Computer Modeling
For Improved Production of Mechanical Excavators

By:

Mehmet Cigla and Levent Ozdemir

[1]Excavation Engineering & Earth Mechanics Institute
Department of Mining Engineering
Colorado School of Mines
Golden, Colorado, USA

ABSTRACT

This paper presents and discusses some of the computer models developed and currently used at the Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM). These include the performance models for full and partial face machines. Examples of input and output of these models will be illustrated for typical mining operations by using machines such as Tunnel Boring Machines (TBM), Continuous Miners (CM), Marietta borer miners and longwall drum shearers. The general approach to modeling and the available models are discussed and some examples of these models are presented. The comparison between the estimated and achieved performance, as well as the degree of improvement in the performance due to balancing and modification in cutterhead design are also discussed.

INTRODUCTION

Mechanical excavators are specialized machines that are capital intensive and site specific. To maximize the benefits of the mechanical excavators (i.e. higher production and lower costs, automation, consistent product size, and safer working environment) to any operation, performance of these machines under specific conditions must be understood. For this purpose, several models have been developed over the years to evaluate the design parameters and their impact on machine performance and also to estimate the production and advance rate of different mechanical excavators. These models are used not only to predict the performance of a given machine in an identified geology, but also to optimize cutter head designs and specify mechanical requirements to achieve production requirements.

These computer models have been developed by using data from rock mechanics testing (UCS, tensile strength, and e.t.c.) and full-scale cutting tests (Linear Cutting Test), and calibrated with field performance data. They have been proven to offer reliable performance estimates, and produce information for improvement of the cutterhead design and layout. Cutterhead design and simulation through computer modeling is the key for designing any mechanical excavator in terms of optimization and production improvement. This method provides for simulating different rock properties, machine conditions, and operational parameters of the mine.

In the mining industry there is a growing demand for rapid and often large-scale excavation in order to develop new orebodies in a faster manner. This generates a cost saving by allowing ore production sooner. The majority of large civil engineering tunneling projects is now carried out by mechanical excavation rather than drill & blast methods. However, drill & blast is also a developed technology, and the choice of method is a matter of economy. Despite of the cost effectiveness of drill & blast in short term, mechanical excavation has many advantages over the conventional drill & blast technique in long term. These include:

- High productivity/Advance rates
- Improved safety
- Minimal ground disturbance
- Reduced support requirement
- Elimination of blast vibrations
- Reduced ventilation requirements
- The uniform muck size, which allows for the conveyor belts
- It is highly conducive to remote control or full automation

All these advantages resulted in mechanical excavation taking a greater share of the rock excavation market for the construction of tunnels, drifts, raises, shafts, any other type of underground openings for both mining and civil engineering purposes. Especially with recent development of versatile machines capable of effectively coping with different ground conditions, the mechanical excavation industry is destined to play a much bigger role in future construction projects. Further, the mining industry is beginning to show a greater interest in mechanical excavation technology as efforts to develop hard rock mobile miners are beginning to show great promise.

PARAMETERS INFLUCING MACHINE PERFORMANCE

The parameters influencing mechanical excavation performance can be divided into six groups:

- Intact Rock Properties
- Rock Mass Properties
- Cutter Type
- Cutting Geometry
- Machine Specifications
- Operational Parameters

Proper application of the mechanical excavators to any mining or tunneling operation depends on the detailed understanding of the parameters described above.

Intact Rock Properties:

It is well known and established that uniaxial compressive strength (UCS) provides the best single indication of rock boreability. Yet, mechanical cutting predictions relying only on the compressive strength may provide widely inaccurate results. Several other intact rock physical property tests may be performed to greatly increase the accuracy of performance predictions for mechanical excavations.

UCS should be measured in accordance with the procedures in ASTM D2938, usually with NX, or 54-mm

(2.125-in) diameter, core samples. The samples should then be prepared to satisfy the requirements of ASTM D4543, When rock volume is limited, EX size core (21-mm) can be used if the material is not too coarse-grained, and diameter must be greater than ten times average grain size. A minimum of five UCS determinations is recommended for statistical significance of the resulting average for the performance prediction and computer modeling of any mechanical excavators.

Tensile strength is another common rock property, which is commonly used in making boreability predictions along with the uniaxial compressive strength of the rock. This parameter is measured using NX-sized core samples cut to a 0.5 length**:**diameter ratio, and following the procedures of ASTM D3967. Brazilian Tensile Strength (BTS) is generally intended to provide an indication of rock toughness from a viewpoint of crack propagation between adjacent cutter paths.

Also, rock abrasivity plays a major role in the cuttability evaluation. For measuring abrasivity, 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 1. 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.

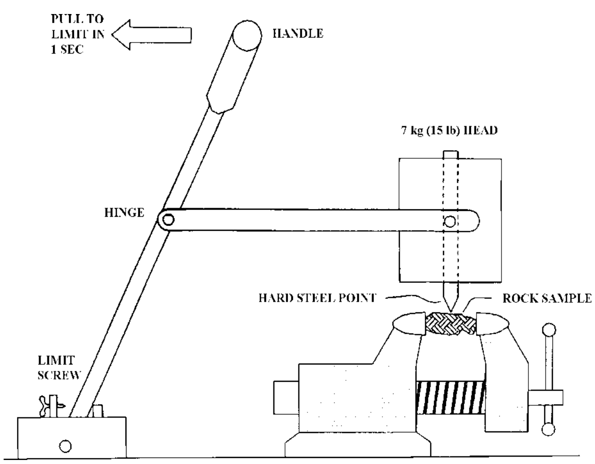

Figure 1. Cerchar Test Equipment

Perhaps one of the most crucial rock properties which affects boreability by mechanical means 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. But tensile strength of the rock sample may not be the real indication of the rock brittleness. One of the tests which helps to define the brittleness of the rock in the laboratory is the Punch Penetration test. In this test, a standard indentor is pressed into a rock sample that has been cast in a confining ring (Figure 2). 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.

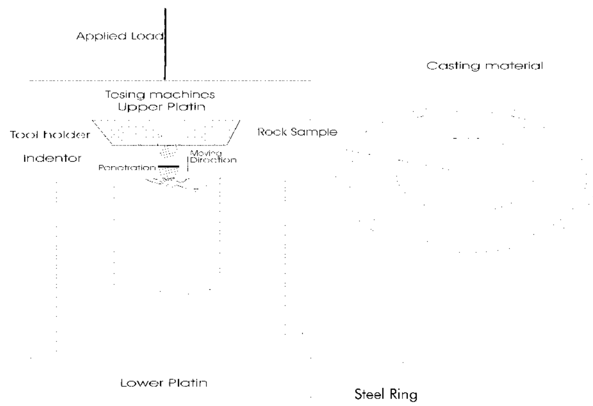

Figure 2. Program Output for Punch Penetration Index

The velocities of compressive and shear ultrasonic waves through the core sample are measured and used to provide an inexpensive way to estimate the elastic modulus and Possion's ratio. Factors such as anisotropy and porosity affect the results, and a minimum of five measurements is recommended in relatively homogenous rock. This mesurement is performed in accordance with the procedures recommended by ASTM D2845, usually on core samples prepared for UCS testing. Figure 3 illustrates the components used in this test.

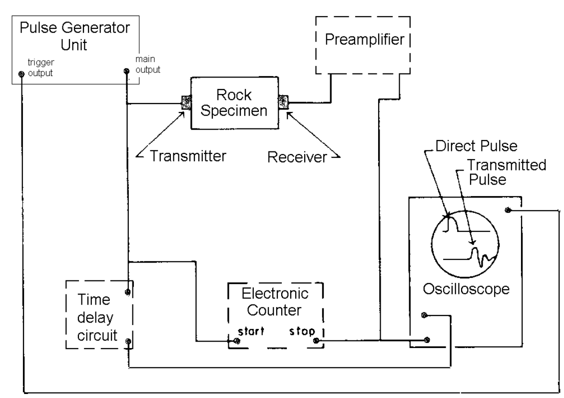

Figure 3. Acoustic Pulse Velocity

Rock Mass Properties:

Geological conditions to be encountered such as joints, 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 as well as instantaneous rate of penetration. Joints and fractures will effect the performance of a mechanical excavator depending on their orientation, frequency, and type. Obviously, opening stability and the support requirements are also affected by the presence of joints and fractures.

Cutter Type:

A crucial aspect of any mechanical excavation system is the cutting tool, which performs the actual rock penetration under certain amount of thrust and torque provided by the mechanical excavator. Cutter types may be classified in two general categories: Rolling cutters and drag bits.

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

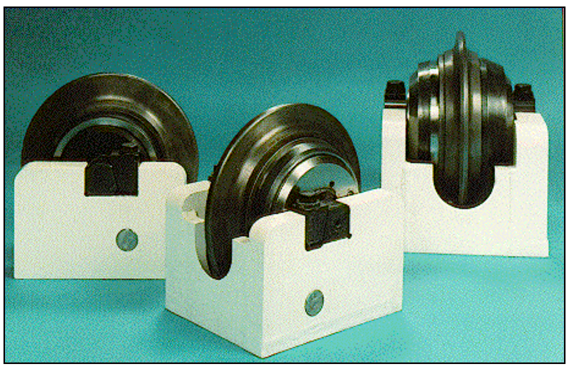

Figure 4. Single Disc Cutters (Robbins)

The second type of roller cutters are the button or strawberry cutters. Button cutters are used on raise boring and shaft drilling applications for various reasons. First, they last longer in terms of footage bored, meaning less often cutter change operations. This is a highly beneficial feature for raise or shaft boring to minimize the cutter changes. In raise or shaft drilling operations, all cutter thrust and power has to be transferred through a drill pipe, severely restricting the amount of load which can be placed on individual cutters on the head. Further, the stiffness of a TBM cutterhead cannot be developed in a raise or shaft bit, unless grippers are provided down hole.

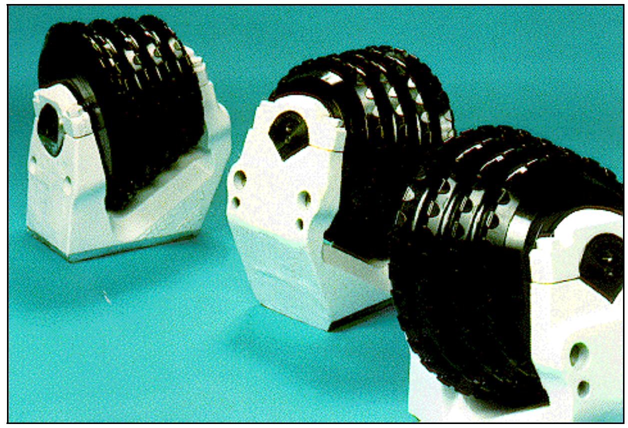

Figure 5. Button Cutters (Robbins)

The two main types of drag cutters in the mining industry are radial and conical bits. Radial cutters are limited to the excavation of softest and least abrasive materials. Continuous miners, longwall shearers and borer miners are the typical mechanical excavators, where radial cutters can be used to cut the softer material such as coal, trona, and salt. While new radial cutters are the most efficient cutters, they are very susceptible to wear. The slightest visible wear on the tip of a radial cutter can increase normal force requirements by 2-3 times. Figure 6 shows example of different radial cutters.

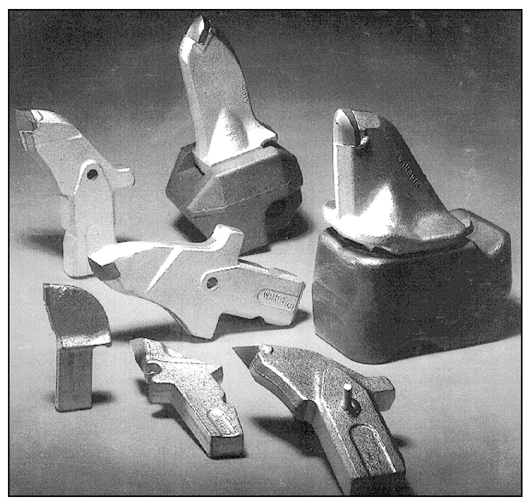

Figure 6. Cutting by Radial Cutters (Sandvik)

The second type of drag cutters are conical bits, which are typically used on continuos miners and longwall sheares to cut the harder rock compared to radial bits, as well as roadheaders. They are more durable than radial cutters and have a self-sharpening property, which is an advantage for longer cutter life compared to radial bits. As a rule of thumb, conical bits are not considered economical for excavation of rocks having compressive strength more than ~80 MPa (~12,000 psi), due to occurrence of extensive bit wear or premature structural failure, compared to rolling cutters. Higher strength rocks may be excavated by conical bits, if the rock mass is significantly weakened by the presence of joints, fractures, bedding or foliation.

Soft rock ***Medium hard rock*** ***Hard rock***

Full Assembly

Figure 7. Conical Bits (Kennametal)

Cutting Geometry:

Cutting tools provide the transmission of the energy by the machine to the rock in order to fragment it. As a result, the geometry and wear characteristics of the cutting tool have a significant effect on the energy transferred to the rock and attainable rate of penetration. The two main factors of cutting geometry, independent of cutter type, are spacing and penetration. Their relationship, along with cutter type and rock properties, controls the efficiency of the cutting process. Also, each of the types of cutters have geometry concerns, which affect the efficiency of cutting.

Cutting geometry of the single disc cutters is defined by its diameter and edge profile. The cut spacing and the depth of the cutter into the rock per cutterhead revolution define the efficiency of the cutting by disc cutters (Figure 8).

Efficient excavation by disc cutter correlates with the formation of large chips between disc cutter paths. A crushed zone develops beneath the cutter as it is forced into the rock. As stresses continue to build up in the crushed zone, radial cracks begin to form and propagate into the rock. When one or more of these cracks meet those developed from adjacent cut, chips are released.

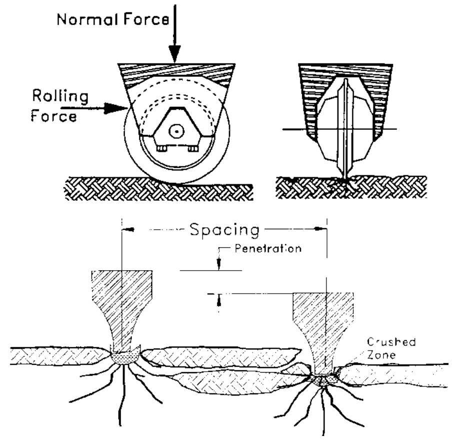

Figure 8. Chip Formation by Disc Cutter

The basic cutting and geometrical variables associated with the operation of button or carbide insert cutters are illustrated in Figure 9. The parameters related to cutter geometry include cutter diameter, button size, row spacing and pitch of buttons on the cutter. The rock fragmentation by button cutters is similar to disc cutting, but much smaller particles of broken rock are generated.

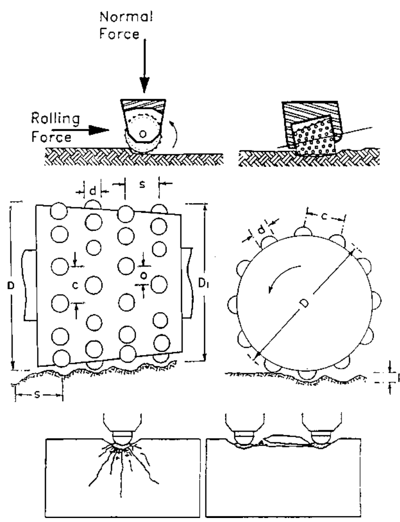

Figure 9. Variables of Button Cutters

The design of the radial bit can be described with a few features, which determine how it will cut the material. Figure 10 shows the cutting action, and the related nomenclature for radial bits.

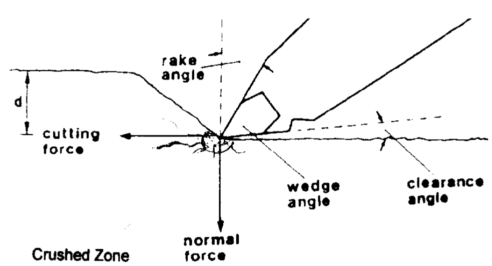

Figure 10. Cutting Geometry of Radial Cutters

The tip of the tool is generally flat with relief angles on the side. The reason for this is to minimize the friction and resistance to tool through the material to be cut. Low friction and resistance will reduce cutting forces, power consumption, vibration, and dust levels.

The rake angle describes the angle between the front of the tip and the shank. A positive rake will ensure a more aggressive cut but will also normally make the tip weaker. A positive rake of 5-10 degrees can be used to cut soft formations at higher rates. A zero rake angle is the most common for various conditions. A negative rake angle will normally keep the tip in compression during cut and thus will have a reduced risk of fracturing. This design may have a tendency to cut slower but last longer.

The clearance angle is the angle between the front of the tip and the edge of the tip. This angle ensures that the tip will not be in contact with the material to be cut all the time, which would lead to loss of energy, excessive heat, and reduced life of the tool.

In addition to the angles, the dimensions and the shape of the carbide are important factors to consider. The front face of the radial bit is normally a chevron (V shape) and has either two flat surfaces or curved surfaces. The curved surfaces have the advantage of making the insert stronger. This curved tip is used in harder cutting conditions.

The basic styles of point attack picks were shown in Figure 7. They have circular shanks and are mounted in a circular holder to allow for rotation and thus theoretically experience even wear during use. The conical carbide tip penetrates the material being cut during a linear or rotational motion. The tool is held in place at certain skew angle to force rotation for the self sharpening effect.

The efficiency and the cutting forces on these bits depend on the shape of the carbide tip. The geometric parameters of the tip include the size of the carbide, which are the diameter of the insert or the cap, the cone angle and the shape of the body. The larger the carbide, the harder the rock it can cut. The tip angle of the carbide has a major impact on the cutting ability and efficiency. Smaller carbides with sharp tips (60^0 - 70^0) are used in soft rock applications such as gypsum, trona, coal, and salt. Larger tip angles (70^0 – 75^0) should be used for harder rock conditions, such as sandstone, limestone, and siltstone. The attack angle of the conical bits plays a major role in the cutting efficiency and tool life. The best attack angle for the conical bit should be along the resultant of normal force (F_N) and cutting/drag force (F_C). In other words, when the resultant force is along the axis of the tool, the tip is always compressed against the body and the body against the holder (Figure 11). This minimizes the bending moments and tension along the tool, thus increasing cutter life.

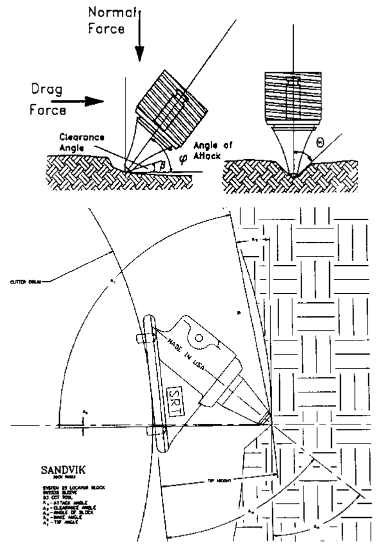

Figure 11. Cutting Geometry of Conical Cutters

In softer rocks, the depth of penetration is typically higher and therefore, the resultant of the normal and cutting/drag force is lower than that experienced in harder rock. This means that the attack angle should be reduced in softer rock. The lower cone angles of the smaller conical tools allow for lower attack angles (45^0 - 48^0) while maintaining a clearance angle between the back of the tool and the rock. In harder rock the opposite is true and lower cutting forces lead to the use of higher attack angles (up to 52^0). This is also consistent with bigger tip angles used on heavy-duty conical bits.

The effect of variation of spacing (S) and penetration (P), and S/P ratio, their impact on the cutting efficiency has been studied extensively in the past. It has been observed that depending on the rock type and cutter type, there is an optimum S/P ratio that can produce the most efficient cutting in terms of minimum specific energy requirements. This optimum ratio can best found by full scale testing, such as Linear Cutting Machine (LCM). Extensive past research and field data analysis have shown that to achieve optimal cutting efficiency with single disc cutters, this ratio should be maintained between 10 to 20; with lower ratios used for tougher rocks and approaching to 20 for more hard and brittle rock (Figure 12). The optimum S/P ratio for drag cutters ranges 1 to 5.

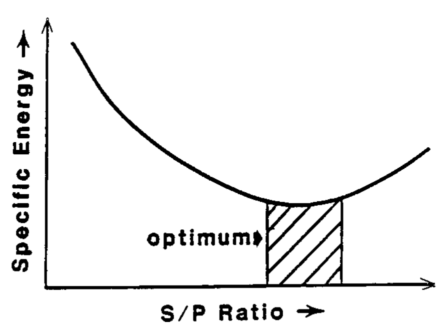

Figure 12. Typical optimum S/P ratio curve

Machine Specifications:

The machine specifications, such as thrust, torque 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 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 (or drag force) resistance of the cutters has to be determined and installed on the head.

Machine specifications must ensure that the requirements are supplied to the cutterhead. In other words, mechanical and operational losses must be accounted for. Mechanical losses are typically provided by manufacturers of gearboxes and other power transfer components. Operational losses for TBMs include towing load and skin friction. For CMs, operational losses include boom stiffness and track spillage.

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.

MODELING LOGIC FOR MECHANICAL EXCAVATORS

Figure 13 illustrates the typical steps taken in the modeling and analysis of mechanical excavators. The first step always 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. With this done, the forces acting on the cutters may be estimated or measured.

In order to estimate the cutting forces, a semi-theoretical model is used. Rock properties and cutter geometry are used as input. The base algorithms are based on extensive full scale testing performed over the two decades. If a higher confidence level is required, cutting forces can be measured through full scale testing on the LCM.

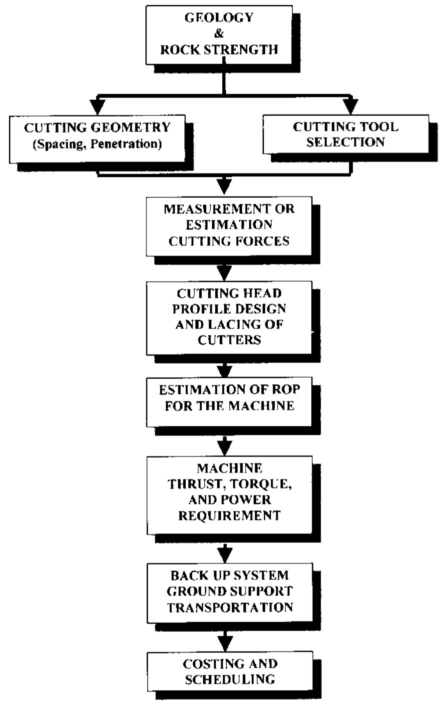

Figure 13. Flow Chart for Modeling Steps

The LCM (Figure 14) 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.

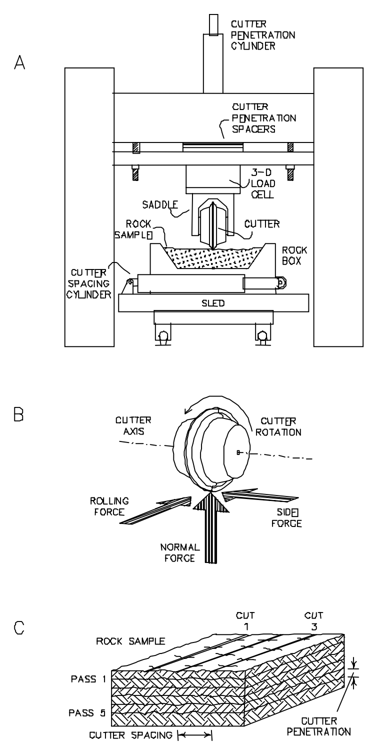

Figure 14. LCM (A) Machine (B) Cutting Forces (C) Cutting Geometry

The normal force requirements are used to calculate necessary effective mass and thrust required of the machine. This is important to ensure that the machine is able to provide the necessary thrust, so the cutters can effectively penetrate into the rock. The rolling/drag force is directly related to the torque requirement of an excavator, and is used to calculate the specific energy requirement. Specific energy is defined as the amount of energy required to excavate a unit volume of rock. Using the specific energy (hp-hr/yd^3), achievable production rates are calculated for a machine with a known horsepower available on the cutterhead. Lower specific energy means that a given machine will produce more material, or that a smaller/less expensive machine may be used to produce the required amount of material. The side force may be used along with normal force and rolling force to balance the cutterhead design.

After the selection of cutter type, cutting geometry and determining the cutting forces, one should consider 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. Input data for cutterhead design and simulation comes from the previous step, which are the cutter type, cutting geometry and cutting forces at certain cutting geometry in order to achieve the desired rate of penetration and the minimum specific energy. After establishing the input data, computer simulation can be performed in order to see whether the new design cutterhead will achieve the desired rate of penetration and will evaluate balance in terms of minimum vibration during the excavation in a given rock conditions and cutting geometry.

Simulation of the new cutterhead can calculate the machine parameters such as thrust and torque based on the cutting forces from LCM or theoretical models. 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.

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

The last step in modeling of any mechanical excavator is the scheduling and cost analysis. There are three important numbers in modeling and costing of a mechanical excavator job. Those are rate of penetration, which is estimated from rock and machine properties that the machine can achieve, machine utilization, which the net boring time as a percentage of the total working time, and abrasiveness of the rock relating to cutter wear.

CSM-EMI MODELING CONCEPT

The principal concept used in the EMI models is to program each cutter individually. The position of the cutters on the cutterhead is defined by geometrical parameters such as spacing, distance from the center and the angular position. The cutterhead geometry is defined by a polar coordinate system for Tunnel Boring Machines. For partial face machines, which represent a 3D problem, a cylindrical coordinate system is utilized. The models will then calculate the penetration per revolution for each cutter and estimate the cutting forces required to penetrate the rock. These forces in turn are used to calculate cutterhead thrust, torque and power requirements. This concept allows modeling any cutterhead layout, pattern, or configuration for design or performance analysis. Another advantage of the computer models for cutterhead optimization is, to balance the cutterhead to minimize the vibrations, thus reducing cutter wear and machine downtime for maintenance.

Tunnel Boring Machine (TBM):

The most commonly used full-face machines are Tunnel Boring Machines (TBM), Raise Borers, and Shaft Drilling machines. CSM computer models are currently available for design optimization and balancing of the cutterhead of these machines. The CSM/EMI computer model for hard rock TBMs is based on the cutterhead profile and intact rock properties. The model utilizes semi-theoretical formulas developed at EMI over the last 25 years to estimate the cutting forces. The output of these models consists of the cutterhead geometry and profile, individual cutting forces, thrust, torque, and power requirement, eccentric forces, moments, and finally variation of cutting forces as the cutterhead rotates. Design modifications can be performed in the models to balance the cutterhead and minimize the eccentric forces and force variations. This is very important in increasing the production rate, cutter and main bearing life, and utilization. Figure 15 shows an example of the input sheet for the program. The information required for the program are project information (project name, location, tunnel diameter, etc.), machine information (cutterhead diameter, geometry of the disc cutters, machine specifications, cutterhead profile if available, etc,), and rock information (UCS, tensile, e.t.c.).

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TBM PERFORMANCE PREDICTION

Tunnel and Machine Input Data

Unit System for Calculations?:	2	1 - English System		
		2 - Metric System		
PROJECT AND TUNNEL INFORMATION				
Project Name:	XYZ	Tunnel Diameter:	7.06	m
Location:	A	Total Length:	3,000	m
Contractor:	B	Area:	39	m2
Owner:	C			
MACHINE SPECIFICATIONS				
Machine Type:	Open Beam	Total Installed Thrust:	15,570	kN
Cutterhead Diameter :	7.06 m	Thrust Efficiency :	90%	
Cutterhead Radius :	3.53 m	Net Cutterhead Thrust:	14,013	kN
No. of Cutters:	50	Max. Cutterhead Torque:	3,625	kNm
Cutterhead RPM:	8.3 rpm	Drive Efficiency:	90%	
Cutter Type:	DISC	Net Cutterhead Torque :	3,263	kNm
Cutter Diameter:	482.6 mm	Total Installed Power:	3,150	kW
Cutter Tip Width:	19.05 mm	Net Cutterhead. Power:	2,835	kW
Maximum Cutter Load:	311 kN	ROP Limit :	7.62	m/hr
Max. Linear Speed:	152.4 m/min	Cutter Wear Effect:	25%	
DO YOU HAVE CUTTERHEAD PROFILE?	1	1 - YES		
		2 - NO		
IF NO, WHAT IS THE FACE CUTTER SPACING?	86.36	mm		

Figure 15. Input Data for TBM Model

Next step in the model is to calculate the cutting forces and required machine parameters to achieve the desired rate of penetration (ROP, ft/hr or m/hr). This program calculates the above parameters for different rock zones defined by the user, and gives the results in a table form, including project, tunnel, and machine specifications. An example output for one of the geologic zones is presented in Figure 16. It also includes a plot, which describes the capability of the given machine at different rock strength (Figure 17).

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TBM PERFORMANCE PREDICTION

TBM PERFORMANCE PREDICTION

Machine Specifications :		Input Data for Geologic Zone	
Machine Type:	Open Beam	Rock Type :	Granite
Cutterhead Diameter :	7.06 m	Rock Origin:	3 Igneous
No. of Cutters:	50	UCS :	138 MPa
Cutterhead RPM:	8.3 rpm	BTS:	14 MPa
Cutter Type:	DISC	Density:	2.5 gr/cm3
Cutter Diameter:	482.6 mm	Grain Size:	1.0 mm
Cutter Tip Width:	19.05 mm	Porosity:	1.0 %
Maximum Cutter Load :	311 kN	CAI :	4.5
Total Installed Thrust:	15,570 kN	Cost of Hub:	$3,700
Thrust Efficiency :	90%	Cost of Ring:	$350
Net Cutterhead Thrust:	14,013 kN	Cutter Diameter:	482.6 mm
Max. Cutterhead Torque:	3,625 kNm	Cutter Tip Width:	19.050 mm
Drive Efficiency:	90%	Face Cutter Spacing:	86.36 mm
Net Cutterhead Torque :	3,263 kNm		
Total Installed Power:	3150 kW		
Net CH. Power:	2835 kW		
ROP Limit :	8 m/hr		

Machine Performance Evaluation :

Machine Thrust :	O.K.	90.01%	of machine thrust used
Machine Torque :	O.K.	90.00%	of machine torque used
Machine Power :	O.K.	100.00%	of machine power used
Cutter Load Capacity:	O.K.	95.61%	of maximum cutter load used
ROP Limit:	O.K.	58.44%	of ROP Limit used

ROP: *8.94* mm/rev ←
4.5 m/hr ←

Maximum ROP controlled by Machine Power

Figure 16. Model Calculation

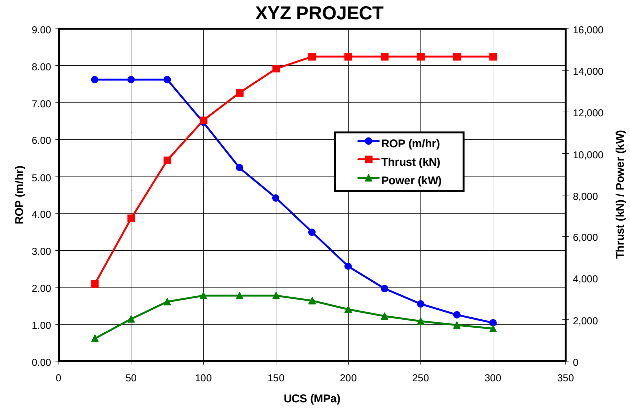


Figure 17. Relationship between UCS and Machine Thrust, Torque, Power.

Continuous Miners and Longwall Drum Shearers:

Due to the similarity of the cutting mode for continuous miners and drum shearers, the same computer program structure can be used to estimate rate of penetration, thrust, torque, and power requirement for the machine or simulation of the cutterhead for each machine. Also the model can simulate different modes of cutting and allow for various depth of sump into the face, different positions while rotating, cutting with part of the cutterhead as opposed to the whole length, cutting partly in the roof or floor, and at different penetration rates.

The information generated from the computer model includes individual cutter positions, penetration, and forces, overall thrust, torque, and power requirements of the cutterhead in the given position, variation of the forces as the head rotates, and finally boom speed and production rate.

Figure 18 shows an example of the input sheet for the cutterhead simulation program of continuous miners or drum shearers. The information required for the program are project information, machine information, cutter specification, and cutterhead position for the cutting mode and rock data.

Earth Mechanics Institute
Colorado School of Mines

Cutterhead optimizationof Continuous Miner

Project Information:

Project :	XYZ	
Location:	Golden, CO	
Owner:	NA	
Contractor:	NA	

Machine Information:

Type:	Continous Miner	
Manufacturer:	Joy 12CM12	
Weight (ton):	NA	
Drum Diameter (mm/in):	1122	44.00
Drum Length (mm/in):	3520	138.04
	500	Active
Shearing Force (ton):	20	
Sumping F (ton):	40	
Max. Torque (ft-lb, kN-m):	34900	26846.15385
RPM:	60	
Power (hp/kW):	400	300
Head Ser. Number:	C&A	
# of Bits Per Head:	67	
Design Symmetry:	y	(y/n)

Cutter Specifications:

Cutter Type:	Minidisc	
Diameter (mm/in):	225	9
Tip Width (mm/in):	7	0.28
Vel. Limit (m/min , ft/min):	162	530
Cutter Vel. (m/min , ft/min):	211	693
Machine overal Mech. Eff.	85%	

Cutterhead Position:

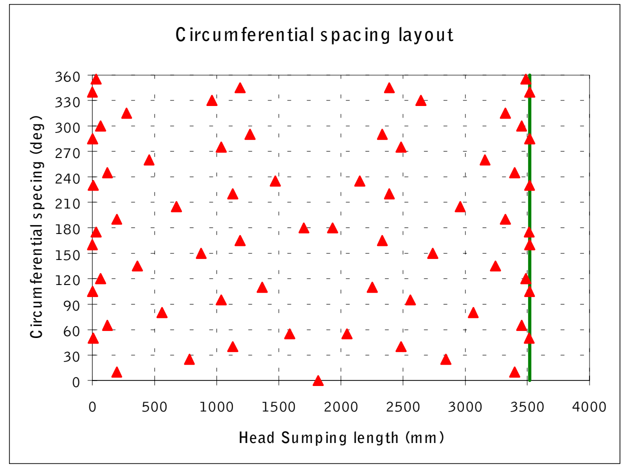
Advance Per Revolution:	80	3.2
Seam Height (mm/in):	1700	68.0
Depth of Cut in Roof (mm/in):	0	0.0
Depth of Cut in Floor (mm/in)	0	0.0

Cutting Mode:

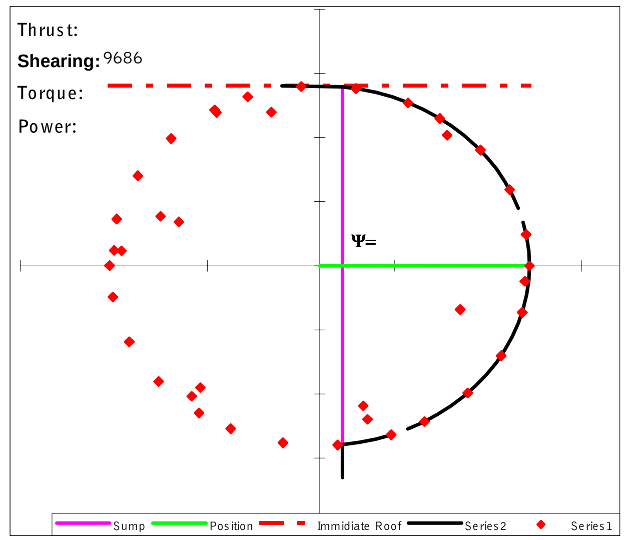
MODE:	1	Sumping	Sumping = 1
			Shearing = 2
Contact Area Angle (deg/rad):	168	2.92	
Relative Posn. Angle (deg/rad):	360	0.06	
Trailing Height (mm/in):	1700	68.0	

Figure 18. Input data Sheet for CM computer simulation

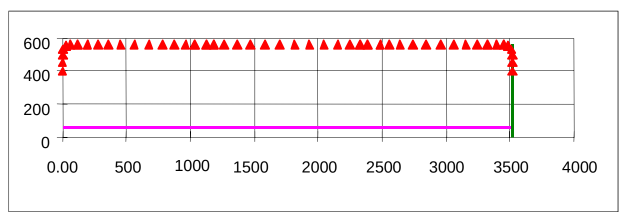
The approach used for modeling of the cutting drum of a continuous miner is to program each bit individually and analyzes the cutting forces acting on the bits. In this computer program, a cylindrical coordinate system is used to define the drum geometry and bit-lacing pattern. Position of each cutter on the drum is defined by its radius from the axis rotation, and the position angle or azimuth. Figure 19 shows the schematic drawing of a cutterhead and parameters used to define the bit position on the drum.



A



B



C

Figure 19. Cutterhead input data for simulation (A) Cutter Allocation on the head, (B) Cutting Mode, (C) Cutterhead Profile

The program allows the user to monitor the variation and graphically represents these variations as the head rotates. Figure 21 illustrates a typical summary of information for a full rotation and variation of thrust, and power for a certain cutterhead design and lacing pattern for sumping mode.

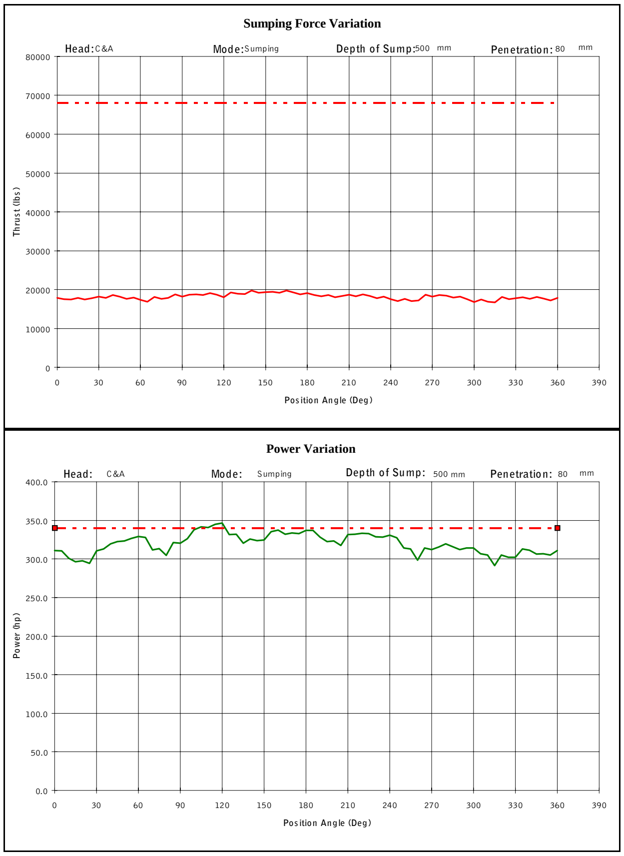


Figure 20. Sample output of the CM modeling program for a full rotation

Marietta Borers:

The model for Marietta borer miners accounts for the actual cutterhead design and allocation of the bits on the different components of the machine. As such, it has three separate modules to include the rotors, trim chain, and/or the cob cutters. Design parameters of each component are input to the program as the variables in the form of spacing and pattern of bit placement on the head.

The model starts with the geometric location of each bit and its position relative to the cutting face. Individual sheets (or modules) allow for cutting into separate material at the roof and floor. As with all of the models, cutting force may be estimated from the rock physical properties or measured from the full scale testing on the LCM.

Figure 21 shows the geometry of the rotors as programmed into the model. The cutting forces as well as the moments working on each rotor and the machine from the action of the rotors are provided by the model.

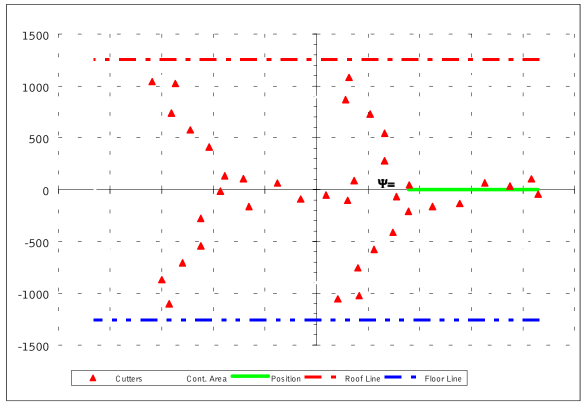


Figure 21. Schematic of rotors by the model.

The sheet for the cob cutter contains all of the pertinent design parameters. The module excludes the material cut by the rotor path and includes over cut that cob might be performed beyond the rotors. The calculated number of bits in contact with the cutting face is incorporated along with the bit force estimations to determine the torque/power needed to rotate the cob cutter for the given geometry and setting of the cut. Figure 22 shows the bit placement on the cob cutter in the model.

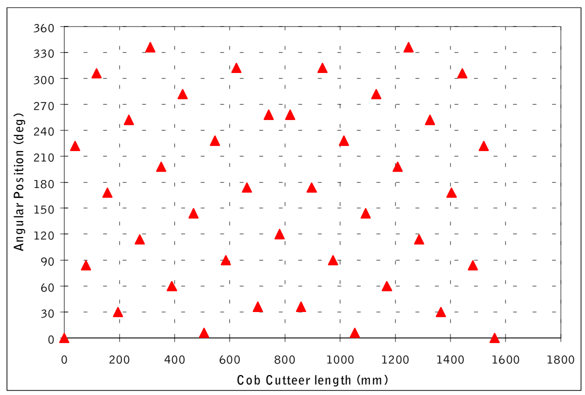


Figure 22. Cob Cutter Bit Allocation

The last sheet accounts for the trim chain. This module includes the design parameter of the chain and the geometry of its path. Similar to cob cutters, it excludes the bits behind the rotor at any given moment and allows for chain rotation with the rotation of the rotor. The cutting forces acting on the chain are estimated and summed up along with the torque needed to run the chain at certain speed. Figure 23 shows the geometry of the chain in the model.

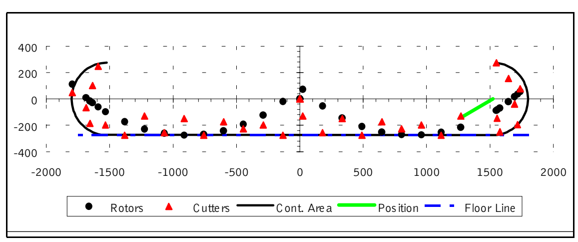


Figure 23. Schematic of chain by model.

The main sheet in the model combines all the related parameters to determine total thrust force (tramming force), total power and side forces for the machine while operating. Figure 24 shows the drawing of the combined elements of machine cutting head. The rotational position of the rotor can be changed to simulate the rotation of the rotors. The cob and chain cutter sheets are linked to the main sheet to allow for the rotation of these components as the rotor moves. The rotation of these components are set in such a manner to be synchronized with the rotor. Overall the effect of different bit positions depth of cut and differential penetration per revolution for given elapsed time is taken into account in the program.

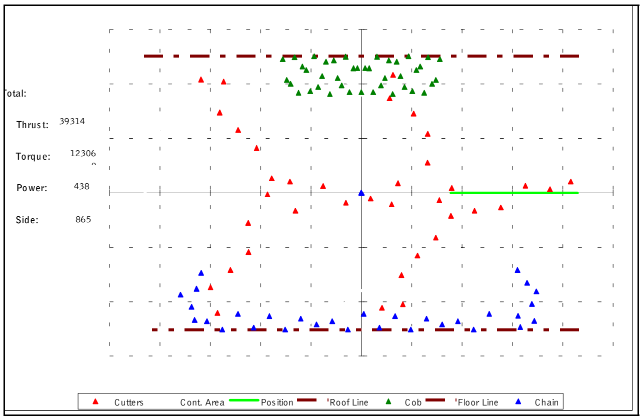


Figure 24. Schematic of all components

The analysis of the combined cutterhead modules is also performed. In this case, forces and power requirements from different components are added together to determine the total machine thrust, torque, and power requirement. The eccentricity of the summed forces may also be evaluated by this model, as well as the other models. Figure 25 shows the eccentricity of the summed forces. By utilizing designs that minimize the eccentric forces, cutter wear may be reduced and also utilization down time caused by excess vibrations.

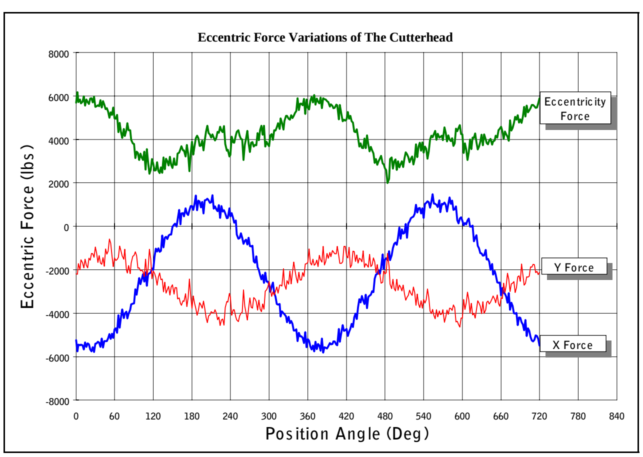


Figure 25. Eccentric Forces

FIELD VERIFICATION FOR COMPUER MODELS

The computer models are checked continuously with the field performance of the machines to validate the engineering approaches taken, calibrate the models and to update the database on which the algorithms are based. This is accomplished by comparing the results of the performance predictions with the field performance data. In addition, measurement of cutting forces and power consumption are made on some machines and compared the respective estimates given by the models.

CONCLUSIONS

Mechanical excavators are specialized machines that are capital intensive and site specific. To maximize the benefits of the mechanical excavators (i.e. higher production and lower costs, automation, more consistent product size, and safer working environment) to any operation, performance of these machines under specific conditions must be understood. This can be accomplished by computer modeling and simulation of the cutterhead design. These models provide a cost effective means to evaluate the parameters influencing the production rates and costs and maximize the efficiency of the operation without the need for costly field trials.

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