Application of Tunnel Boring Machines in Underground Mine Development

M. Cigla, S. Yagiz & L. Ozdemir
Excavation Engineering & Earth Mechanics Institute, Department of Mining Engineering, Colorado School of Mines, Golden, Colorado, USA

ABSTRACT: Because of their demonstrated capabilities in attaining high rates of advance in civil tunnel construction, the hard rock mining industry has always shown a major interest in the use of TBMs for mine development, primarily for development of entries, as well as ventilation, haulage and production drifts. The successful application of TBM technology to mining depends on the selection of the most suitable equipment and cutting tools for the rock and ground conditions to be encountered. In addition to geotechnical investigations and required rock testing, cutterhead design optimization is an integral part of the machine selection to ensure a successful application of the machines in a specific underground mine environment. This paper presents and discusses selected case histories of TBM applications in mining, the lessons learned, the process of laboratory testing together with machine selection and performance estimation methods.

1 INTRODUCTION

There is a constant and growing demand in the mining industry for rapid excavation to develop new orebodies faster in order to reduce overall development costs. The majority of civil engineering tunneling projects is now carried out by mechanical excavation rather than drill and blast methods. Drill and blast is also a well-developed technology, and the choice of excavation method becomes a matter of economics for both civil construction and mining. Faster development schedules and lower costs can be achieved with mechanical excavators when supported by adequate mine planning and detailed performance analysis. Accurate estimation of production rates and costs for mechanized excavation systems increases the economic confidence and provides justification for the high capital investment associated with mechanical excavator use. Mechanical excavation offers numerous advantages over drill and blast for all types of mine development, including:

- Personnel safety is greatly improved due to elimination of blasting and toxic fumes.
- With machine excavation, ground disturbance is drastically reduced, which results in significantly lower support requirements to provide a safe and stable opening.
- The smooth walls created by machine boring also mean reduced ventilation requirements.
- Unlike drill and blast, machine generates a uniform muck size, which allows for the implementation of continuous material haulage systems, such as conveyor belts.
- Machine excavation provides a continuous operation, making it highly suitable for remote control and automation.

In this paper, recent case studies, geological effects and current state of the art in machine performance prediction methods are discussed.

2 TBM APPLICATIONS IN UNDERGROUND MINING

TBMs have been used in mining operations from time to time almost as long as TBMs have been operation. Unfortunately, they have not been nearly as successful as in civil tunneling. The earliest application of TBMs in mining dates back to late 50's. This was followed by several attempts in 60's and 70's in other underground mining operations (including coal mining in England). The penetration rates achieved by the machine in most of these projects were far above the capabilities of any drill and blast operation, yet overall tunneling costs could not be justified for widespread use of these machines in other mining operations. The common shortcomings of these earlier applications were:

- The usage of smaller disc cutters with low load capacities, which was far less than what, was required for efficient cutting of the rock formations encountered.
- Limited power available on the machines
- Lack of ability to cope with unexpected ground conditions, such as very broken ground or fault zones.
- Some of these machines were just refurbished to fit to their new job. They were not originally designed for mining applications.
- Lack of experience of the crew with these machines caused very low machine utilization rates.
- Forcing the machines to sometime follow the formation and consequently, frequent need for turning and steering.

In recent years, the mining industry has witnessed several breakthroughs resulting in successful application of the TBMs in mining operations. The main reason for the success is due to the experiences gained within over two decades of applying these machines in different projects, new technological advances in cutter design, machine components, hydraulic and electrical systems, increased use of computer and electronic controls. And finally, willingness of the manufacturers to design machines specifically suited for mining operations.

Two most recent successful applications of TBM technology in mining have been in the San Manual copper mine and the Stillwater platinum mine in the United States, as discussed below.

2.1 San Manual Mine, Magma Copper Company

Magma Copper Company's San Manuel mine is located approximately 72 km north of Tucson, and 11 km west of San Manuel, Arizona.

Geological interpretation developed during mining in the San Manuel ore body led to the discovery of the Kalamazoo orebody in the mid 60s. The Kalamazoo is the upper half of the San Manuel ore body, sheared and moved nearly 2,500 m down dip at a 25-degree angle. Geologically, Kalamazoo ore body is the result of intrusion by late Cretaceous age granodiorite porphyry into a Precambrian age porphyritic quartz monzonite. Both are members of the granite family of rocks, differing mineralogical only slightly in composition. The Kalamazoo and San Manuel ore bodies were once part of a single ore body created as a nearly vertical, cylindrical shell surrounding the contact of the host quartz monzonite and the invading granodiorite porphyry.

The Lower Kalamazoo was being developed for a block caving operation, with modified stope design and belt conveyor ore haulage. As shown in Figure 1, the mine development plan called for approximately 12,800 m of drifting in two levels. After a detailed trade-off study, the mine elected to use a TBM for all development work.

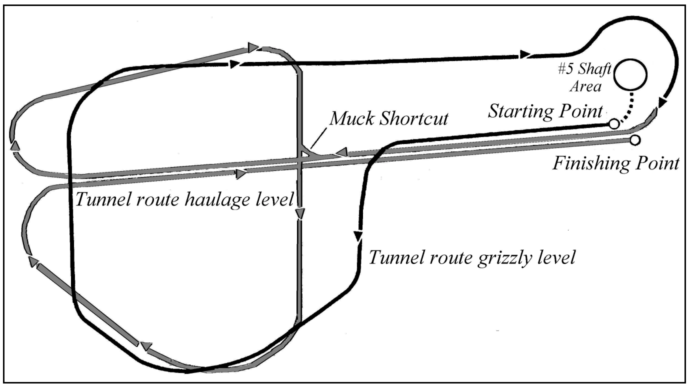


Figure 1. TBM tunneling route.

The Magma Copper selected a hard rock, main beam TBM from Atlas Copco Robbins (Figure 2) for the Lower Kalamazoo development. The cutterhead and main beam were built in two pieces to meet the space and weight limitations imposed by the mine's shaft. Some of the features of the machine are given in Table 1.

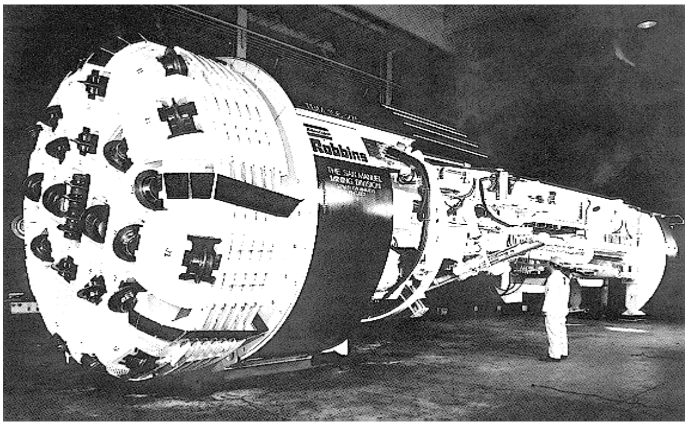


Figure 2. San Manual TBM (Robbins).

Table 1 Robbins TBM Specifications.

Boring diameter		4.62 m
Cutterhead	Installed power	1259 kW
	RPM	4 – 12
	Thrust	7,340 kN
Cutters	Number	33
	Tip width	15.875 mm
	Diameter	432 mm
	Maximum load	222 kN/cutter
Boring stroke		1.575 m
Minimum turning radius		105 m
Weight		225 t

The TBM's excavation route included the stable quartz monzonite of 150 MPa to 180 MPa unconfined compressive strength. The bore path also crossed the San Manual Fault six times and The Virgin Fault five times. The San Manual is a flat dipping fault with a l-m wide clay zone that follows the bore some 30 m at a time but influences a total of 190 m; The Virgin Fault dips steeply but a series of related minor faults produces poor rock conditions for about 500 m. In addition, where dacitic, andesitic and rhyolitic dikes contact the granodiorite and quartz-monzonite, weak zones 0.2-m to 0.6-m wide affect the bore approximately 180 m. Along most of the TBM's path, hydrothermal metamorphosis has weakened the rock further by veining, fracturing and jointing. Unsupported wall stability ranged from 30 minutes to months. Magma Copper chose to take a systematic approach to rock support and installed ring beams the full length of the bore path.

Clay plugging the cutterhead was one of the problems. Other difficulties encountered included were trouble starting the cutterhead and keeping it rotating in soft, collapsing ground. This was partly due to ground subsiding onto the top of the cutterhead, partly due to sidewall collapse. It was also found that the machine's side supports gouged the tunnel walls in weak ground. Not only did this contribute to sidewall collapse, it also made it impossible for the machine to be steered along the narrowest of the curves along the tunnel route.

Due to these problems, the TBM could not initially reach its planned rate of advance and it became obvious that modifications were needed to make the machine reach its design performance under very difficult ground conditions. All options were reviewed and as a result, the following modifications were made:

- Two cutters were removed to permit enlarging the buckets for a better muck flow.
- To improve cutterhead "starting" and "pull-through" capabilities, cutterhead drive torque was increased with better stall characteristics.
- The cutterhead speed was reduced from 12 to 9.3 rpm. This improved the running torque by some 29 %.
- The roof support was extended forward by a canopy over the rear of the cutterhead to within a short distance from the outermost gauge cutter.
- Fingers were added to the side supports to increase the surface area of those supports.
- The side roof supports were separated from the side supports to allow for independent operation.

All the modifications were executed in 23 days, very close to the planned schedule. The modifications greatly improved the performance of the TBM in all areas. Results since the modifications are shown in Table 2, which compares the TBM progress before the modifications with results following the modifications.

Table 2. Comparison of machine performance.

	Before	After
Average Daily Advance, m	6.46	22.6
Best Shift, m	19.2	21.6
Best Day, m	37.5	44.5
Best Week, m	141.7	263
Best Month, m	333.5	831.2

Overall, this was a successful application of TBM in underground hard rock mining and allowed the mine to meet its accelerated schedule for the development of the new orebody.

2.2 *Stillwater Mine, Montana*

Stillwater Mining Company (SMC) is developing a second underground palladium and platinum mine about 21 km west of their existing Nye operation in Montana. A 5,650-m tunnel is required to gain access to the ore-bearing horizon (J-M reef). Associated by-product metals include rhodium, gold, silver, nickel and copper.

As shown in Figure 3, the access tunnel (Adit #1) is being driven at an azimuth of 208° with a plus 1/2% vertical grade approximately 5,650 m to reach the reef.

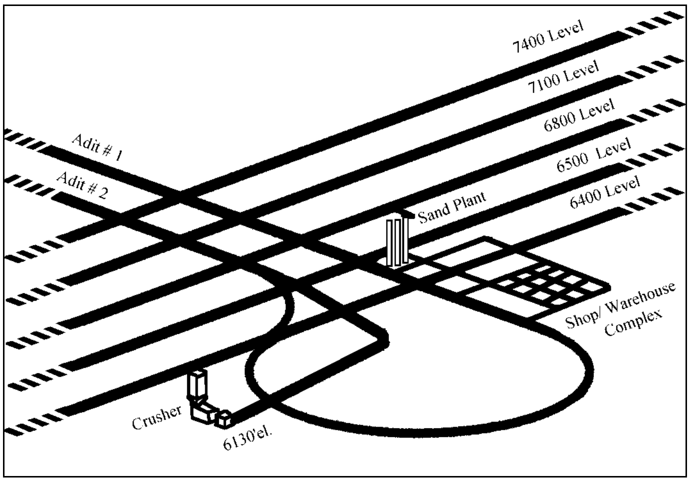


Figure 3. East Boulder Project.

The tunnel geology consists of approximately 1,006 m of sediments, 2,530 m of gabbro, 430 m of norite, 1,140 m of anorthosite, 335 m of olivine gabbro, and 210 m of troctolite. Rock uniaxial compressive strengths are as follows: limestone 60-140 MPa, gabbro 70-190 MPa, norite 100-150 MPa, and anorthrosite 60 -190 MPa. In general, the unconfined compressive strength test results show a wide range of values from 60 to over 190 Mpa.

Because of their earlier successes with TBM use, the Stillwater mine decided use TBMs for all development work for the mine. The first TBM was custom designed and built by Construction and Tunneling Services (CTS) of Seattle Washington. Table 3 lists the basic specifications of this machine. The machine was delivered to the project site in July 1998 and reassembled and field-tested. Independent contractors were used to drive the 5,650-m long, 4.6-m diameter tunnel, starting from Adit #1. The excavation was completed at the other end of the reef on July 29, 2000. Crews and equipment will access to western section of the reef through this tunnel.

Table 3. Specifications of the CTS Machine.

Boring Diameter		4.58 m
Cutter head	Installed Power	1345 kW
	RPM	11.6/3.8
	Thrust	8,545 kN
Cutters	number	26 - 432 mm
		3 - 406 mm
	Tip width	15.875 mm
	Maximum load	222 kN/cutter
Boring Stroke		1,220 mm
Minimum turning radius		61 m
Weight		275 t

Efficient access into the East Boulder Mine was essential to achieving a 1,800-t/day-production rate. The most essential element in the acceleration of the project schedule was to establish a second means of access and the ventilation required for underground development. Accordingly, SMC purchased a second TBM for the excavation of adit #2. This was the same machine as used in San Manual Mine in Arizona. An independent contractor refurbished this machine to the specifications shown in Table 4.

Table 4. Specifications of Robbins Machine.

Boring Diameter		4.62 m
Cutter head	Installed Power	828 kW
	RPM	12/4
	Thrust	7,300 kN
Cutter	Number	33
	Tip Width	15.875 mm
	Diameter	432 mm
	Maximum load	222 kN/cutter
Boring Stroke		1,550 mm
Minimum turning radius		105 m
Weight		225 t

A 914-mm wide conveyor belt was used for material haulage from the second drive. A key feature in the rapid development of the East Boulder Mine was to use this conveyor for all development and production rock haulage when the tunnel reaches the East Boulder workings.

Initial production is expected to begin in 2001, with mine operation at 1,800 t/day. When East Boulder reaches full production, the annual production rate will be 450,000 to 500,000 oz of palladium and platinum annually.

3 TBM PERFORMANCE PREDICTION METHODS

As noted before, a key factor in TBM applications to any tunneling project is the accurate prediction of attainable penetration rates and the cutter costs. This is necessary in order to compare the economics of TBM use vs. drill and blast excavation.

3.1 Factors Influencing TBM Performance

The parameters influencing Tunnel Boring Machine performance can be summarized as:

- Intact rock properties
- Rock mass properties
- Cutter geometry
- Cutting geometry
- Machine specifications
- Operational parameters

Proper application of the TBMs to any mining or civil tunneling operation depends on the detailed understanding of the parameters given above. The following is a brief discussion of these parameters when assessing the economics of a TBM application.

3.1.1 Intact Rock Properties

It is well known and established that the uniaxial compressive strength (UCS) of rock is the most commonly measured rock property. UCS can be used to evaluate the resistance of the rock against the indentation of the cutting tool into the rock surface. Great attention must be paid as to how the sample failed during UCS testing. Figure 4 illustrates a typical structural and non-structural failure of UCS sample. Those samples, which are observed to fail along existing rock defects, such as joints, fractures, bedding or foliation, are classified as structural failure. Where the sample failure is not controlled by any defects and occurred in an “intact” manner, the sample is noted as having failed in a non-structural manner. This classification is of crucial importance since the structural failures do not represent the actual rock strength and therefore, are excluded from any boreability predictions. However, mechanical cutting predictions relying only on the compressive strength may provide inaccurate results. Several other intact rock physical property tests need to be performed to increase the accuracy of performance predictions for TBMs.

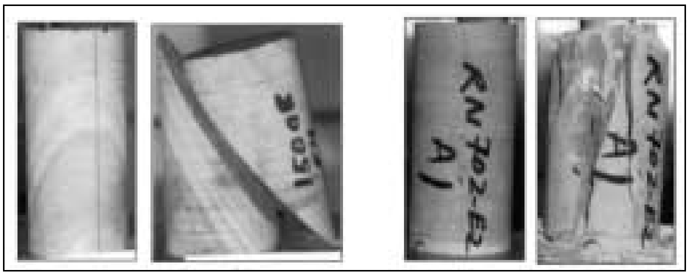


Figure 4. Typical structural (left) and non-structural (right) failures on cores.

Tensile strength is another common rock property, which is used in making boreability predictions along with the uniaxial compressive strength of the rock. Brazilian Tensile Strength (BTS) is generally intended to provide an indication of rock toughness from a viewpoint of crack propagation between adjacent cutter paths. As in UCS testing, great attention must also be paid as to how the sample failed during BTS testing. Figure 5 illustrates a typical failure of structural and non-structural failure. All the structural failures are excluded to present the true tensile strength of the rock.

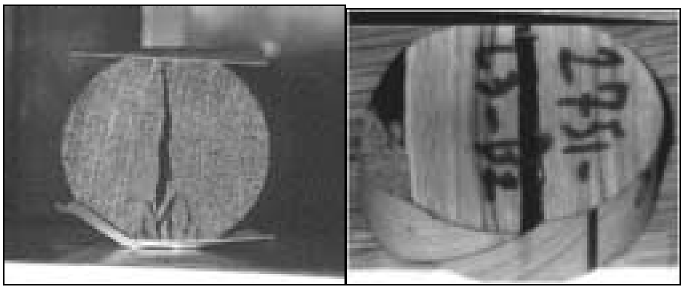


Figure 5. Typical failure modes in tensile test

Another rock property, which affects boreability, is the brittleness or the plasticity, which the rock exhibits when subjected to the mechanical forces generated by the cutting action of an excavator. In general, rock cutting efficiency of any mechanical tool improves with increasing brittleness exhibited by the rock formation. Thus, brittleness is a highly desirable feature of the rock from a boreability standpoint. One of the tests, which help assess the brittleness of the rock in the laboratory, is the Punch Penetration Index test. In this test, a standard indentor is pressed into a rock sample that has been cast in a confining ring as shown in Figure 6. The load and displacement of the indentor are recorded with a computer system. The slope of the force-penetration curve indicates the excavatibility of the rock, i.e., the energy required for efficient chipping.

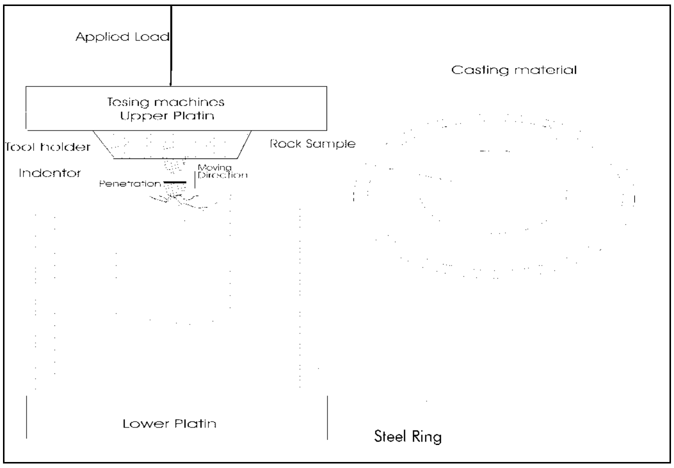


Figure 6. Punch Penetration Test Set-up

Rock abrasivity together with strength is used to estimate cutter wear during TBM excavation. The Cerchar Abrasivity Index (CAI) has proven to be fairly accurate and is commonly used for cutter life estimation. A series of sharp 90° hardened pins of heat-treated alloy steel are pulled across a freshly broken surface of the rock, as shown in Figure 7. The average dimensions of the resultant wear flats are related directly to cutter life in field operation. The geometry of the planned excavation then allows calculation of the expected cutter costs per unit volume of material.

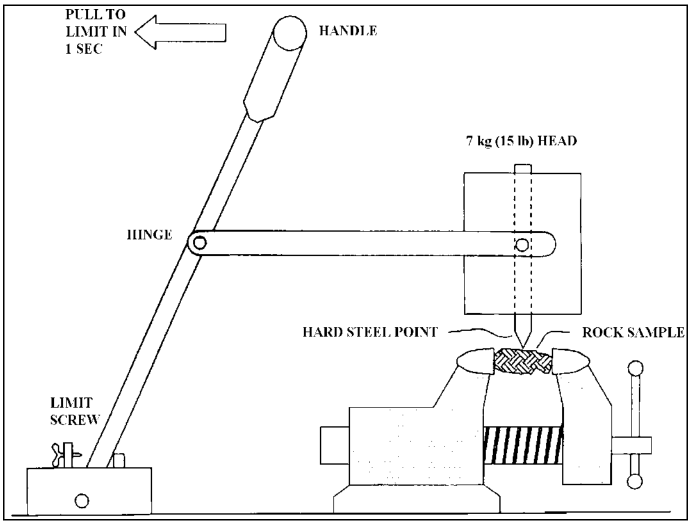


Figure 7. Cerchar Test Equipment.

3.1.2 Rock Mass Properties

In foliated/bedded rock, foliation can play a significant role in rock fracture propagation between cuts, depending on the foliation direction with respect to the direction of machine advance. Figure 8 illustrates the orientation of foliation planes with respect machine advance. Angle "α" is defined as an angle between tunnel axis and the foliation planes

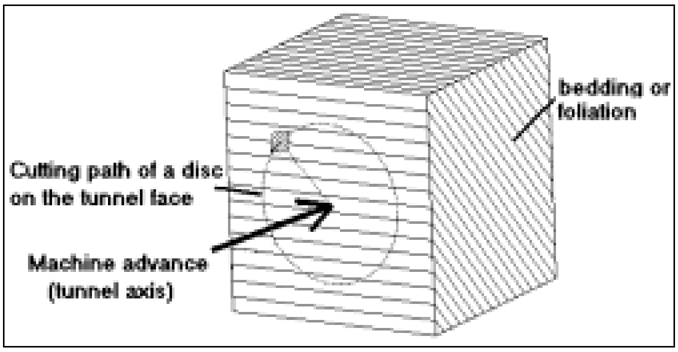


Figure 8. Definition of Foliation angle with respect to machine advance.

When machine advances parallel to foliation planes (Figure 9), crack propagation is forced to occur across the foliation planes. This reduces machine penetration because of increased difficulty of rock breakage.

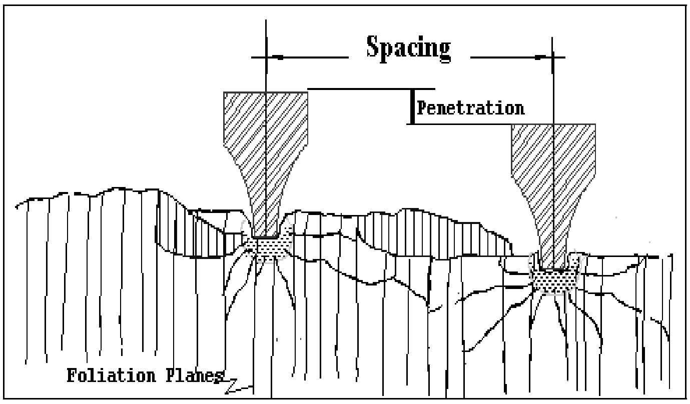


Figure 9. Cutting direction parallel to foliation.

When the foliation is perpendicular to direction of machine advance, rock failure occurs along foliation planes as shown in Figure 10. This case generally represents the most favorable boreability as the foliation planes assist crack initiation and growth between adjacent cuts.

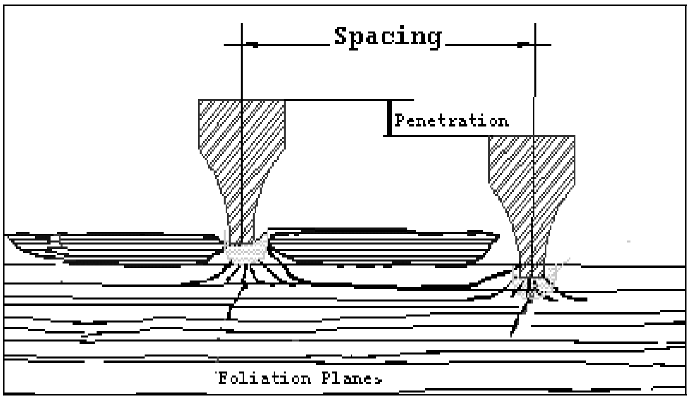


Figure 10. Cutting direction perpendicular to foliation.

One way to integrate the foliation effect in machine performance modeling is to measure the tensile strength of the rock in different directions as shown in Figure 11. The loading direction of the sample can be selected based on the machine advance with respect to foliation/bedding planes in order to represent the crack propagation across or along the weakness planes.

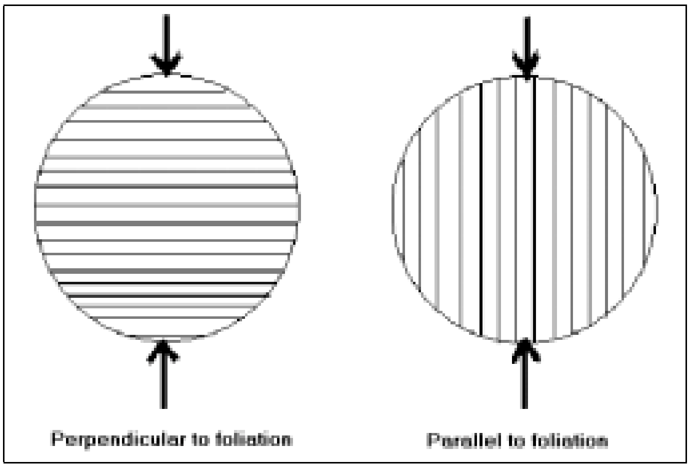


Figure 11. Loading direction for tensile testing.

Joint sets in the rock mass can also have a major effect on machine performance. The studies performed by NTNU (Norwegian University of Science and Technology) provide one of the most extensive database for estimating the ROP based on rock mass properties (Bruland & Nilsen, ISRM 1995). Rock mass fracturing means fissures and joints with little or no shear strength along the planes of weaknesses. Joints are continuous; they may be followed all around the tunnel contour. Fissures are non-continuous; they can only be followed partly around the tunnel contour. Table 5 shows the class for joints and fissures used in NTNU model. The smaller the distance between the fractures, the greater the influence on the penetration rate of the machine.

Table 5. Joint and Fissure Classes.

Class	Spacing (cm)
0	-
0 – I	160
I –	80
I	40
II	20
III	10
IV	5

The fracture factor k_s for fissures and joints is shown in Figure 12, as a function of fissure or joint class and angle between the tunnel axis and the planes of weakness (α angle). From this figure, "k_s" can be determined for each set of weakness planes. Based on this information, the effect of fissures and joints is evaluated on the penetration rate of the machine.

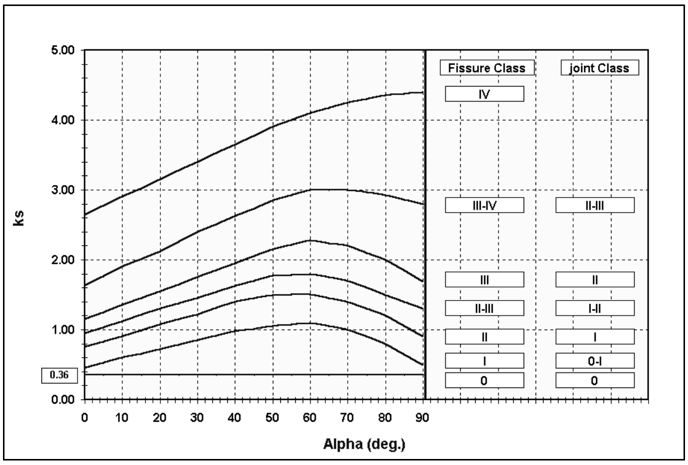


Figure 12. Determination of k_s fracturing factor.

Geological conditions to be encountered such as 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, which is a key parameter in scheduling. Analysis of field performance of different TBM projects is the foundation for estimating the effect of these geological features in the rock mass.

3.1.3 Cutter Geometry

Cutting tools provide for the transmission of energy generated by the machine to the rock in order to cause fragmentation. As a result, the geometry and wear characteristics of the cutting tool have a significant effect on the efficiency of energy transfer to the rock and the attainable rate of penetration.

Single disc cutters are the most commonly used roller cutters for hard rock Tunnel Boring Machines (Figure 13). They are the most efficient types of rolling cutters since the entire capacity of the bearing is concentrated into a single, narrow edge.

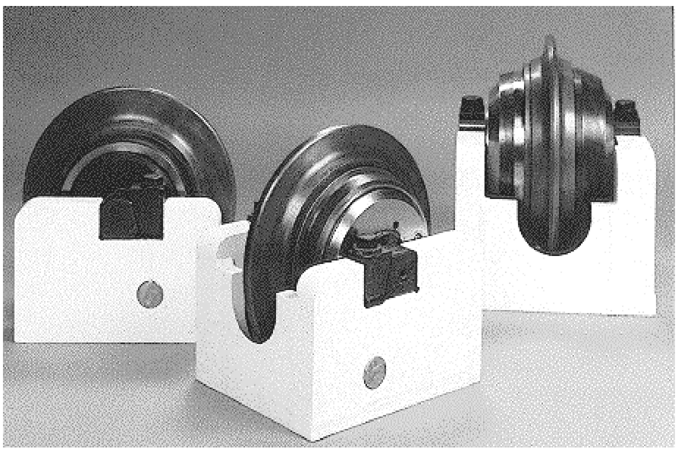
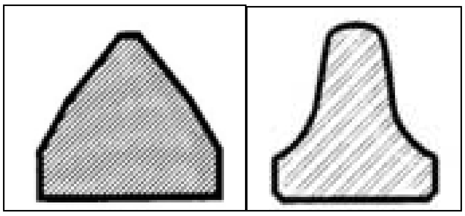


Figure 13. Single Disc Cutters.

Until about two decades ago, disc cutters utilized on TBMs featured a V-shaped edge profile (Figure 14A) with an included angle varying from 60 to 120 degrees. Although this profile provided for high rates of advance when the cutter was new, its performance, as expected, was found to drop rapidly, as edge wear developed and the rock-cutter contact area became larger. To ensure a more consistent cutting performance with increasing edge wear, the so-called constant-cross section (CCS) cutters were developed. The CCS cutters (Figure 14B) are designed to maintain a more or less constant profile as edge wear occurs. This means the machine performance does not decline as rapidly with cutter wear. These advantages have led to the CCS cutters becoming an industry standard on TBMs.



(A) (B)

Figure 14. (A) V-shape and (B) CCS disc cutter profiles.

The ring diameter is another variable, which affects disc cutter performance. Since their introduction, disc cutters have steadily grown in size from about 305 mm to present-day 483 mm cutters. Development work for even bigger size cutters is underway. For the same thrust load on the cutter, increased diameter causes a reduction in the depth of cutter penetration into the rock because of larger cutter footprint area. However, larger cutters provide for higher bearing capacity, which more than offsets the performance loss brought about by the wider cutter-rock contact area. In addition, larger cutters rotate slower for a given machine rpm which means less heat generation during boring. They also contain more cutter material to wear out before replacement becomes necessary, again contributing to longer ring life. All these features combined thus lead to improved cutter life and reduced excavation costs.

3.1.4 Cutting Geometry

The cut spacing and the depth of the cutter into the rock per cutterhead revolution define the efficiency of the cutting by disc cutters.

As would be expected, the spacing of cutters has a significant impact on the chipping mechanism and the efficiency of boring. As shown in Figure 15, there exists an optimum spacing for a given cutter penetration where the interaction between adjacent cuts is maximized. This optimal spacing is usually expressed as the ratio of spacing to penetration. Extensive past research and field data analysis have shown that to achieve optimal cutting efficiency, this ratio should be maintained between 10 to 20; with lower ratios used for tougher rocks and the higher ratios approaching to 20 for more hard and brittle rock. The manufacturers extensively use this ratio when they design the cutterhead.

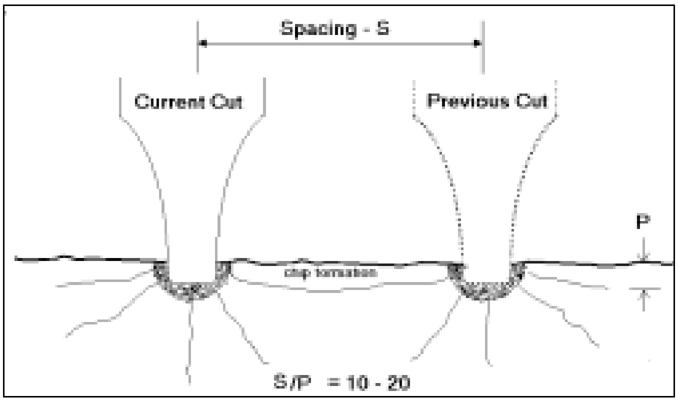


Figure 15. Effect of S/P ratio on cutting efficiency.

3.1.5 Machine Specifications

The machine specifications, such as thrust and power are the key to providing sufficient amount of forces and torque to support the excavation operation. Machine thrust should provide the enough force to efficiently penetrate the tools into the rock surface. Also, the cutterhead torque and power requirements to rotate the head at the required penetration rate and overcome the rolling force resistance of the cutters has to be determined and installed on the head.

3.1.6 Operational Parameters

In every mechanical mining operation, there are some operational constraints, such as the haulage capacity, ground support requirements, water-handling, etc. that limit the productivity of the machine. In addition, other factors such as tunnel grade and curves impact machine utilization and consequently productivity. All these factors must be taken into account when application of mechanical excavator to a particular operation is considered.

3.2 Performance Prediction for TBMs

The CSM/EMI computer model for hard rock TBMs is based on the cutterhead profile and rock properties. The model utilizes semi-theoretical formulas developed at EMI over the last 25 years to estimate the cutting forces. The output of this model consists of the cutterhead geometry and profile, individual cutting forces, thrust, torque, and power requirements, eccentric forces, moments, and finally variation of cutting forces as the cutterhead rotates.

The first step in performance estimation involves characterization of the rock and the geologic conditions. This is provided by the intact rock and rock mass properties mentioned earlier.

The next step is to select the proper cutting tool and cutting geometry. Disc cutters are the most commonly used cutting tools for TBMs. The only parameters need to be taken into account are cutter diameter and cutter tip width. Table 6 gives the commonly used disc cutters on today's TBMs.

Table 6. Disc Cutters for TBMs.

Cutter Diameter, mm	Max. Cutter Load, kN	Cutter Tip width mm
432	222	15.875
	267	19.05
483	311	19.05

After selection of cutter and cutter geometry, the forces acting on the cutters are estimated or measured. The algorithms have been derived from extensive full scale testing performed over the two decades at Earth Mechanics laboratory of Colorado School of Mines.

If rock samples are available, cutting forces can be also measured through full scale testing on the LCM. The LCM (Figure 16) features a large stiff reaction frame on which the cutter is mounted. A triaxial load cell, between the cutter and the frame, monitors forces and a linear variable displacement transducer (LVDT) monitors travel of the rock sample. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing.


Figure 16. Linear Cutting Machine.

LCM test can be used not only for measurement of cutter forces, but also to select the most suitable cutter in order to achieve the most efficient cutting.

This means different diameter cutters with different tip widths can be tested in order to observe their performance at different spacings and penetrations. Actual rock sample from the field can also be tested. This eliminates the need for any scaling effects.

After the selection of cutter type, cutting geometry and determining the cutting forces, the next step is to optimize the cutterhead design and cutter lacing on the head. Among the parameters influencing the performance of a mechanical excavator, the easiest parameter to control is the cutterhead design. The input data for cutterhead design and simulation comes from the previous steps, which are the cutter type, cutting geometry and the required cutting forces to achieve the desired rate of penetration and the minimum specific energy. Simulation of the cutterhead is also used to calculate the machine parameters, such as thrust, torque and power requirements. Rather than working with average cutter spacings and forces, CSM/EMI model analyzes each cutter individually since actual cutter forces vary across the cutterhead depending on their location and angle with respect to machine axis (Figure 17). In case of an existing machine, required machine parameters are first calculated and then evaluated to determine if the machine is able to sustain the estimated or desired rate of penetration.

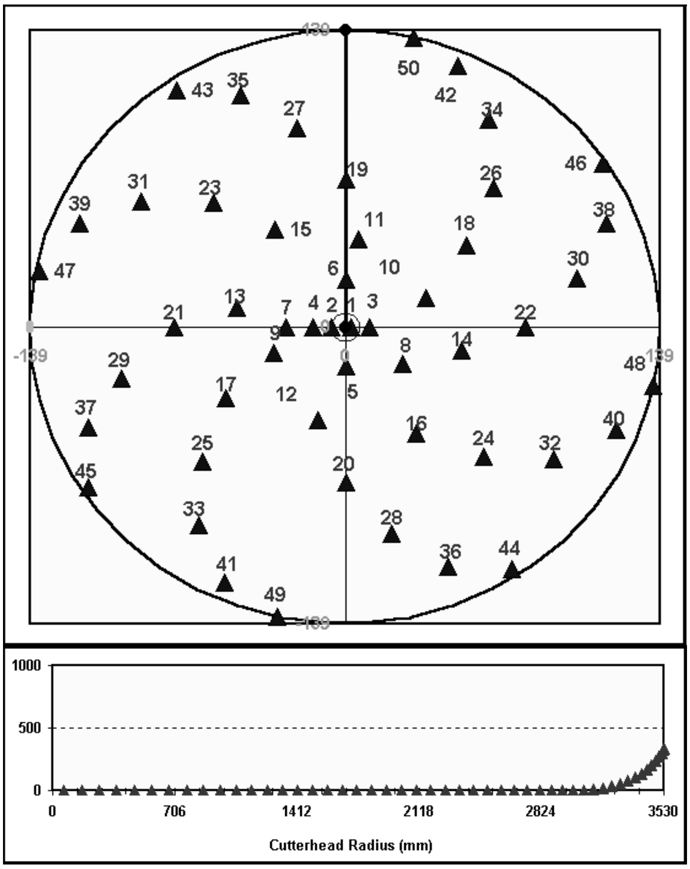


Figure 17. Cutterhead profile

The program then calculates the penetration rate on an iterative basis until one of the machine limits in terms of thrust, power or cutter load capacity is exceeded. The same calculation is repeated for each rock type in order to evaluate the machine performance in a given geology. An example output for one of the geologic zones is presented in Figure 18. The program also includes a plot, which describes the capability of the given machine at different rock strengths as shown in Figure 19.

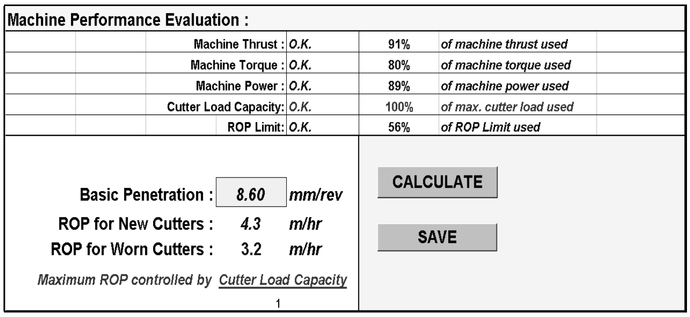


Figure 18. Calculation of ROP

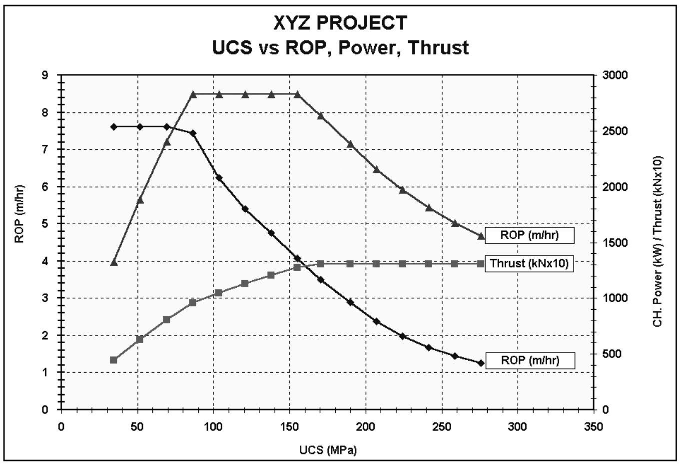


Figure 19. Relationship between UCS and Machine Thrust, Torque, Power

If the rate of penetration and machine parameters are known, back up and mucking systems of TBM can be designed to match the tunnel advance rate.

The last step in modeling of any TBM application is the scheduling and cost analysis. There are two important numbers in modeling of a TBM job. Those are rate of penetration, which is estimated from rock, and machine properties that the machine can achieve, and machine utilization, which is the net boring time as a percentage of the total working time. The total available working time cannot be entirely utilized to excavate rock. It is reduced by equipment and job site related down times. Once machine utilization is estimated, daily advance rate (m/day) can be calculated from rate of penetration and machine utilization. This calculation needs to be repeated for all the reaches if the tunnel drive is divided into sections in terms of geological conditions and technical requirements of the project. This will help the designer determine the time required to excavate the tunnel and the overall costs.

Table 7 illustrates an example of CSM/EMI model output for scheduling of a typical TBM tunnel.

Table 7. Example output of a scheduling

Rock Type	Section #	Length (m)	Slope (%)	Curvature (YES/NO)	ROP (m/hr)	Machine Utilization %	Advance Rate m/day	Completion time	
								days	months
Sandstone	1	2530	1	NO	6.4	35%	16.3	155	6
Granite	1	1463	1	NO	2.6	30%	5.8	253	10
Gneiss	1	457	1	YES	2.1	25%	3.8	122	5
Gneiss	2	1524	1	NO	2.1	30%	4.5	338	14

4 CONCLUSIONS

There are several special issues that have to be identified and dealt with when introducing a new piece of equipment in mining operations. The past experience with TBMs in mining industry has shown that a thorough study is needed to match the machine and the surrounding environment. The issues, which need to be considered, include:

1. Multiple speed cutterheads to provide a high torque at lower speed for operating in highly fractured/blocky ground

2. The use of back-loading cutters to avoid unnecessary delays and potential safety problems associated with cutter changes in the face.

3. Ability to install a variety of ground support measures such as bolts, wire-mesh, shotcrete, and steel sets where the ground is first exposed. Rock drills for roof bolting, ring beam erector for steel sets installation, and probe hole drilling equipment too see what is ahead of the machine are some of the features that should available on the machine.

4. The circular shape created by TBM may not be suitable for certain mining applications in particular the haulage drifts. There are options available to resolve this problem. One alternative is to utilize TBM generated muck to backfill behind the machine to provide a flat floor. The shape of the TBM drift can also be modified to a more suitable geometry by a secondary excavation operation using drill and blast. Another option is to mount a set of boom cutters on sides of the TBM to produce a horseshoe shaped entry.

5. A better understanding of expected ground conditions will allow for optimization of machine design to fully cope with the ground conditions to be encountered.

6. Improved performance prediction so that project economics and completion schedules can be assessed more accurately.

REFERENCES

Allum, R. & VanDerPas, E. 1995. TBM Technology in a Deep Underground Copper Mine. *Rapid Excavation and Tunneling Conference: 129-143*

Alexander, C. 1999. Development of Stillwater Mining Company's East Boulder Project Using Tunnel Boring Technology. *SME Annual Meeting*. Denver CO, USA: 1-8

Cigla, M. & Ozdemir, L. 2000. Computer Modeling For Improved Production of Mechanical Excavators. *SME Annual Meeting. Salt Lake City UT, USA*

Bruland, A., Nilsen, B. 1995. Tunneling Performance Estimation based on Drillability Testing. *Proc. 8th ISRM Congress on Rock Mechanics*. Vol. I: 123-126

Rostami, J. Ozdemir, L. and Nilsen, B. 1996. Methods for Predicting Mechanical Excavation Performance and Costs, *Proceedings of Annual Technical Meeting of the Institute of Shaft Drilling Technology (ISDT), Las Vegas, May 1-3, 1996.*

Ozdemir, L. 1990. Recent Developments in Hard Rock Mechanical Mining Technologies" *4th Canadian Symposium on Mine Automation, Saskatoon, Canada, Sept. 1990.*