Comparison Between CSM and NTH Hard Rock TBM Performance Prediction Models

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ABSTRACT

The important issues related to the performance and cost estimation of hard rock Tunnel Boring Machines (TBM) are presented and discussed in this paper. General approaches for performance prediction of TBM, which is one of the most popular mechanical excavators are addressed. Two of the most successful performance prediction models, namely the Colorado School of Mines (CSM) and the Norwegian Institute of Technology (NTH) models and their most recent modifications, improvements, and some recent applications are presented. A comparison is made between the results of both models in two tunneling projects.

1. INTRODUCTION.

TBMs are currently utilized in massive scale in underground construction and tunneling both in civil construction and the mining industry. In the recent years, along with the advancement of the machine manufacturing in many aspects, and rapid advances in technology as a whole, specially information and computer technologies, powerful and somewhat smart machines have been introduced in the market. These machines have generally increased productivity and set new excavation footage records. In spite of all these advancements, there seems to be a lack of complete understanding of the rock cutting process due to the very complex nature of the problem. As a result, not all the parameters affecting the rock cuttability and hence machine performance in the field are identified and their effects fully explored.

Over the years, several researches have been conducted and models developed for performance prediction of mechanical excavators. In a nut shell, they can be divided into two distinguished approaches. One is based on the cutting forces acting on the individual cutters and the other is based on the achieved performance of the machine in the field as a whole system. Each one of these approaches has its own set of advantages and disadvantages, and similarly slightly different area of application.

Table 1. contains some information about the field of application as well as the area of strength and weaknesses of these models. As can be seen, both systems have evolved to a certain level of maturity and reliability, and as will be shown later in this paper. They produce fairly close estimates on machine performance. It must be noted that this paper will be equally applicable to performance prediction of all full face machines.

2. EMPIRICAL PREDICTION METHODS, NTH METHOD

Empirical performance prediction methods are based on the historical field performance of machines in certain rock types. Typically, the models are a set of empirical graphs and equations obtained from the regression analysis between rock properties, ground conditions, machine parameters, and rates of penetration. The main significance of these methods is the fact that they naturally incorporate the effects of the ground and the excavation system as a whole in their entire complexity. This means that all the effects of ground conditions, rock properties, machine parameters, and operational and practical constraints have already been accounted for. The estimates made by these methods are more easily accepted by the operators and, within the realm of current technology, are very reliable. Meanwhile, since these methods rely heavily on the past data, their forecasting capabilities are somewhat limited by the similarity of the old and the new systems. In other words, with the speedy progression of machine technology and capabilities, the predicting ability of these models are limited.

Table 1. Summary of issues related to the two approaches to performance predictions systems.

Methodologies / Issues	Force Equilibrium Approach*	Empirical Methods **	Notes
Cutter Forces	Yes	No	
Cutter Geometry (type, shape, etc.)	Yes	No	
Cutting Geometry (spacing & penetration)	Yes	Partially	
Machine Design Issues	Yes	Partially	
Face Layout	Yes	No	
Diagnostics and Design Modifications	Yes	No	
Adaptability and the Ability to Develop New Technologies	Yes	Very Limited	
Ability to Exchange Information Between Different Excavation Systems	Yes	No	
Rock Strength and Physical Properties	Yes	Partially	
Rock Property Indices	Partially	Yes	
Ground Conditions	Indirect	Yes	
Rock Mass Properties (joints, faults etc.)	Indirect	Yes	
Performance Prediction	Yes	Yes	
Cutter Cost Estimation	Yes	Yes	
Operator Sensitivity / Judgment	No	Some	

* Based on individual cutter forces
** Based on Field Performance

Some of the most referenced methods in this group are the NTH or Norwegian method (Listrud 1988, NTH 1995, Bruland et. al. 1995.), Total Hardness method (Tarkoy 1975), and Nelson’s method (Nelson et. al. 1985). Among the above mentioned methods, the NTH method is more widely accepted and used in the industry, specially in the Europe. This method has good merits, proven to be very reliable, and being up dated frequently through the time. The model was originated with the start of the tunnel boring operations in Norway, and was continuously upgraded as more projects were completed.

The NTH model uses a group of rock parameters and indices, which were originally developed for drillability of the hard Nordic rocks. These parameters were later tied into

Table 2. Parameters used by NTH Model.

Rock Mass Properties	Machine Parameters
- Fracturing, Joints, etc. - Drilling Rate Index (DRI) - Abrasivity, CLI	- Cutter Thrust - Cutterhead RPM - Cutter Spacing - Installed Power

some standard rock properties such as uniaxial compressive strength and abrasiveness indices, etc. Table 2 shows the input to the NTH model. The basic testing and measurement starts with a set of tests as follows:

1. Brittleness test "S_{20}", which is the percent (weight %) of rock passing through 11.2 mm screen after being pounded with a 14 kg impactor 20 times from the original sample pieces (crushed and screened) between 16 mm and 11.2 mm.

2. Sievers' J index "S_J", an index determined by miniature drilling with a certain bit geometry, bit weight, and number of rotations, to measure the depth of penetration.

3. Abrasion testing "*AV*", which is a measure of the time dependent abrasion on tungsten carbide from crushed rock powder.

These indices are then used in proper charts to yield drilling rate index (DRI), cutter life index (CLI), bit wear index (BWI), and correction factors "K", which is found from the joint classes (from 0 to IV). These together with cutter load capacity and machine diameter etc. gives the estimate of base penetration (in mm/rev). This penetration is then converted to the net penetration rate (or Instantaneous Penetration Rate IPR) and multiplied by utilization gives the advance rate. Further detailed information about this model, its rock index tests, equations, and the charts can be found in the given references on NTH model.

3. CUTTING FORCE METHOD, CSM MODEL

The basic philosophy behind this method is to start from the individual cutter forces and determine the overall thrust, torque and power requirement of the entire cutterhead. The estimated values are then compared to the machine installed or available thrust and power, the maximum achievable penetration is obtained. The estimate of the cutting forces may be provided by the actual full size cutting test, which is the most reliable and accurate method, or estimated based on the available formulas. Full size cutting tests are performed in several places and in effect take all the parameters effecting the rock cuttability, such as rock strength, toughness, and cutting geometry into account. Obviously, miniature cutting tests have proved to have some shortcomings when it comes to simulating field conditions, specially when it comes to the effects of grain size. These tests are available with some minimal costs and can take the guess works out of the estimation process.

Also, the formulas developed for estimation of forces are merely based on the full size cutting tests of different cutters in various rock types. The models use some rock property values such as compressive and tensile strength and combined with cutting geometry and cutter information, they give an estimate of cutting forces, namely normal and rolling forces. Example of such formulas can be found in Roxbourogh (1979), Sanio (1986), Sato (1991, 1993), and Rostami (1991, 1993). The later one which was developed at the Colorado School of Mines, has been used in various project with a high degree of success. The original formula to estimate the total force (combination of rolling and normal) was as follows:

$$F_t = \frac{P^{o}\Phi R T}{1+\psi}$$

Where: F_t = Total or resultant force
R = Radius of cutter
T = Tip width or thickness
ψ = Constant for the pressure distribution function (typically 0.2 to -0.2 decreasing with the increased cutter tip width)
Φ = Angle of the contact between the rock and disc cutter

$$\Phi = \cos^{-1}\left(\frac{R-p}{R}\right)$$

p = Penetration per revolution
P^o = Pressure of the crushed zone, estimated from the rock strength and cutting geometry as $P^o = f(\sigma_c, \sigma_t, S, T, R, p)$.
σ_c = Uniaxial compressive strength of rock
σ_t = Tensile strength of rock
S = Spacing between the cuts.

The original formula for the pressure of the crushed zone was obtained from the regression analysis of the data available at the time and several formulas were offered in the references. Naturally, these formulas were limited in their application by the range of data that was in the data base. The limits were at the time both in the rock strength properties and cutter size and geometry. Recently, these equations were up dated with cutter sizes from 125-480 mm (5-19 in) and rock strengths from 30-250 MPa (5-40 ksi) and the range of several other parameters were extended. A new equation for the pressure of the crushed zone was derived by regression analysis of the new database. This equation, being the result of regression analysis, is not dimensionally correct if a linear or polynomial combination of variables is used. Yet, if a logarithmic regression is used, the right combination of parameters may be derived. The results of the later analysis is very close to the right dimension, which is the force over area (same as pressure or stress). In order to correct the dimension for the above formula, the pressure formula can be expressed as:

$$P^\circ = C.\sqrt[3]{\frac{S}{\Phi\sqrt{RT}}.\sigma_c{}^2\sigma_t}$$

In this formula, C is a coefficient (about 2.12) and similar to Φ (angle), it is dimension-less. The dimension of the overall formula is the same as pressure. In either case, to estimate the normal and rolling forces, the following formulas can be used.

$$F_n = F_t Cos\left(\frac{\Phi}{2}\right) \text{ and } \quad F_r = F_t.Sin\left(\frac{\Phi}{2}\right)$$

Where: F_n = Normal force
F_r = Rolling force

This is based on the assumption of a uniform pressure distribution ($\beta = \Phi/2$ angle of the resultant force from the normal) in the contact area, which has been proved to be true. The following steps to complete the performance prediction with this method are as follows:

1. Calculate the total thrust requirements as: $Th^* = \sum_1^N F_n \approx N.F_n$
2. Calculate torque as: $Tq^* = \sum_1^N F_{ri} R_i \approx 0.3.D.N.F_r$
3. Calculate rotational speed as: $RPM = \frac{V}{\pi D}$
4. Calculate power requirement of the head $HP^* = \frac{Tq^*.RPM}{5250}$.
5. Calculate installed thrust and power by using an efficiency factor η (i.e. $Th=Th^*/\eta$)

Where: D = is TBM diameter
N = Total number of cutters
V = Linear velocity limit of the cutters (i.e. 150 m/min=500 ft/min for 17" cutters)

With all the parameter fixed in a certain rock type using a specific machine, penetration is the only variable that can be increased till one of the limits is reached. In other words, the penetration rate of the machine is the maximum penetration per revolution that can be achieved within the available machine parameters. This process can be easily programmed on the computer and performance prediction summaries generated.

4. COMPARISON OF THE METHODS

The input and output of the two models have been listed in Table 3. As can be observed, the rock properties used in the CSM model are very basic common tests provided by most geotechnical reports, including compressive and tensile strength. The input to the NTH model consists of the indices related to the same rock strength parameters, but tested and measured in term of a special indices. Also, for cutter life estimates, CSM model utilizes the Cerchar Abrasivity Index (CAI) where as NTH model uses specialized abrasiveness value (AV). It can be and has been shown that these

Table 3. Input and outputs of the two Models.

	CSM Model		**NTH Model**	
	Parameter	Units*	Parameter	Units**
Input	Cutter Radius	(in)	Fracturing	Classes (0-IV)
	Tip Width	(in)		
			Brittleness	S_{20} Index
	Spacing	(in)		
			Drillability	Sievers' J Index
	Penetration	(in)		
			Abrasiveness	AV index
	Rock UCS	(psi)		
	Tensile strength	(psi)	Porosity	%
			Cutter Dia.	(mm)
	Existing TBM			
			Cutter Load	(kN)
	Diameter	(ft)		
	RPM	rev/min	Spacing	(mm)
	Num. of cutters	#		
	Thrust	(lbs)	Machine's	
	Torque	(ft-lbs)	Diameter	(m)
	Power	(hp)		
Output	Cutting Forces	(lbs)	Num. of cutters	#
	Normal-Thrust	(lbs)	RPM	rev/min
	Rolling / Torque	(lbs/ ft-lbs)	Thrust	(Ton)
	Power	(hp)	Power	(kW)
	Basic Penetration	(in/rev)	Basic Penetration	(mm/rev)
	Rate of Penet.	(ft/hr)	Rate of Penet.	(m/hr)
			Torque	(kN-m)
	Head Balance	force/moments		
	Machine spec.'s	(th, tq, hp, etc.)	Utilization	%
	Perform. Curve	Graph (rop-vs-th	Advance Rate	(m/day)
		tq-vs-th)	Cutter Life	(hr/cutter)
	Utilization	%		
	Advance rate	(ft/day)		
	Cutter Life	(hr/cutter)		

* Proper conversion in formulas and constant required for Metric system.

** Special tests and indices at NTH

parameters are interrelated. There are several graphs and charts relating these parameters together (i.e. DRI and UCS, CAI and AV & CLI, etc.). The output of the models are also listed in Table 3. The CSM model can generate a thrust-torque-penetration relationship for a certain machine, from which the penetration rate can be estimated. The NTH model, similarly, can estimate the penetration rate for a given level of machine thrust. Both models use standard utilization factors to estimate the advance rate.

The two prediction models have been compared several times with the results being very close to each other. Specifically, in intact rock where borability is not effected by joints and discontinuities the results are almost one to one. Both models have also been

Table 4. Comparison of the two models for some projects.

	Standard TBM		High Power TBM	
	CSM	NTH	CSM	NTH
Yucca Mountain				
Welded Tuff*				
- Penetration (mm/rev)	6.09	5.94	8.88	7.89
- IPR (m/hr)	2.33	2.28	3.73	3.31
- Cutter Life (m/cutter)	3.44	5.26	6.86	9.48
Stanley Canyon**			Field	
Windy Point Granite		Class I	performance	
- Penetration (mm/rev)	3.26	3.35-3.38		
- IPR (m/hr)	2.34	2.39-2.41	2.96	(Fracture
- Cutter Life (m/cutter)	NA	1.26		class II
Pikes Peak Granite				3.64 m/hr)
- Penetration (mm/rev)	3.16	3.19-3.25		
- IPR (m/hr)	2.25	2.27-2.32	2.26	
- Cutter Life (m/cutter)	NA	1.68		

* Bruland et. al. 1995,

** Deer et. al. 1995

compared to field performance of TBMs on many occasions, with high degree of success. Table 4 shows the comparison of the two models in the case of Yucca Mountain project.

As mentioned earlier, the empirical system is able to incorporate rock mass properties and ground condition directly into the predictions. The force equilibrium method is more flexible with machine design parameters and allows design modification to optimize the cutterhead layout, machine specifications, and check cutterhead balancing. There are some coordinated efforts to combine the two models into a universal system that can provide the ability to work on the machine specifications and layout using the force estimation method, and meanwhile account for the rock mass effects while running performance predictions.

5. CONCLUSIONS

The experience gained from laboratory testing of the disc cutters and field performance of TBMs has led to development of reliable performance prediction models. Among the models available today for performance prediction of hard rock TBMs, the NTH and CSM models are the most widely used in the industry. Although these models were developed on different basis, their results are very comparable. In spite of their success in most cases, the lack of a comprehensive understanding of the rock cutting process sometimes causes less accurate estimates by these models. This is where the rock shows somewhat strange cutting behavior. In any case, the most reliable source of information and performance prediction remains to be the full scale cutting test to eliminate the guess work and provide first hand information on rock cutting behavior. At the present, the CSM model can be used to estimate the basic penetration and provide the ability to improve machine design and the NTH model applied to adjust CSM estimate and incorporate the effects of discontinuities and rock mass.

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