ROADHEADERS PERFORMANCE OPTIMIZATION FOR MINING AND CIVIL CONSTRUCTION

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ABSTRACT

Roadheader performance and related parameters are reviewed and their effects on the production and advance rate are discussed. Among the parameters influencing the machine performance, the most important one is the cutterhead design which could be optimized for a specific application. The procedures and the approach used in design optimization is reviewed. A computer program which has been developed for implementation of these procedures is also presented in this paper.

INTRODUCTION

Roadheaders are the most flexible and thus the most common mechanized excavators utilized in the construction of tunnels or development and production in underground mines. These machines are very mobile and can excavate various size, shape and type of openings. They provide immediate access to the face which is very favorable from a support installation viewpoint. Also they are less capital intensive than most other mechanized tunneling machines and therefore, can provide favorable economics. The limitation of roadheaders in cutting hard and abrasive rock formations, along with being operator sensitive, however, restricts the widespread application of these machines in mining and civil underground construction. Generally, a rock formation with an unconfined compressive strength in excess of 100 MPa (15,000 psi) is considered to be unsuitable for excavation by roadheaders unless it is highly jointed or fractured. This limit reflects the lack of stiffness on the part of machine to hold the cutters in contact with the rock, as well as the excessively higher bit costs and low production rates that are encountered in excavation of hard and/or abrasive rock formations.

However, roadheaders are commonly used in soft to moderately hard and non to moderately abrasive rocks. The challenge they face is to overcome the limit of rock strength and abrasiveness that they can cut. In order to improve the cutting ability of roadheaders, extensive studies on bit and cutterhead designs have been conducted over the past two decades. The result of these studies show that bits must achieve deep penetrations to allow efficient cutting, high production, and prevent excessive bit wear. Deeper penetrations, however, create high forces on the head, which require high machine power and mass to react to these forces. Therefore, heavy duty hard rock machines with higher power and more mass have been developed and introduced into the market by manufacturers in recent years. The performance of a machine with a given weight and installed cutterhead power is highly dependent on the head design and bit allocation. A well balanced cutterhead can produce much higher production rates due to reduced vibration of the head and improved rock bit contact. This paper presents the results of a study performed

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at the Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM) on the cutterhead design parameters and the approaches used to optimize the head design to minimize head vibrations and to maximize production rates.

BACKGROUND

The roadheader production rate and bit costs are controlled by several parameters including:

- ✧ Rock parameters, such as rock compressive and tensile strength, percent of hard and abrasive mineral content (i.e. quartz), rock fabric and matrix type and hardness, existence of oriented mechanical properties in the mineral composite, and elastic behavior of rock material.

- ✧ Ground conditions, such as degree of jointing (RQD), joint conditions, ground water, fault zones, mixed face situations, and overall rock mass classification and support requirements.

- ✧ Machine specification, including machine weight, cutterhead power, sumping, arcing, lifting, and lowering forces, cutterhead type (axial or transverse), bit type, size, and other characteristics, number and allocation of bits on the cutterhead, and capacity of the back up system.

- ✧ Operational parameters, such as shape, size, and length of opening, inclination, turns or cross cuts, sequence of cutting and enlargement operation, number of rock formations in the tunneling path, ground support method, and work schedule meaning number of shifts per day and days per week etc.

A combination of these parameters determines the production capacity of a given machine in a certain rock formation and ground condition. A full account of parameters affecting roadheader performance and methods for production estimates is given in Neil 1994. Among these parameters, there are some that can not be controlled. They include the rock and ground conditions as well as some operational parameters. Therefore, when a tunnel or drift is planned to be excavated under a certain condition with requirements specific to the particular project, the only controllable parameters are machine parameters. Normally, the first step is to determine whether roadheaders are feasible and can work with a reasonable production rate under given situation. Second step is to select the class and general specifications of machine to be considered for the job among the machines available in the market. Third step is to match the current machine characteristics to the rock and ground conditions in hand to maximize its production rate. This can be accomplished through a thorough study of design parameters and design optimization practice. Also, for the existing machines already working in the job site, it is always beneficial to conduct such study to increase the productivity and reduce excavation costs.

There have been numerous studies on possible modifications to achieve higher production rates when utilizing roadheaders. Also, the rock strength limit for roadheaders has been constantly challenged due to the need for a mobile hard rock excavator in the industry. The following are some solutions proposed for increasing the productivity of roadheaders and extend their economic applicability to harder rocks:

- change in material and design of bits,
- improve the machine design to respond to the overall cutting head forces,
- improve the cutterhead design.

Bit Design and Materials

The first consideration in bit design relates to the limitations that the bit shape and rock mechanical properties impose on the forces applied to the rock. Obviously, for achieving the deeper penetrations, higher cutting forces are required, and there is a limit to the maximum force that could be applied on the bits. Bit material must be abrasive resistant and ductile to withstand the impact loading while cutting in quartz rich rock types. Use of tungsten carbide with cobalt alloys has partially solved the problem and improved bit life. Also, new brazing and surface treatment techniques to improve the abrasive resistance of the bit shanks have enhanced bit durability. In terms of bit shape, point attack (conical) bits, although they are not self sharpening as sometimes claimed, have increased bit life and efficiency due to their ability to maintain a certain profile over an extended period of time. Use of these bits has almost become standard on heavy-duty roadheaders and has improved their productivity. Application of disc cutting technology on the roadheaders can improve the cutter life and enable these machines to attack harder rocks. A minidisc cutter has recently been developed at the Colorado School of Mines. The cuter is 12.5 cm (5 in) in diameter, and cantilever mounted on a 5 cm (2 in) shaft using a needle bearing. The forces required to achieve a certain depth of cut with the minidisc are substantially lower than the regular disc cutters due to the smaller foot print area. The minidisc is light weight, very easy to handle and replace, and requires about the same space as the standard bit blocks on the roadheader cutterheads. With these unique features, minidisc is a highly promising solution for extending the application of roadheaders to excavation of harder rock formations.

Machine Design

Machine design mainly refers to the machine mass and the ability to react to the cutting forces acting on the cutterhead. Machine mass and overall geometry determines the magnitude and direction of the maximum forces that can be applied on the cutterhead. In essence, the force capacities of the machine (i.e. sumping, arcing, lowering, and lifting force) are dictated by the machine mass. Larger machine mass is usually associated with the larger cutterhead sizes to provide for the reaction forces needed to achieve high production rates. One of the limiting factors has traditionally been the sumping force or the thrust capacity of the machine. This force is normally supplied by the tractive effort of the crawlers, which is generally inefficient, especially in soft and wet floors. Installation of telescopic booms on new generation of roadheaders has, to a large extent, mitigated this problem. Telescopic booms provide the sumping force while the machine remains stationary. This allows a better use of machine mass and friction between the crawler and the ground. Installation of a set of stelling jacks to increase the arcing force capacity and higher installed cutterhead power have also contributed to improved cutting ability of the roadheaders. Occasionally, larger size arcing rams have been used to increase arcing force and allow for a better use of machine mass which increases production rates (while arcing), without the need for any change in machine hydraulic system.

Cutterhead Design

Between the two types of roadheader cutterheads, the ripping (transverse) and the milling (in line or axial) heads, the ripping type is more suitable for hard rock cutting. This is due to more efficient cutting during sumping, due to resultant forces acting along the boom (and not perpendicular), better use of machine mass, and more efficient cleaning of the face. On either type of heads, an optimal design is necessary to match the rock cutting characteristics and maximize the production rates. The design parameters include the spacing between bits, location of bits, their tilt angle, and the skew angle. The spacing between the bits must be optimized by analyzing rock failure behavior and anticipated depth of penetration. Also, cutterhead layout must be balanced by controlling the placement of the cutters to create an even bit (force) distribution to minimize vibrations. This issue is of crucial importance since the increased spacing means less number of cutters and potentially higher vibrations. The head vibration can have adverse effects on the production rate, machine life, and maintenance. Consequently, an optimized cutterhead design, achieved by well balanced bit distribution and minimized vibration, can enhance the performance of a given machine and is the objective of the current paper as discussed in the following sections.

CUTTERHEAD BALANCING AND VIBRATION

The cutterhead vibration refers to the overall force variation on the head caused by interaction between the bits and the rock. The force variation is a function of the number of bits in contact with the rock, the spatial position of bits in three dimensional space, and the depth of penetration for each bit. A combination of these parameters determines the total forces acting on the cutterhead at any given point in time. Obviously, since the cutterhead is rotating, time translates into spatial and rotational position. In other words, the resultant force on the cutterhead depends on the number and distribution of bits for any angular segment of the cutterhead in plan view (see Figure 1). Meanwhile, the depth of penetration for each bit depends on its position with respect to the cutting face. That is, bits may cut a crescent shape path in the rock or cut at constant penetration depending on the mode of operation and bit position (Figure 2).

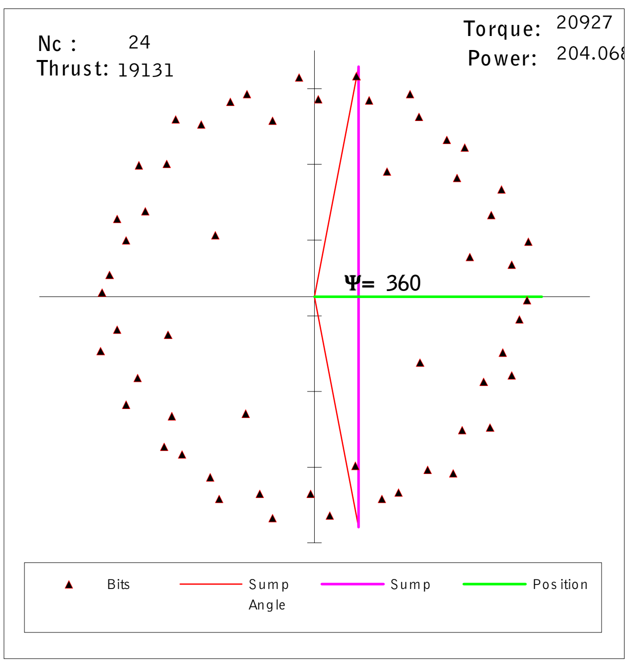

Figure 1. Plan view of the cutterhead bit layout pattern (with 115° angular spacing).

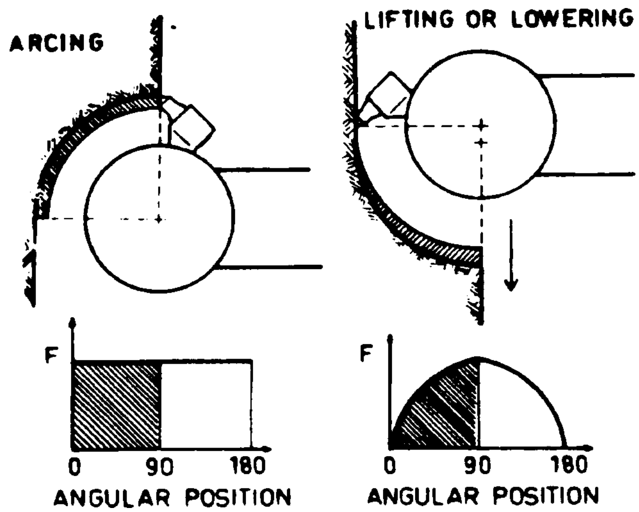

Figure 2. Shape of cutting area of the bits in various cutting modes (After Hekimoglu 1991).

The force requirements for cutting at a certain depth with a fixed spacing vary as the bits penetrate into transverse the rock. This variation results from the pressure build up at the bit tip and the subsequent release of the pressure and therefore, the forces due to chip formation. However, an estimate of the average cutting force can be developed for cutting at a certain depth of penetration, as follows:

$$F_n = A.\, p^b$$

Where Fn= Normal force (lbs)
P = Penetration (in)
A,b = coefficients found from cutting test

This force estimation formula is derived by curve fitting to the force data obtained from linear cutting test performed in the laboratory under full scale cutting condition (i.e. Figure 3.). The drag force can be estimated from the normal force using the drag coefficient, which is defined as the ratio of drag to normal force. This coefficient usually varies between 0.45 to 1.0 depending on the rock type and the bit penetration. Normally the drag coefficient is measured along with the cutting forces while running direct force measurement tests. Consequently, the force requirements for cutting at a certain depth of penetration are estimated, and used for cutterhead total force and power estimation, as well as balancing.

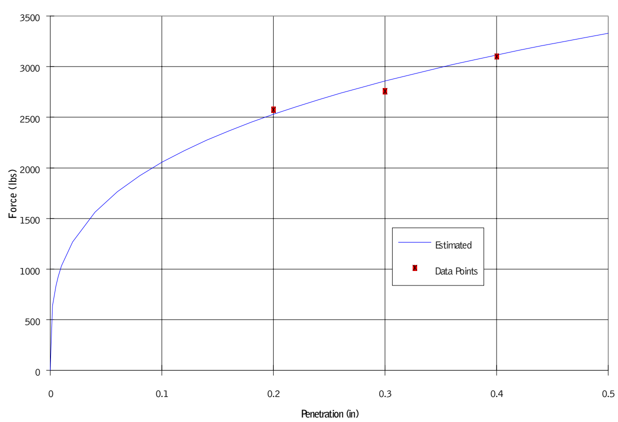

Figure 3. Estimated and measured normal forces.

For a given machine, design optimization begins by choosing a proper bit spacing to maximize the cutting efficiency in a given rock type. The most efficient cutting is when the specific energy , defined as the energy needed to cut a unit volume of rock, is minimized. It has been shown by extensive laboratory and field studies that the minimum specific energy occurs in a range of spacing to penetration (S/P) ratio between 2-4 for point attack cutters. Another approach which has also been used to define the optimum spacing is the breakout angle of the rock. This approach is widely used by roadheader manufacturers and in essence, is another way of deciding on the optimum S/P ratio. In this method, the line spacing between the bits is determined from desired depth of penetration and the break out angle, which is the angle between the crater surfaces created by crushing and chip formation under the bit. Both the optimum S/P ratio or the break out angle are controlled by the brittleness of the rock and are most accurately determined by actual cutting tests.

Using the bit spacing and cutterhead geometry, the bit layout in cross section can be accomplished by defining the position and tilt angle of the bits. The tilt angle of each bit is selected such that it is perpendicular to the cutting surface (or cutting profile). At this stage, the number of bits required on the head, and general dimensions of cutter head (length and diameter) are specified. The next step is to determine the angular positioning of the bits to achieve an optimum bit distribution and minimize head vibrations. Due to the complex and tedious operation involved in these calculations, this can be best accomplished by computer modeling.

COMPUTER MODELING FOR CUTTERHEAD OPTIMIZATION

A computer program was developed for bit allocation on the cutterhead, as well as to simulate the cutting process of the designed head (Rostami et. al. 1993a ,b) . This program has the capability to determine the position of the bits in 3D space taking into account rock properties, the cutterhead geometry and the depth of sump. The program checks for rock-bit interaction and determines the number of bits in contact with the rock at any given rotation angle of the head. The actual penetration of each individual bit which is in contact with the rock is calculated and the force requirements for a given depth of penetration are estimated. The estimated forces are then projected on three mutually perpendicular axes (Cartesian coordinate system) established on the cutting head. The projected forces summed together to estimate the total force and moment requirements of the head in each mode of operation, namely the sumping and the arcing (slewing or shearing) modes. The calculated cutting parameters (e.g. sumping or arcing forces, torque and power) are then recorded for each position of the head as it rotates 360° with the desired angular increment. Table 1 is an example of the program output for rotating a certain head design 360°, at 2° increments. Also, some statistical manipulation of the data is done in a summary box to evaluate the average, maximum, and minimum cutterhead force/power requirements as well as percent of variation in each mode of cutting. The percent of variation is defined as the ratio of standard deviation to the average value of the parameter. The result of the cutting process simulation can also be plotted against the rotational angle and used for vibration analysis of the head (Figure 4).

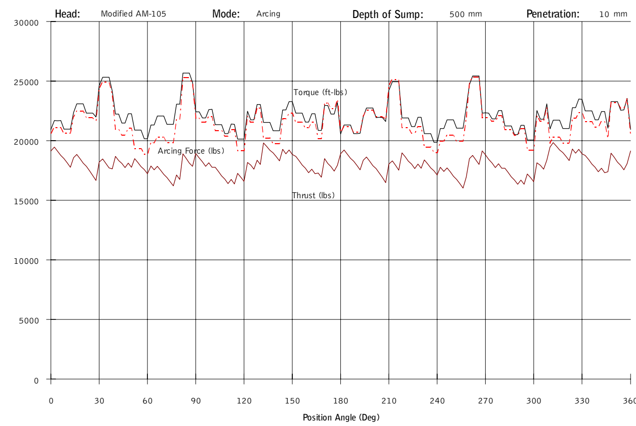

Figure 4. An example of vibration monitoring output, cutterhead thrust and torque variation.

Table 1. Program output for simulation of cutterhead rotation at 2° increment

Cutter Head Type:	Modified AM-105				
Mode of Operation:	Arcing				
Depth of Sump:	500	mm		Penetration: 10	
Average	17,962	22,063	215	21,445	24
STDEV	805	1,293	13	1,543	0.68
%Variation	4%	6%	6%	7%	3%
Maximum	19825	25667	250.2901	25333	25
Minimum	16025	19857	193.6342	18855	23
Position Angle (Deg)	Thrust (lbs)	Torque (ft-lbs)	Power (hp)	Arcing Force (lbs)	Number of Bits in Cont.
0	19131	20927	204.1	20624	24
2	19448	21673	211.3	21093	25
4	19113	21672	211.3	21093	25
6	18754	21675	211.4	21093	25
\\	\\	\\	\\	\\	\\

The force variation and the related graphs can be used as an indicator of the magnitude and frequency of vibrations on the cutterhead. This means that peak force/torque requirements can be identified and bits repositioned to eliminate these peaks or at least attempt to reduce their magnitude to a range within a few percent of the average. In addition, these variations are evaluated to improve the cutterhead design so that the cutting process becomes smoother with minimal variation. For this purpose, the number of bits in contact must remain nearly the same as the cutterhead rotates, which means changing the angular spacing to allocate bits evenly on any cutting section of entire the cutterhead.

An algorithm for bit allocation based on the concept of equal circumferential or angular spacing of bits was used to achieve an even distribution of bits and forces on the head (Hekimoglu et. al. 1991). This algorithm determines the angular position of the bits on the head to maintain a relatively constant number of bits in any given section of the cutterhead. The angular positioning of the bits controls the bit distribution on the head once the number of bits is calculated from the selected spacing and the number of starts. Figure 5 is an example of bit allocation map for a double tracking, four start head (Figure 1 shows the plan view of the same head). The allocation algorithm must be modified for double or triple tracking, as well as the number of starts (2, 3, 4 ..6 etc.). In essence, the algorithm defines the positioning angle of one bit (in a set of bits, 2 for double tracking and 3 for triple tracking and so on) from the previous bit in the same start. The bit allocation map together with the cutterhead plan and side views as produced by the program on a real time basis when an angular spacing value is selected, provides an excellent visual aid for the designer. The advantage of these drawings is that some of the problems in the design and bit allocation can be identified immediately and the proper adjustments made to eliminate them. These problems such as bits grouping in lines or being too close causing potential difficulties in fabrication can be identified readily and the adopted angular spacing ruled out. A good example is using an angular spacing of 15°, 30°, or 45° which will result in regrouping of bits in lines. Similarly, very small spacing (or values close to 180° in a double tracking pattern) can cause physical interference between the bit blocks.

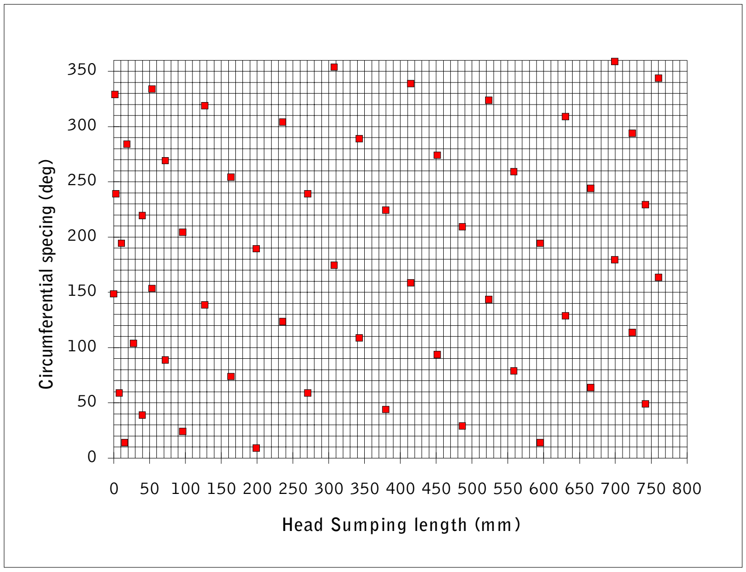

Figure 5. An example of bit allocation map for 115°

The procedure to find the optimum angular spacing begins with selecting a few random values and looking at the patterns of bit distribution in the allocation map and in plan view. The next step is to use an angle and run the cutterhead rotation program at a desired sumping and penetration depth. The result of this program can be used to verify the type and magnitude of variations on the designed cutterhead layout. An angle close to the previous value is then selected and the result of cutting simulation is compared to the first one to observe whether the change has improved the vibration characteristic of the head. A systematic use of the bit allocation program with the monitoring program guides to determining the optimal angular spacing which results in lowest percent variation. Also, the vibration charts (Figure 4) created by the simulation program can be observed to detect any unusually high peak forces. It must be mentioned that minimal variations may occur several times in a range between $0°$ to $180°$, in which case the lowest value of variation can be considered to be the overall optimum, given that the bit block interference or extreme high peaks are already eliminated. The combination of bit allocation algorithm, the vibration simulation, and the performance monitoring in one program provides an ultimate optimization tool for cutting head design of partial face machine, especially roadheaders.

CONCLUSIONS

The results of extensive laboratory testing and computer modeling show that the performance of roadheaders can be improved substantially by optimizing the cutterhead design to achieve higher production rates at lower bit costs. Among the parameters affecting the machine performance, the cutterhead design is the easiest to control and optimize. This can be accomplished through the evaluation of rock cutting behavior and matching the cutterhead design to the rock and ground conditions. Optimum line spacing for a given bit in a certain rock type can be determined accurately by full scale laboratory cutting tests. The optimum angular spacing for cutterhead layout can be determined by using the bit allocation and cutting simulation programs. The application of these optimum values in cutterhead design will ensure maximization of production rates for the roadheaders.

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