Performance Prediction Models for Hard Rock Tunnel Boring Machines

Ahmad Ramezanzadeh,
PhD student, URGC, INSA of Lyon, France

Jamal Rostami,
Assi. professor, Dep. of Mining Eng., Univ. of Tehran, Iran

Richard Kastner,
Professor , URGC, Géotechnique, INSA of Lyon, France

Abstract. Tunnel Boring Machine (TBM) is one of the most popular tunneling equipment in the industry. Modern hard rock TBMs are very versatile and have been used very favorably in various ground conditions while setting advance rate records of over 170 m a day. There has been a lot of research on development of models to allow accurate prediction of machine rate of penetration in given ground conditions. These models, although successful in prediction of machine performance in many cases, are short of accounting for some of the parameters affecting machine performance in a variety of grounds. Moreover, with more accurate predictive capabilities and better understanding of operational parameters, accurate planning and cost estimation is possible, which allows for wider area application for TBMs. This justifies the initial high investments for the machine and facilitates increased productivity by proper planning of the back up system, matching machine specifications to the jobs site conditions, and reduces the risks involved in using a machine for a particular project.

Study and analysis of the rock cutting process by disc cutters is very important since discs are the most common cutting tools used on hard rock TBMs. The previous studies on this subject have been instrumental in developing models for estimation of rock cutting forces needed for design analysis and optimization as well as performance prediction of machines such as TBMs. This paper, offers a brief review of the previous research works in this field including an overview of rock indentation by disc cutter, failure mechanism, important parameters influencing on the performance. Also, models developed for performance prediction of hard rock TBMs based on the cutting forces will be introduced along with empirical models used for an overall estimation of the machine rate of penetration in a given ground condition. The paper will finally review the current efforts underway by the authors for improving the accuracy of the models.

1.Introduction

TBMs have become the method of choice in tunneling industry, in a variety of tunnel sizes, and ground conditions from soft ground and soil to rock tunnels. The advantages of these machines include the rapid excavation and advance rates compared to alternative methods, while offering a safe working condition. Some of the restrictive issues with application of TBMS in tunneling projects i.e. inflexibility of the machines in coping with variable ground conditions and the high capital cost of the machines have been mitigated in recent years. This was done by the new machine capabilities in working in various ground conditions and the raising cost of additional skilled labors involved in alternative methods, which not only offsets the initial cost of machines , but it increases the cost and duration of the project thus delaying its ability to generate revenue or provide intended services.

In Rock tunneling, TBMs have become a rather standard method of excavation in urban environment or tunnels longer than roughly 2000 m with a circular profile. Large size tunnels for transportation applications, with non-circular profile (i.e. horse shoe or near rectangular) which was excavated by drill and blast method, are frequently built by TBMs now a day. The additional excavation to a circular shape by a TBM is more than justified by the increased advance rates and the use of the space for ventilation and leasing for utility lines. Some recent examples of this application can be seen in projects such as Lotschberg, Gerhard, in Switzerland, and Guadarrama in Spain. Also, the uses of Double or Telescopic shields in "One Path" tunnel construction have become very popular in water tunnels. This machine allows the excavation and simultaneous installation of the segmental lining and by being protected by the shield; it allows the operators to tolerate changing and often adverse conditions.

However, successful application of a TBM in a tunneling project requires thorough investigations both on the ground conditions as well as the machine design features and the design of back up systems. On may fronts, the ability to predict the machine's rate of advance is crucial for planning of the work as well as cost estimation. Among several approaches to this issue, there are two principal sets of models developed and used in the industry. This includes the empirical models, led by the Norwegian (NTNU) model, and the cutting force methods, led by the CSM model. These models each have some points of strength and weaknesses and there are efforts underway to improve the accuracy of these models and to mitigate their deficiencies. This paper will offer a brief review of some of the previous works in this area, while offering its comments on the state of the art in performance prediction of hard rock TBMs.

2. General review of basic aspects of rock cutting with disc cutters

2.1. Disc Cutters

Disc cutters have been used on hard rock excavation machines, primarily TBMS, since mid 1950's. Early disc cutters had a V-shaped profile, which due to rapid loss of efficiency as tip wear occurred, were replaced by Constant Cross-Section (CCS) in late 1970's. CCS profiles were preferred since they could maintain their efficiency as the tip wore out. Over the years, disc cutters have significantly improved in performance as a result of the development and utilization of more wear-resistant materials, i.e. special steel that allows increased bearing capacity and a more efficient cutting edge profile.

Disc cutters have proven to be the most efficient cutting tools among the different types of cutters used in hard rock excavation by creating large chips. In operation, each disc cutter is designed to cut a kerf (Figure 1). The spacing of kerfs and their relationship to cutter penetration is a very important parameter affecting chip formation and machine performance. Disc diameter ranges from 325 to 475 mm (15 to 19 inches) with 431 mm (17 inch) cutters being the most common size used on TBMs today. Since their initial development, the 17" disc cutters have undergone extensive improvements both in their bearing design and the cutter ring material. The loading capacity of 17" cutters are typically about 260 kN/cutter with linear velocity limit of about 175 m/min. These two parameters control the amount of machine thrust and cutterhead rotational speed, RPM.

2.2. Principal aspects of disc cutting

Developing an understanding of basic principles of disc cutting is an important issue in design and performance predictions TBM. Figure 1 shows the action of the disc cutters while cutting rock. Here chips are formed by fracture propagation to an adjacent groove.

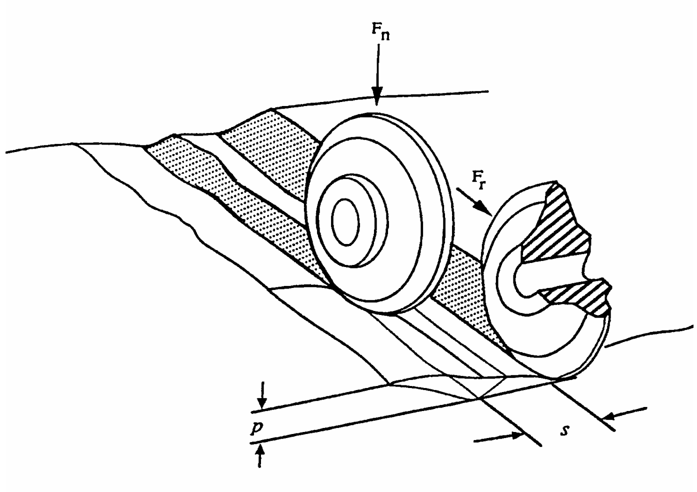

Figure 1. Disc force and geometry for kerf cutting (Nelson 1993)

The muck created in this process includes the fine materials from crushing and chips from fracture. The fines are active participants in disc wear. Typical dimensions rock chips are 5- 15 mm thickness with width on the order of spacing of grooves, and lengths one to three times the chip width. For efficient disc cutting by a TBM; several items are important including the following:

- The cutter penetration and normal force must be sufficient to generate contact stresses adequate to form a crushed zone.
- The stresses in this crushed zone must be high enough to initiate crack propagation into the less damaged surrounding rock between grooves.
- The adjacent, unloaded, groove (a free surface) and its local zone of cracked rock must be near enough so that lateral cracks from loaded groove can interact and extend to create a chip.
- There must be a disc force component adequate to maintain cutter movement, in spite of the rolling resistance or drag associated with penetration process (Nelson 1993).

2.3. Failure mechanism

The principal aspects of rock fragmentation in disc cutting are illustrated in figure 2. The high thrust allows the cutters penetrate a small distance into the rock face (1 to 10-15 mm, depending upon the strength of the rock). Very high contact stresses are developed beneath the cutter tip which results in the creation of a highly crushed zone of rock material, usually referred to as the pressure bubble. This zone generally is in a hydrostatic state of stress, producing tensile stresses along its boundary. When the stress level is sufficient to exceed the rock tensile strength, cracks are developed. When these cracks extend far enough to adjacent groove(s) or meet with cracks already developed, from adjacent cuts, chips are formed

Naturally, any rock directional properties can significantly affect the initiation and growth of cracks and the resultant chip formation. Hence, in foliated and closely bedded rock formations or where rock exhibits a preferential grain alignment and/or orientation, specific attention needs to be given to the potential impact of these features on TBM performance.

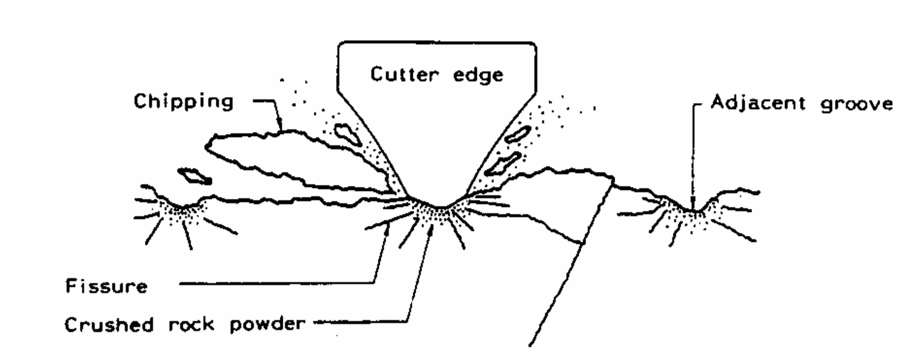

Figure 2. Failure mechanisms under the cutter edge (Ozdemir1999)

2.4. Important parameters on TBM performance

Extensive review of literature indicates that the most important parameters that would be used in TBM performance studies can be divided into two major categories as follows:

Ground Condition: This includes parameters related to intact rock characteristics and rock mass conditions, listed below:

A. intact rock characteristics:

- Intact Rock Strength(e.g. Uniaxial Compressive Strength "UCS", Brazilian Tensile Strength "BTS", Point load index "I_{50}")
- Toughness(Punch Penetration index, Fracture Toughness index)
- Hardness and drillability
- (Siever's J-value, Total & Taber hardness index, Schmidt hammer Hardness)
- Brittleness(Swedish Brittleness S20, B1= σc / σt and B2= [(σc - σt) / (σc + σt)])
- Abrasiveness indices (Cerchar "CAI" , Abrasion Value "AV")
- Others(Poisson ratio "ν", Elasticity module "E", Internal friction angle "ϕ", Porosity, grain size etc.)

B. Rock mass conditions or discontinuity:

- Discontinuity spacing "Js", RQD
- The angle between the tunnel axis and the planes of weakness (Discontinuity Dip and Dip Direction)
- Rock mass classifications such as RMR, Q and GSI.
- Other issues such as in situ stresses, Ground water conditions

TBM Operational parameters: Theses parameters could be listed as follows:

- Thrust (load per cutter)
- Torque
- RPM
- Power
- Disc specifications such as:
    1. Number of disc on cutterhead (and their spacing)
    2. Disc geometrical spec.(e.g. diameter, tip width, angle of tip)
    3. Disc mechanical spec. (e.g. maximum load capacity, allowable velocity)

From these parameters, some useful information can be calculated as follows:

- Cutting coefficient ($C_c = F_r / F_n$)
- Penetration index ($R_f = F_n / Prev$)
- Ratio of disc spacing to penetration (*s/p*)
- Critical thrust, achieving to *Prev*=1mm
- Specific energy

3. TBM Performance Prediction models

A wide variety of performance prediction methods and principles are used in different countries and by various TBM manufacturers. Some of the methods are based mainly on one or two rock parameters (for instance uniaxial compressive strength and a rock abrasion value) while others are based on a combination of comprehensive laboratory, field and machine data. In general, methods for TBM performance prediction models are classified in the following categories:

1. Theoretical/Experimental models (based on laboratory testing and cutting forces)

2. Empirical methods (based on field performance of TBMs and some rock properties)

Following is a brief review of some of these models.

3.1. Theoretical/Experimental models

Several approaches have been used for evaluation performance prediction of TBMs by different researchers. Some of the most important methods will be discussed in the following:

Cutter load approach

The most important parameters in TBM design include installed power, cutter head RPM, thrust, and disc spacing. These parameters influence the resulting penetration rate. In practice, typical disc spacing is between 60 and 100 mm. Disc rolling velocity and loading capacity determines cutterhead 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 cutterhead 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, specific energy of cutting is minimized. This occurs in S/p ratio of about 10-20 for disc cutting.

Since the mid-1950s, considerable research has been performed on the estimation of disc cutter forces. 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. Influence of joints and plane of weakness were examined by Roxborough (1975), Ozdemir and Miller (1978), Sanio (1986), Sato et al. (1991), and 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." Some of the models developed for estimation of the cutter load are discussed below.

1. Roxborough and Phillips (1975) used basic principles and cutting geometry to calculate the theoretical normal and rolling forces on a single V-shape disc cutter. This model was an early attempt to predict cutting forces and hence TBM performance. The normal force required for penetration was basically the product of the area of the disc contact against the rock surface and the compressive strength of the rock. A formula was offered to determine the normal and rolling forces from rock uniaxial compressive strength, disc diameter and penetration.

$$F_N = 4 \cdot \sigma_c \cdot \tan\frac{\phi}{2} \cdot \sqrt{D \cdot P^3 - P^4} \qquad (1)$$

Where: F_N = normal force, σ_c = uniaxial compressive strength, D = disc diameter, P = penetration, ϕ = one-half of cutter tip angle.

The rolling force is estimated as follows:

$$FR = 4 \cdot \sigma_C \cdot P^2 \cdot Tan\, \phi/2 \qquad (2)$$

Obviously, any model for estimation of cutter load must include the spacing between the cutters, which is not included in this model.

2. Sanio (1985) proposed a tensile failure model for chip formation and introduced some equations for the estimation of cutting forces, as follows:

$$F_n = 2.p.Tan\left(\frac{\alpha}{2}\right)\sigma_\circ \quad \text{(Force per unit width)} \qquad (3)$$

Where: α = Tip wedge angle, σ_o= Hydrostatic pressure in the crushed zone.

Sanio offered a formula for estimation of the crushed zone pressure from Fracture toughness, also extended this equation to account for joint effects, basically by using a factor as a function of joint orientation.

3. Sato et al. (1991) followed Sanio's work and used the same approach, but on a rotary cutting machine (not linear cuts). He offered the following equation:

$$F = k.P^a.S^b \qquad (4)$$

Where: F = Force, k = Coefficient of cutting, P = Penetration, a = Penetration coefficient, ~0.5 for normal force, ~1 for rolling force, S = Spacing, b = Spacing coefficient, ~ 0.5 (0.43) for both forces.

The rolling coefficient (Fr/Fn) is independent of spacing and increases with the square root of penetration. The coefficients b and a are almost independent of rock type, where as k is a function of both rock type and cutter geometry. In this study, k was found to have little or no correlation with fracture toughness, as stated by Sanio (1985), nor with fracture surface energy, as mentioned by Nelson (1986). Additionally, k had no significant correlation with rock uniaxial and tensile strengths. Specific energy of cutting, however, has shown a strong correlation with rock uniaxial compressive strength.

Sato et al. (1993) later expanded their studies to include the effects of tool orientation at an angle to the cutting surface. The following equations are modified version of their previous formulas for force estimation:

$$F_N = A.P^m \quad \& \quad F_R = B.P^n \qquad (5)$$

Where: m, n = Coefficients of penetration for normal and rolling forces (~ 0.5 and 1.0, respectively)

$$\begin{aligned} A &= K_n \,\mathrm{Tan}(\frac{\varphi}{2}+\alpha)\sqrt{D.S} \\ B &= K_r \,\mathrm{Tan}(\frac{\varphi}{2}+\alpha)\sqrt{S} \end{aligned} \qquad (6)$$

$$K_n = 0.13\ E^{0.36} K_{Ic}^{0.23}\ (kN/mm^{1.5})$$
$$K_r = 0.11\ E^{0.4} K_{Ic}^{0.28}\ (kN/mm^{1.5})$$

Where: K_{Ic} = Rock fracture toughness to be determined from ISRM method, Φ= Angle to the cutting surface, α = Angle of cutter tip.

Excepted for CSM updated model, other models mentioned above are based on V-shape cutters; these cutters are no longer used on TBM or other mechanical excavators. For long-term wear and performance, CCS (constant cross-section) cutters have been favored over the V-shape cutter (Rostami et al. 1996).

4. CSM model has been developed and named after research works at Colorado School of Mines'. The first version of this model was developed by Ozdemir et al. (1977) and was updated by Rostami (1993, 1997). The CSM model estimates the cutter forces for a given penetration (mm/rev), based on rock properties, and cutter and cutting geometry. The formula can be used to estimate forces for a given penetration or maximum obtainable penetration for a given set of machine specifications in a given rock, through iterations. The model is based on a large data base of full scale linear cutting tests performed on rock samples in the CSM laboratory. The model dose not systematically incorporate rock mass fracturing in the prediction model but recently some modification has been offered for taking into account the effect of rock mass conditions for prediction of TBM performance by Cheema (1999) and Yagiz (2002).

Rostami (1991, 1993) formulas have been used in various projects with a high degree of success. The total estimated resultant cutting force demonstrated in Figure 3 was derived as follows:

$$F_t = \int_0^{\phi} TRPd\theta = \int_0^{\phi} TRP^{\circ}\left(\frac{\theta}{\phi}\right)^{\psi} d\theta = \frac{TRP^{\circ}\phi}{1+\psi} \qquad (7)$$

Where: Ft = Total resultant force, T = Cutter tip width, R = Cutter radius, ϕ = Angle of contact area between rock and cutter,

$$P = P^{\circ}\left(\frac{\alpha}{\phi}\right)^{\psi} \qquad \& \qquad \phi = Cos^{-1}\left(\frac{R-p}{R}\right) \qquad (8)$$

P = Pressure of crushed zone

Ψ = Power of pressure function, Po = Base pressure in the crushed zone at the point directly underneath cutter, α = Position angle.

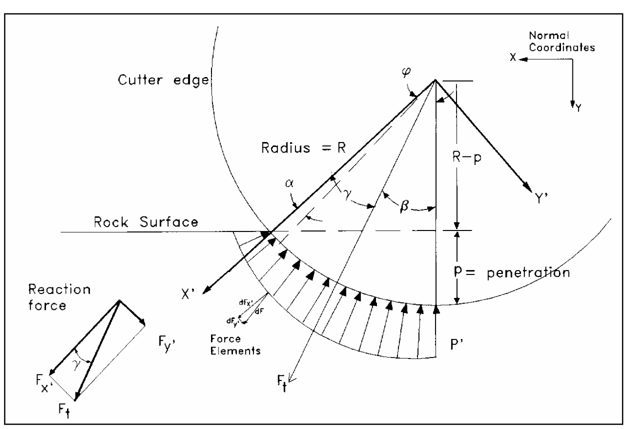

Figure 3. General Shape of Pressure Distribution with Power Function (Rostami 1991)

In these equations, T and R are cutter geometry parameters, which are known. The angle ϕ can also be calculated once the penetration is known. The power of the pressure function, Ψ varies between 0.2 for V-shape and very sharp cutters to -0.2 for wider tip cutters, and often can be set to 0.1.

The base formula was force as a product of pressure and area of contact. Yet the equation for estimation of the pressure of crushed zone P^0 was derived by regression analysis on available data within CSM database. As such, this equation was not dimensionally correct and was a linear or polynomial combination of several variables. Therefore, if a logarithmic regression was to be used, the right combination of parameters could be derived. The results of the later analysis performed over an extended database by Rostami (1997) produced equations which are very close to the right dimension, and subsequently were rounded off to offer a dimensionally correct equation.

Using the equations derived from regression analysis of measured forces by Rostami (1997), base pressure P^o can be estimated as follows:

Where: C = Constant, ~2.12, S = spacing between the cuts, σc = uniaxial compressive strength of

$$P_0 = C\sqrt[3]{\frac{\sigma_C^2 . \sigma_t . S}{\phi\sqrt{R.T}}}$$

rock, σt = tensile strength of rock.

For TBM performance estimates, with all parameters fixed in a certain rock type using a specific machine, penetration is the only variable that can be increased till one of the limits (i.e. cutter load, thrust, power, etc.) 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.

3.1.2. Specific energy approach

1. 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 reduction in specific energy of cutting is realized and also showed that the forces increase approximately linearly with spacing until S/P value of 15-20 is reached.

Snowdon discussed the relationship between the normal and rolling forces by using selected British rocks and described he relationship between the normal and rolling force as follows:

$$\frac{F_{Normal}}{F_{Rolling}} = 21.71 \cdot p^{-0.656} \qquad (10)$$

Where: p = penetration per revolution

Snowdon concluded that the variation of the most effective S/P ratio with rock strength indicates that if fixed disc spacing is used, the optimum penetrations for different rock strengths lie in a range attainable by tunnel boring machines.

2. Boyd (1986) presented a model that uses a totally different approach. The rock mass is assumed to have a specific energy (in kW-h/m^3) that is needed for disintegration. If the cross sectional area of the tunnel and the installed cutterhead power are known, the penetration rate can be calculated by the following equation:

$$ROP = \frac{HP.\eta}{SE.\ A} \qquad (11)$$

Where: ROP = rate of Penetration (m/h), *HP* =installed cutterhead power (kW), η = Mechanical Efficiency Factor, SE= specific energy (kWh/m^3), A = tunnel cross sectional area (m^2).

This method can be used for performance prediction of all types of mechanical excavators including TBMs, Roadheaders etc.

3.1.3. Mathematical/statistical simulation approach

1. Neuro Fuzzy approach is an alternative modeling approach to assist in the prediction of the performance of TBMs that is presented by Alvarez Grima et al. (2000). The principal constituents of this modeling approach are fuzzy sets, fuzzy logic, approximate reasoning, neural networks and data clustering. These are combined into a so-called hybrid modeling framework the neuro-fuzzy modeling provides a powerful tools to use vague and imprecise (fuzzy) information on the rock or soil present in the subsurface.

Further, it allows us to use large amounts of data, which the physical meaning is not obvious (e.g. rebound test data on rock cores or geophysical well logging parameters). By using ANN (Artificial Neural Network) analysis, relationships of such data with geotechnical significant information can be established and used. Perhaps the most interesting feature of this approach is that anyone can cope scientifically with subjectivity and uncertainty in engineering process, rather than blindly avoiding them (Alvarez Grima 2000).

2. Nelson prediction 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.

3.2. Empirical models

Many efforts have been made to correlate laboratory index test results to TBM penetration rate. Prediction equations are either empirically derived or developed with a theoretical basis using force equilibrium or energy balance theories. In both cases, simplifications on disc indentation geometry and contact zone stress distribution, leads to deriving coefficients by correlation of certain parameters within the database.

Most prediction methods agree on trends, but empirical methods are case-specific in terms of geology and machine characteristics. However, a general statement of caution 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.

3.2.1. Laboratories studies

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

1. Graham (1976) introduced a model in which the penetration rate is computed 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.

$$P = \frac{3940 \times F_L}{\sigma_{cf}} \qquad (12)$$

Where: σ_{cf} = Uniaxial compressive strength (kN/m$^{2)}$, F_L = Average cutter force (kN), P = Penetration per revolution (mm/rev).

2. Farmer and Glossop (1980) presented a model in which the penetration rate is computed by using the average cutter force and the tensile strength of the rock. The model is based on eight different 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.

$$P = \frac{624 \times FL}{\sigma tf} \qquad (13)$$

Where: σ_{tf} = Tensile strength (kN/m^2), F_L = Average cutter force (kN), P = Penetration per revolution (mm/rev).

They noted a strong correlation between the tensile strength of the rock and TBM performance. From performance prediction point of view, it is obvious that a single rock property and machine property were not enough to estimate TBM performance accurately.

3. 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. The equation developed is as follows:

$$V = \frac{6 \cdot P^{1.2} \cdot N \cdot h}{F_c^{1.2} \cdot r^{0.6}} \qquad (15)$$

$$PW = 28.45 \cdot D + 9.07 \cdot D^2 \qquad (16)$$

Where: V = Rate of penetration (m/h), P = Thrust per disc periphery (kN), N = Speed of cutting head (rev/s), h= Average number of disc per kerf, F_c = Uniaxial compressive strength, (Mpa), r= Average radius of disc (m), PW = Power (kW), D = TBM diameter (m).

The model includes a number of parameters that affect TBM performance. However, the only rock property used in this model is unconfined compressive strength. The model does not consider rock mass properties, such as joints or other intact rock properties, such as tensile strength, which can have a significant effect on TBM performance.

4. Bamford (1984) developed the relationship given below 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. He proposed the following equation:

$$\mathrm{P} = 0.535 \cdot \mathrm{S} - 8.49 - 0.00344 \cdot \mathrm{T} - 0.000823 \cdot \mathrm{N} + 0.00137 \cdot \phi \qquad (17)$$

Where: P = Penetration rate (m/hr), S = Schmidt hammer hardness, T = Machine propel thrust force (t), N = NCB cone indenter index (N/mm), Φ = Angle of shearing resistance (degree).

Although a good correlation was found to exist between the above predictor and field performance, the model does not incorporate the rock mass properties and a number of machine parameters may be affected by different geological conditions. The model incorporates simple intact rock properties that are cost effective to measure; on the other hand, the applicability of the model in different site conditions is limited.

5. Nelson et al (1983) have developed a performance prognosis model with analysis of construction records documents of TBM performance during the excavation of four tunnels in sedimentary rocks as follows:

$$\mathrm{Pr} = 10.45 - 1.19 H_A \qquad (18)$$

Where: Pr= penetration per revolution of TBM, H_A= Taber abrasion hardness developed by Tarkoy and Hendron (1975).

During their study, it was concluded that the penetration rate depends on operating thrust and torque in addition to rock type, and as a minimum, penetration rate should be considered in terms of thrust. Therefore, they proposed a correlation between rock index property (H_T, total hardness) and penetration rate normalized with thrust as follows:

$$FPI = 5.95 + 0.18 H_T \ \ \& \ \ H_T = H_R \cdot \sqrt{H_A} \qquad (19)$$

Where: H_T= Total hardness, H_R =Schmidt Hammer Rebound hardness, FPI = Field Penetration Index, average cutter load/ penetration per revolution, (kN/mm or lbs/in).

6. 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. In the RSR method, the strength of the intact rock is only partially accounted for by the rock type and classification by hardness. This is perhaps one of the reasons why UCS was included in Innaurato's model. The method is based upon 112 homogeneous sections: however, no information is provided on the number of bored tunnels.

$$P = \sigma_C^{-0.437} - 0.047 RSR + 3.15 \qquad (20)$$

Where: P= TBM penetration rate (m/h), RSR= Rock Structure rating, σ_C = Uniaxial Compressive Strength of intact rock (MPa).

3.2.2. Field Studies and Investigation*s*

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.

1. NTNU model: Bruland et al (2000) presented an updated version of the model presented by Lislerud (1983), which was developed by the same Norwegian research group. The first version of the model was published in 1976 by Johannessen et al. (in Norwegian). The changes in Bruland's model are limited.

The intact rock properties are included 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 that 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.

2. 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). The principals' equations of his models are presented as follow:

$$\mathrm{Pr} = 5 \cdot Q_{TBM}{}^{-0.2} \qquad (21)$$

$$Q_{TBM} = \left(\frac{RQD_0}{J_n}\right) \cdot \left(\frac{J_r}{J_a}\right) \cdot \left(\frac{J_W}{SRF}\right) \cdot \left(\frac{20^9 . SIGMA}{F^{10}}\right) \cdot \left(\frac{20}{CLI}\right) \cdot \left(\frac{q}{20}\right) \cdot \left(\frac{\sigma_\theta}{5}\right) \qquad (22)$$

Where: Pr = penetration rate (m/hr),RQDo= RQD(%) of the rock mass that interpreted in the tunneling direction, Jn, Jr, Ja, Jw, and SRF rating are Q system parameters, except that Jr and Ja should refer to joint set that most assists(or hinders) boring, F=average cutter load (tnf) through the same zone, SIGMA= rock mass strength estimate(Mpa) in the same zone, CLI= Cutter Life Index(NTNU), Q= quartz content (%), σ_θ =induces biaxial stress on tunnel face(Mpa) in the same zone.

3. 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 unfractured specimens of solid rock and by basing predictions on the strength characteristics of intact rock (Robbins1980).

4. Discussion and result

TBM performance prediction models had been developed on two primary basis, field observation, and laboratory testing. The first group of models is based on the machine performance in given geological conditions, using certain parameters and indices to represent the ground. Examples of such models are NTNU (University of Science and Technology of Trondheim in Norway, formerly NTH) TBM prognosis system, and models offered by Tarkoy, Nelson, and a few others. The advantage of these models are their ability to take into account the ground conditions specially rock mass behavior while including the complexity of machine operational parameters. These models are partly limited in their use for scenarios where new machine parameters are introduced and also lack ability to be used in machine design and optimization.

The Norwegian or NTNU model is based on the field performance of TBMs. It is well known that finding reliable field data is very difficult but University of Trondheim has gathered data from several projects for about 280 km of tunnel since 1976. The model is based on TBM performance in the tunnels and as such it has overall machine operational parameters in a given rock mass and the results in terms of performance. This model does not involve the details of cutting forces and sees the boring operation in a global view. There are some views that believe the model is very sensitive to joint effect. This remains to be verified beyond expert's feeling to an established fact through analysis of available information to come to a conclusion and develop new set of curves to show the effects of joint sets. Also, the ability of the model to predict TBM performance and relationship between the machine parameters and new features can be verified and proved by this effort.

On the other hand, the models based on laboratory testing are based on the cutting forces acting on the tools, namely disc cutters. An example of these models and by far the most widely accepted system is the one offered by the CSM. This model is based on linear cutting tests which measure the cutting forces and thus allow relating the forces to rock and cutter parameter. It allows users to estimate forces and use them to evaluate machine performance based on machine specifications. CSM model can simulate head action and can be used for cutterhead design, balancing, machine specifications, optimization, and matching machine thrust and torque for a specific project and show the actual forces on the cutters and can help the manufacturers and operators alike in related issues. The main rock parameters used in the model includes the UCS and BTS (Brazilian) and for cutter cost estimates it uses CAI. It is obvious that as good an indicator that UCS is it can not reflect rock cutting behavior in its entirety. However, the reason that it was used in the model is its popularity since it is the first parameter measured rather easily in literally every project. However, the model lacks the effects of rock fabric and its cutting behavior (brittleness and toughness). There are efforts to cover this shortcoming by addition of punch test results or a rock texture factor to this equation as an adjustment factor.

Due to its inherent basis for development which is the laboratory testing on intact rock, the second shortcoming of the CSM model is the lack of rock mass parameters, since it was not possible to have such data within the realm of laboratory experiments and tests. In this respect, there are works such as Sanio, Sato and a few others who suggested adjustment factors to estimate cutting forces in jointed rock. But this approach can not go far and can not produce the needed results, since the effect of joints on micro scale and on cutting forces can be far ignored by the virtue of cutterhead motion and changing direction of cutting while head turns. Thus such formulas although interesting, can not show much of accuracy in TBM performance prediction in rock mass. The logical way to look at this issue is to factor the effect of rock joints and rock mass on to overall machine performance and this is were NTNU model can be applied. In short, a combination of CSM and NTNU models would allow the flexibility to look into machine design issues while providing for an accurate model for performance prediction in various ground conditions.

Currently the authors are involved in a study to combine the two models. This is done by review of the database of the two systems and develops a joined database for further statistical analysis. So far, the data from over 70 km of tunnels have been entered into a database and work is underway to apply the CSM model to the available set of data to account for the parameters such as rock strength, cutting geometry, and machine operational parameters. This leaves the expected rate of penetration and achieved rate in the field due to the rock joints and effects of rock mass. With a thorough analysis of the impact of rock joints on the machine performance, it is anticipated to develop new set of graphs or adjustment factors to account for such effects. Similarly, there are efforts under way by other groups to address some of these issues at CSM and NTNU. Meanwhile, other research studies are also being performed on the impact of machine and ground conditions on Utilization. Successful completion of these studies will allow more precise estimate of machine performance for Hard Rock TBMs.

5. Conclusions

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. Efforts are underway by the authors in a joint research between University of Tehran and INSA of Lyon. This involves developing a database of TBM tunnels to include machine and rock parameters as well as joint information. The basic rock and machine parameters will be used to develop estimates of machine performance in intact rock and then the joint system will be factored in to see how much the joint system has affected the machine performance. Correlation between the two sets of data would offer experimental/empirical formulas for evaluation of joint effects on machine performance. For the time being, it is recommended to utilize more than one model for performance evaluations to avoid potential of misleading estimates that could cause costly burdens on related tunneling projects.

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