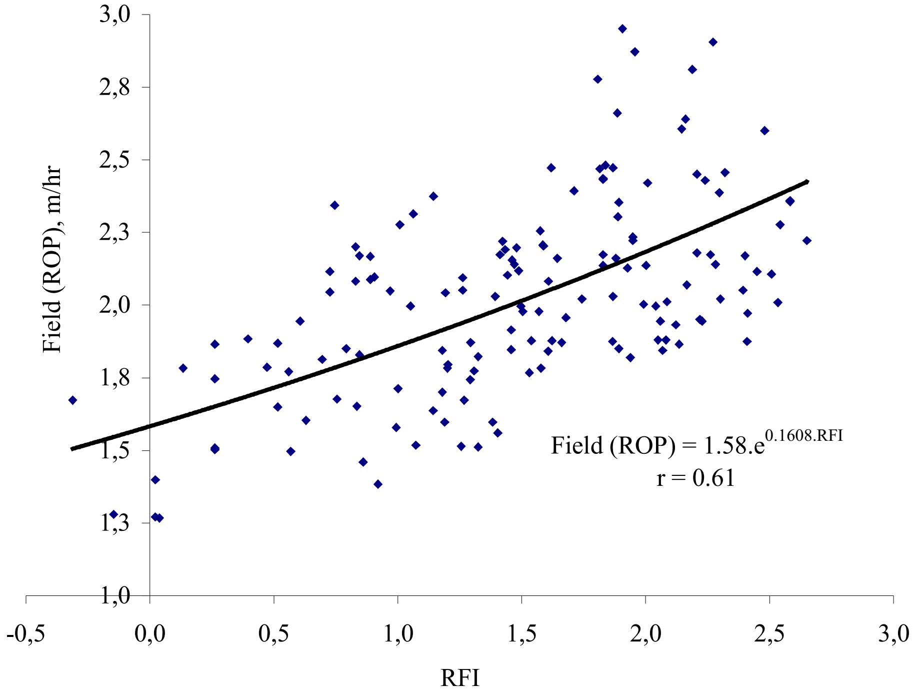

Figure 1. Relationship between RFI and field penetration rate

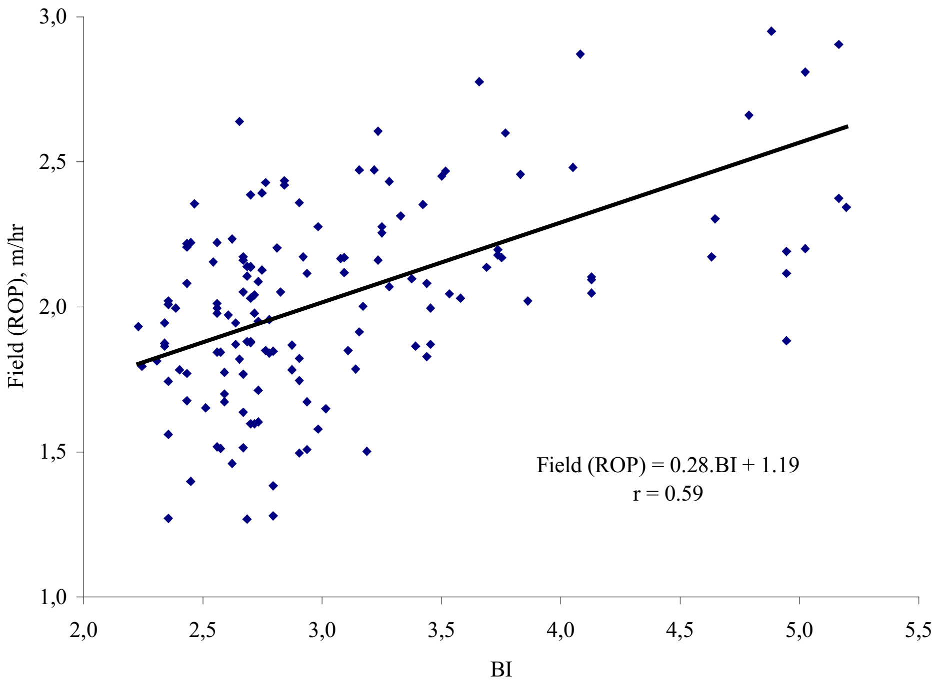

Figure 2. Relationship between BI and field penetration rate

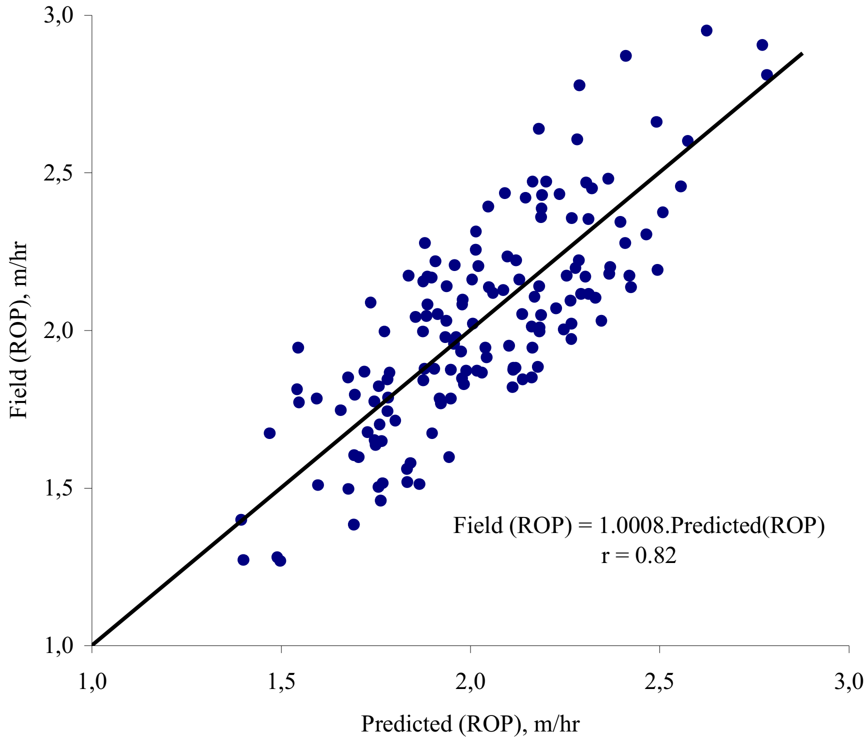

Figure 3. Relationship between field penetration rate and predicted penetration rate (Yagiz, 2002)

THE MODEL FOR TBM PERFORMANCE PREDICTION

The modified model input parameters are composed of machine parameters, together with intact and rock mass parameters (Figure 4). The model concept and the incorporation of developed equations (for RFI and BI) into the CSM model is described below.

The modified model is developed in Microsoft Excel macro media. The normal forces (F_n) are all in a column and their summed value represent the machine thrust requirements into the model. In the same manner, the rolling forces (F_r) are estimated and listed in another column. The rolling force, combined with the radial distance of each cutter from the centre of the cutter head, determines the torque required to overcome the rolling resistance for that position. The sum of individual torques for the cutters is the cutter head torque requirement. This value, together with the rotational speed of the cutter head (rpm) is then used to calculate the cutter head power requirements. Cutters are individually programmed in subsequent rows, with each row representing one cutter and containing the required information for that cutter. The positions of the cutters on the cutter head are defined by simple geometrical parameters, such as spacing, which determine their distance from each other and, therefore, the radius of each cutter from the center, its angular position (in a polar coordinate system), and the tilt angle, which is the angle between the disc and the tunnel axis. Thus, the cutter head geometry is defined in a polar coordinate system.

The model can be used to estimate TBM performance in one rock type (Figure 5) or for a condition where several rock types may be present in the tunnel face and intact rock data sheet was given in Figure 6. First, the rock mass fracture data (spacing and orientation of fractures) and tunnel bearing is entered into the spreadsheet. The Alpha angle (α) is then calculated as a function of tunnel bearing and fracture orientation. RFI was calculated as a function of the alpha angle and the fracture spacing (Figure 7). BI was calculated as a function of punch penetration tests results. Taking the TBM specification and rock property data, the model then performs all the necessary calculations using the force-penetration algorithms and adjustments.

The model accomplishes the required calculations using an iterative approach. It starts from a low penetration rate and gradually increases it until one or more machine specifications reach their limits (including thrust, torque, power requirement) (Figure 8). It then records the corresponding penetration rate as the maximum achievable penetration rate for a given rock type. The same procedures are followed for all other rock types to be encountered in the tunnel. All predicted results, including penetration rate, TBM thrust, torque and power used for obtained penetration rate, specific energy and average cutter cost, are then summarized and listed in a spreadsheet (Figure 9).

CONCLUSIONS

The CSM model was modified for performance prediction of fractured hard rock tunnelling machines by quantifying the rock fracture features and brittleness of intact rock as adjustment factors in the model. As a result of the research, the effects of rock strengths including uniaxial compressive and Brazilian tensile strength, rock brittleness and rock mass fracturing were evaluated and the following results were achieved.

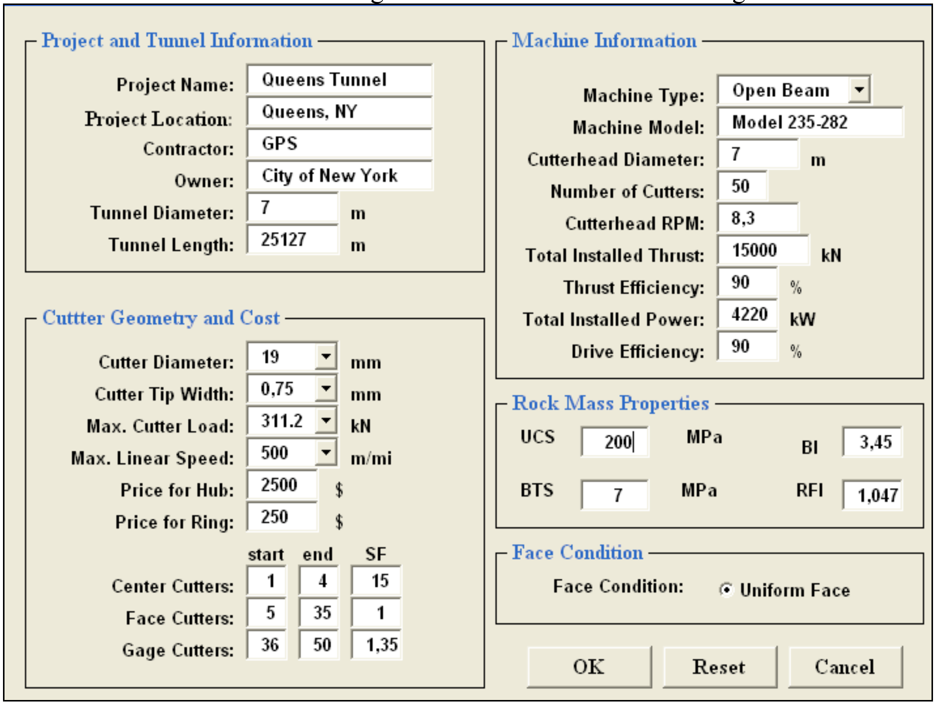

Figure 4. Input data for modified CSM predictor model

TUNNEL FACE CONDITION

Go to Intact Rock Properties

Cutterhead Diameter :		7,00	m	
		7000	mm	
Deflection for Rock Boundaries :		0	deg	
Face 1 :	Azimuth :	113,83	deg	
		246,17	deg	
	Boundary :	113,83	-1413,90	3201,70
		246,17	-1413,90	-3201,70
		Total Area :	38.484.510	mm^2
	% of the Partial Area :		25,0%	
		Partial Area :	9.621.128	mm^2
	Calculated Partial Area :		9.621.128	mm^2
Face 2 :	Azimuth :	90,00		
		270,00		
	Boundary :	90,00	0,00	3500,00
		270,00	0,00	-3500,00
		Total Area :	38.484.510	mm^2
	% of the Partial Area :		25,0%	
		artial Area :	9.621.128	mm^2
	Calculated Partial Area :		9.621.128	mm^2
Face 3 :	Azimuth :	66,17		
		293,83		
	Boundary :	66,17	1413,90	3201,70
		293,83	1413,90	-3201,70
		Total Area :	38.484.510	mm^2
	% of the Partial Area :		25,0%	

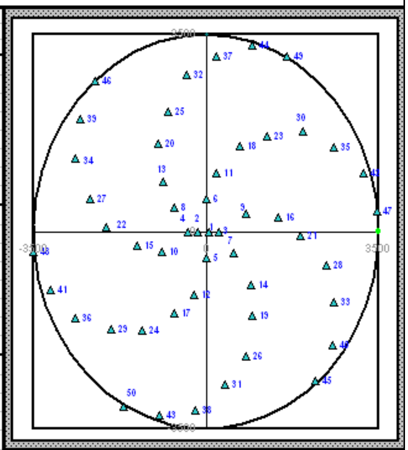

Figure 5. Spreadsheet for input parameters of tunnel face condition

INPUT DATA FOR INTACT ROCK PROPERTIES

Go to Rock Mass Properties

Geological Information			Intact Rock Properties			Disc Parameters
Geological Formations #	Stations (m)	Rock Type	Compression UCS (Mpa)	Tensile BTS (Mpa)	Abrasivness CAI	Cutter Ring/Hub Ratio
1	269	Metamorphic	215	10	3,5	5
2	280	Metamorphic	230	7	4,4	5
3	301	Igneous	180	8	4,6	5
4	473	Dyke	210	6	3,9	5

Figure 6. Spreadsheet for input parameters of intact rock properties

INPUT DATA FOR ROCK MASS PROPERTIES											
"ROCK FRACTURE & BRITTLENESS INDICES" (RFI & BI)										Go to ROP	
Tunnel	Tunnel	FRACTURE ORIENTATION		INPUT PARAMETERS					Alpha	Rock	Brittlenes
Stations	Bearing	Strike	Dip	T. Bearing	Strike	Dip	Peak Slope	Fs	Angle	Fracture	Index
(m)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	Index	(cm)	(deg)	Index	
269	N47E	N31W	36SW	47	149	36	200	160	35	1,05	3,14
280	N47E	N35E	90	47	35	90	172	160	12	0,38	2,70
301	N47E	N15W	44SW	47	165	44	172	80	38	1,68	2,70

Figure 7. Spreadsheet for input raw data and output for rock mass properties and brittleness behaviour of the rock

MACHINE PERFORMANCE EVALUATION			
Machine Thrust :	O.K.	90%	of machine thrust used
Machine Torque :	O.K.	100%	of machine torque used
Machine Power :	O.K.	100%	of machine power used
Cutter Load Capacity:	O.K.	90%	of max. cutter load used
ROP Limit:	O.K.	52%	of ROP Limit used
			See Model Result
Basic Penetration Rate:	**0,116**	*mm/rev*	
Rate of Penetration:	**1,900**	*m/hr*	Calculate ROP
"Maximum ROP controlled by	*Machine Power*		Save Result
	1		

Figure 8. Calculated rate of penetration from the modified CSM model

PREDICTED MACHINE PERFORMANCE							
						Return to Project	
PROJECT INFORMATION			TBM SPECIFICATIONS				
Project Name:	Queens Tunnel		Machine Type:	Model 235-282		Total Installed Thrust:	15.000 kN
Location:	Queens, NY		Cutterhead Diameter:	7,00	m	Thrust Efficiency :	90%
Contractor:	GPS		No. of Cutters:	50		Net Thrust:	13.500 kNm
Owner:	City of New York		Cutterhead RPM:	8,3	rpm	ax. Cutterhead Torque:	4.857 kNm
Tunnel Diameter:	7,15	m	Cutter Type:	Disc Cutter		Drive Efficiency:	90%
Total Length:	25127	m	Cutter Diameter:	19	mm	let Cutterhead Torque :	4.371 kNm
Area:	40	m2	Cutter Tip Width:	0,75	mm	Total Installed Power:	4.220 kW
			Face Cutter Spacing:	86	mm	Net Cutterhead Power:	3.798 kW
			Maximum Cutter Load:	311	kN	ROP Limit :	25 m/hr

	Rock Properties			ROP		Average Forces		TBM			Average Cutter Life		Average	
Stations	UCS	BTS	CAI			Normal	Rolling	Thrust	Torque	Power			Cutter Cost	Specific Energy
(m)	MPa	MPa		mm/rev	m/hr	kN	kN	kN	kNm	kW	hrs	m3/cutter	$/m3	kW-hr/m3
269	200	9	3,0	0.61	1,25	228	17	10.095	5.282	1.855	88	113	9,14	28,9
280	199	9	4,0	0,80	1,56	242	20	10.868	6.363	2.235	88	141	7,31	27,8
301	199	9	5,0	0,11	2,28	274	28	12.317	8.730	3.066	88	207	5,01	26,2
473	190	9.0	3,5	0,14	2,98	299	35	13.437	10.890	3.824	88	269	3,84	25,0

Figure 9. Summary of the modified CSM model results for the tunnel

Uniaxial compressive and Brazilian tensile strength of the rock are not sufficient on their own to estimate TBM performance since these two parameters do not represent actual rock mass strength especially for fractured rock conditions. Rock fractures in the rock mass have a major impact on TBM performance in hard rock tunnels. Widely spaced fractures oriented parallel to the tunnel axis ($\alpha = 0^{o}$) provide the least benefit to TBM performance, and closely spaced fractures oriented around 50-65 degrees to the tunnel axis provide the best rate of penetration (Yagiz, 2002). However, if the rock fractures are very close to each other then fractures provide less benefit and may reduce the TBM advance rate due to decreasing TBM utilization and increasing time required to install support. Brittleness behaviour of the rock is another main parameter which must be accounted for in estimating machine performance. The TBM penetration rate was found to increase as rock became more brittle, resulting in more efficient fracture development and chip formation. It is concluded that spacing, and orientation of rock fractures and rock brittleness can be more important than the intact rock strength for TBM performance for fractured and sheared rock condition.

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