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A REVIEW OF PARAMETERS INFLUENCING THE PERFORMANCE OF TUNNEL BORING MACHINES

BY

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ABSTRACT

This paper reviews the parameters influencing the performance of tunnel boring machines along with concepts behind the modeling of the cutterheads for design and performance analysis. The general approach to modeling is discussed and some examples are presented.

INTRODUCTION:

Tunnel Boring Machines (TBMs) are special equipment that are capital intensive and site specific. To maximize the benefit of the TBMs (i.e. higher production and lower costs, higher degree of automation, more consistent product size and quality, and finally better working environment) to any operation, performance of these machines under a specific ground condition must be thoroughly studied. For this purpose, several models have been developed over the years to study the design parameters and their impact on machine performance and also to estimate the production and advance rate of different machines. These models provide a better understanding of the interaction between the machines and the rock to facilitate improvements on the design of the cutting system to enhance machine performance.

This paper presents and briefly discuss the model developed and currently used at the Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM) for full face machines. Examples of the input and output of these models will be illustrated for typical tunneling machines such as Tunnel Boring Machines. This model, in conjunction with rock mechanic and full scale cutting tests, offer reliable performance estimates, produce information for improve-ment of the cutterhead design and layout, and assists operators in making decisions while selecting or operating a TBM.

BACKGROUND

The continuous push for competitiveness and cost containment in mining and underground civil construction always forces the operators to improve their operations. Widespread use of mechanical excavators has for the most part been the response of the industry to this pressure. These machines have set numerous records and have significantly improved productivity, as well as overall system efficiency. Yet the capital intensity of these machines have resulted in hesitation on the operators part to apply them in their operations.

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It is only with proper production and cost analysis that a operator can make justification for such capital investments. This incorporates modeling of the cutterhead for design analysis and performance prediction.

These models are based on either the estimation of the cutting forces on individual cutters, or based on the field performance of specific machines in certain geology. The first approach is employed by CSM to develop models due to availability of full scale rock cutting test data.

PARAMETERS INFLUENCING MACHINE PERFORMANCE.

The parameters influencing the machine performance can be divided into four groups. This includes the physical and mechanical properties of the rock formations to be cut and the geological conditions present, the cutting parameters (i.e. cutter type, shape, and cutting geometry such as spacing) and cutterhead lacing, machine specification and capabilities, and finally operational parameters. These parameters are discussed in more detailed in the following sections.

Rock Properties and Geological Conditions

The geological conditions present at the cutting face is the parameter that has to be dealt with and can not be entirely controlled. Meanwhile, the conditions have to be properly understood and the properties of the rock formations need to be tested and measured. There are several tests that are commonly used with respect to characterization of the rock properties. The most important and most frequently measured properties include the unconfined compressive and tensile strength of the rock. Also, rock abrasivity and toughness play a major role in the cuttability evaluation. There is no universal test accepted in the rock cutting community to quantify these two variables. For measuring abrasivity, Cerchar Index has proved to be fairly accurate and is commonly used for cutter life estimation. Also, in the lack of other tests, rock tensile strength is often utilized to represent rock toughness. Observation of the rock fabric with microscope in a thin section also yields a number of valuable information about the grains, their size, shape, and orientation, intergranular bonds, bedding or schistosity, and microstructures which from time to time has been found to control cutting behavior of the rocks.

Geological conditions to be encountered such as joints, structural features, faults, and groundwater can have a major impact on the machine selection, application, operation, and the production rate. These parameters must be accounted for when estimating the machine utilization for performance prediction purposes.

Cutting Tools and Cutting Geometry

The rock cutting tools range from radial drag tools for very soft nonabrasive rocks, to conical point attack tools for soft to moderate strength rocks, and roller cutters for hard and abrasive rocks. The range of application of each type of tools is defined and accepted by machine manufacturers.

The cutting geometry refers to spacing between the cuts and the penetration of the tool into the rock surface. These factors directly control the efficiency of the cutting and specific energy requirements of cutting a certain rock. The variation of spacing (S), penetration (P), and $^{S}/_{P}$ ratios and their impact on the cutting efficiency have been studied extensively in the past. It has been observed that depending on the rock type and tool, there is a range of $^{S}/_{P}$ ratios that can produce the best results, identified by minimized specific energy requirements. This range can best be found by full scale cutting tests. In other words, the performance of a certain machine can be optimized by changing the cutting geometry.

Cutterhead design, layout, and cutter allocation are the most important parameters in optimizing machine performance. The design is mainly controlled by the cutting geometry with the consideration of the overall cutting pattern and cutterhead geometry. The spacing between the cutters has to be optimized and cutting profile configured. Cutters must be tilted at the gage to produce the required profile and be perpendicular to the cutting surface to minimize side forces. The cutter allocation on the head is crucial to balancing of the head and therefore affects both the productivity and the cutter life. Cutters must be evenly distributed on the head to create a uniform distribution of the load and minimize the force and torque variations. Altogether, cutterhead design can significantly impact the success of a mechanical excavation system.

Machine Specification

The machine specification pertains to the mechanical design of the machine to provide sufficient amount of forces and torque to support the excavation operation. This includes the ability to generate enough thrust to sustain the normal forces above the threshold needed to penetrate into the rock. Also, the cutterhead torque and power requirements to rotate the head at the required penetration rate and overcome the rolling resistance of the cutters have to be determined and installed on the head.

Operational Parameters

In every tunneling operation, there are some operational constrains such as the haulage capacity, ground support requirements, water handling etc. that ultimately limits the productivity of the machine. It is very likely that in soft ground these parameters become the bottle neck as opposed to the hard rock applications where ability to cut the rock imposes a limit to the productivity. In addition, other factors such as tunnel grade, curves, impact machine and utilization, hence productivity. All these factors have to be taken into account when application of a machine to a particular operation is considered.

General Approach to Modeling

As mentioned earlier, among the parameters influencing the performance of a TBMs, the easiest (and the least expensive) parameter to control is the cutterhead design. In order to improve design of the cutterhead, the rock cutting process and the relationship between the cutter type, cutting geometry, and the rock has to be accurately established. These

relationships have been studied in detail and a variety of formulas have been developed to quantitatively express them. The modeling of the TBMs incorporates these formulas to predict the performance and analyze the design of the cutterhead. The general approach to the modeling can be divided into two groups. The first group is the empirical models which rely heavily on the field data. The second one is the semi-theoretical models which are based on the cutting forces on individual cutters. Each approach has its area of strength and weakness. The main advantage of the second type of models, which includes the CSM models, is their high flexibility and the ability to optimize cutterhead design. These models are equally applicable to all types of machines (full or partial face) and provide a basis to evaluate new types of machines, tools, and designs. A list of issues related to the two groups of models is given in Table 1.

Input Parameters

Fig. 1 shows the typical steps taken in the modeling and analysis of mechanical excavators. As can be seen, the first step always involves characterization of the rock and the geological conditions. A detailed description of the specific tests and their application for machine selection, cutterhead design and optimization, as well as performance prediction can be found in the literature.

Table 1. Summary of issues related to the two approaches to modeling.

Methodologies Issues	Semi-Theoretical Approach*	Empirical Methods **
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

The input parameters of the CSM models are the cutting forces (normal, rolling/drag, and side) and the cutterhead layout. The most reliable source of cutting force data is the full scale cutting test. Figure 2 shows a schematic drawing of the cutting test apparatus currently used at CSM. The testing equipment, often referred to as Linear Cutting Machine (LCM), is capable of cutting rock samples with actual cutters at the spacing and penetrations typically used in the field. The forces are measured by a triaxial load cell and recorded for further analysis. This test eliminates all uncertainties associated with cutting rocks since it inherently accounts for all the rock and cutter characteristics. The rock samples required for the cutting test need to be at least about 0.5 m (2 ft.) cubed and can be obtained from the large pieces produced by blasting or from outcrop of the formation. Also, when required, samples can be made out of large diameter cores. Overall, the benefits gained from performing the cutting tests in term f improved productivity significantly outweighs the marginal costs of testing, investigatio nd modeling.

In cases where rock cutting test data is unavailable (due to the limited access to the rock formations in the tunnel alignment or underground mining development areas) physical property test performed on the core samples can be utilized for modeling purposes (Rostami et al. 1994, Neil et. al. 1994, Rostami & Ozdemir 1993).

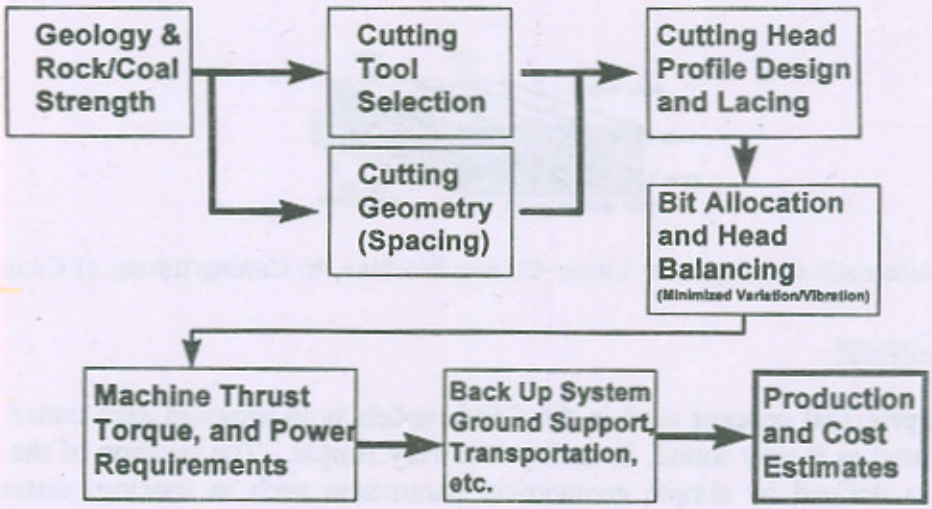


Figure 1. Tyical design and modeling steps and flow chart.

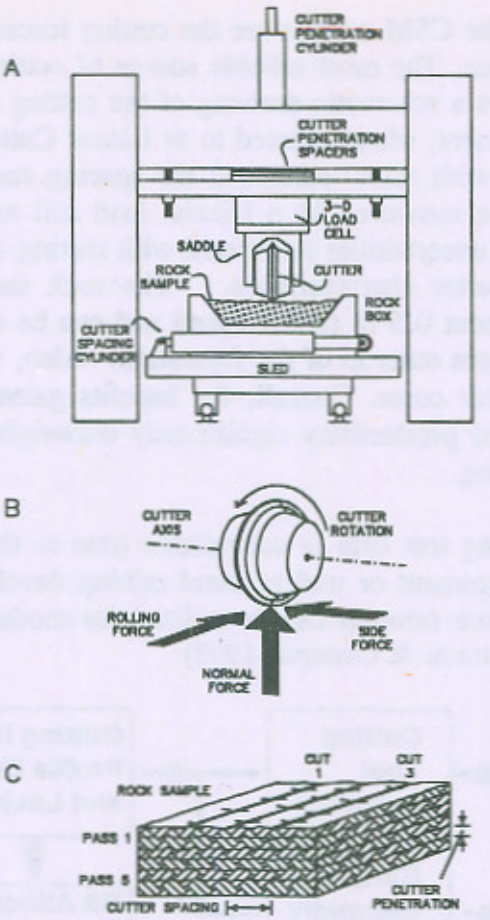


Figure 2. Schematic drawing of a) Linear Cutting Machine, b) Cutting forces, c) Cutting Geometry.

Modeling Concept

The principal concept used in the CSM models is to program each cutter individually. As complicated as it may sound, in reality it is very simple. The position of the cutter on the cutterhead is defined by simple geometrical parameters such as spacing, distance from the center and the angular position. Thus, the cutterhead geometry is defined in a polar coordinate system. This is sufficient for modeling full face machines since they can normally be considered a 2D problem. The model will then estimate the penetration per revolution for each cutter and determine the cutting forces required to penetrate the rock. These forces in turn are used to estimate cutterhead thrust, torque, and power requirements.

This concept allows modeling any cutterhead layout, pattern, or configuration for design or performance analysis. The model allow analysis of forces on the individual cutters and avoid overloading by making adjustments in the layout. Example of the model will be given in the following section.

AVAILABLE MODEL FOR FULL FACE MACHINE.

The model available at EMI/CSM has been developed for a variety of purposes in cooperative research programs with machine manufacturers, contractors, mining companies, consultants, and government agencies. The model has been extensively utilized by mining and civil construction industries in different stages of projects starting from the early geotechnical investigations and pre-feasibility studies, to actual project development, engineering, design and planning, and finally for productivity improvement of existing operations. The model has evolved in scope and applications over the years and are continuously up graded as more information becomes available. The data-bases used for the development of the model is also updated to support the model to include more rock types and cutters. This includes data from both the full scale cutting tests performed at the laboratory facility as well as the field performance of various machines. The model has been programmed on P.C. based computer for easy access, high accuracy and speed of calculations, and the ability to examine effects of various parameters on machine performance. The model is all developed in the spread-sheet environment (mainly MS. Excel®) for the accessibility of the data to the designer.

Full face machines, except for borers used in mining potash or trona, are the machines which excavate circular opening. These machines cut the entire face at once and all the cutters are in contact with the face ant any given time. The most common full face machine is the Tunnel Boring Machine (TBM). Also, included in this category are raise boring and drilling machines, shaft boring and drilling machines, rotary drills, reamers, and finally micro-tunneling (pipe-jacking) machines.

CSM computer models are currently available for design optimization and balancing of the cutterhead of these machines, in particular the TBMs. In addition, EMI/CSM has models for performance prediction and cutter life/cost estimation based on the cutterhead profile and rock physical properties. These models utilize semi-theoretical formulas developed at EMI to estimate the cutting forces. There are also more complex models for simulation of cutting a mixed face with hard intrusions in a soft matrix, cutting a banded mixed face with several rock types present at the face, and cutting in a bi-directional mode. The output of the models consists of the cutterhead geometry and profile, individual cutter forces, overall thrust, torque, and power requirement, eccentric forces, moments, and finally variation of cutting forces as the cutterhead rotates. Design modifications can be done in the models to balance the head and minimize the eccentric forces and force variations. This is very important in increasing the production rate, cutter and main bearing life, and utilization.

VALIDITY OF MODEL

The model is checked continuously with the field performance of the machines to validate the approaches taken, adjust the models for more accuracy, and update the databases. This is accomplished by comparing the results of the performance predictions with the field performance data. In addition, measurements of cutting forces and power consumption are made on some machines and compared with the respective estimates given by the model.

The results of these comparisons have proved that the model is based on sound engineering principles, the approaches are correct, and the predictions are accurate.

The field comparisons have been performed in several occasions with TBM operations where the predicted performance was within less than 10% of the actual machine performance (Rostami et. al. 1996). The model has allowed accurate analysis of different design parameters without the need for costly fabrication of cutterheads and field trials. The recommended design modifications provided for more efficient cutting coupled with higher productivity as the modified machines significantly outperformed the original designs. The predicted rates of production were within 5-10% of the achieved production rates.

CONCLUSION

Tunnel Boring Machines are site specific and are sensitive to the rock and geological conditions to be encountered at the excavation site. To maximize the productivity of these machines in any operation, their behavior and particularly the cutterhead design has to be evaluated and optimized. This can be accomplished by computer modeling and simulation of the cutterhead design. The computer models can assist the operator to perform analysis of the TBM performance and incorporate specific measures to improve their efficiency. The model provide a cost effective means to explore the parameters influencing the production rates and costs and to maximize the efficiency of the operation without the need for costly field trials

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