PRODUCTION ESTIMATING TECHNIQUES FOR UNDERGROUND MINING USING ROADHEADERS

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ABSTRACT

Roadheaders are one of the most popular mechanized excavators used in mining and civil underground construction. These machines are primarily used in soft to medium hard rocks. This paper reviews the parameters associated with the application and operation of roadheaders and presents a method for estimating cutting performance.

Introduction

Roadheaders are a unique class of mechanical excava-tion machines that break rock by utilizing tungsten carbide tipped cutting tools laced in a specific geometry on a spherical rotating cutting head. The cutter head is driven by an electric motor through a heavy duty epicyclic or transverse gearbox for either milling or ripping cutting actions. The cutter boom is connected to a pedestal that allows unrestricted boom movement throughout a fixed maximum profile. Boom movement is controlled by hydraulic cylinders sized to provide force sufficient to maintain the cutting head in contact with the face, and the machine is track mounted to allow tramming from one work face to another.

The ability of roadheader or boom type machines to operate and cut effectively in hard rock has been limited by the system stiffness, the ability of cutting tools to withstand high normal forces, and the inability of carbide inserts to resist impact or the heat generated from impact in high silica rocks. Several roadheader manufacturers have recently developed high horsepower, large mass machines in an effort to increase performance capabilities and to broaden the applications base of traditional roadheaders into hard rock cutting. Recent developments in bit and cutter technology, coupled with the development of high torque output at low RPM and improved system stiffness, have successfully improved the cutting ability of roadheaders.

Background

Roadheaders have traditionally operated in sedimentary rock with an unconfined compressive strength of less than 100 MPa (~15,000 psi). Occasionally harder rocks have been excavated where joints, bedding planes, fractures or other planes of weakness were present. As rock strength and especially silica content increase, the performance of roadheaders drops off dramatically. The reasons for this include:

- the inability of the cutting tools to take high penetration force,
- the inability of the machines to maintain the bit in the cut or the ability of the bit to track,
- the low mass available to react to the required force,
- lack of understanding of the physical properties of the rock related to cutting forces.

In the following section the factors effecting the operation of roadheaders will be reviewed.

Rock Properties

Several rock properties affect the cutting forces acting on a bit or the overall force requirements of the cutting head, hence, performance of the roadheaders. They include:

* Density or specific gravity, affects the muck handling properties of the excavator.
- Uniaxial compressive strength (UCS) is one of the most important parameters affecting rock excavability.
- Splitting tensile strength (Brazilian test) indicates the toughness of the rock fabric.
- Ultrasonic pulse velocity (acoustic velocities) reflect the competency of the rock and its brittleness and strongly affect its ease of excavation.

- Elastic constants, (Young's modulus and Poisson's ratio) which also indicate the competency and brittleness of the rock.
- Cerchar abrasivity index (CAI) is a direct abrasion test that gives a strong indication of the bit wear.
- Abrasivity estimated from the quartz content of the rock is a rough measure of the abrasiveness of the rock.
- Compressive to tensile strength (UCS:T) ratio is a measure of the toughness of the rock fabric.
- Point load strength directly indicates the forces required to penetrate and fail the rock.
- Punch strengths is an alternative form of point load test that uses indenters resembling excavator cutters and bits.

Force Measurements

The three-dimensional forces experienced by a rock cutting tool can be measured directly with the aid of a linear cutting machine (LCM), such as that maintained by the Colorado School of Mines (CSM). The LCM is a rigid, instrumented steel frame that holds a single cutting tool in place while a rock sample is forced past it. The tool and rock are full sized. The depth of penetration and speed of cutting during tests are controlled, as is the distance between cuts. The values of these parameters are chosen to mimic the action of multiple cutters on a field excavator, which directly affect the forces acting on the cutting tool during excavation. Different combinations of cut spacing and penetration expressed as a ratio (the S/P ratio) are tested to assess cutter performance.

The forces are measured by a load cell in the base of the cutting tool while traversing a single cutter along a line through the rock. The readings are recorded at a rate of 1,000 sample per second, averaged, and used to calculate the energy required by the cutter to excavate a unit volume of the rock (specific energy of cutting). The optimum S/P ratio is the one that requires the lowest specific energy of cutting. This ratio is found by testing several combinations of spacing and penetrations.

In addition to measured forces, information on the rock chipping and failure process, fracture surface characteristics, and geometry can be recorded. All these data then are incorporated in a lacing design for the cutterhead. Therefore, the design is directly related to actual cutting of the rock to be encountered in the field, eliminating expensive guesswork.

Machine Calssifications

Roadheaders can be divided into two types: milling (axial) with the cutterhead rotating around the boom axis, and ripping (transverse) with the head rotating perpendicular to the boom axis. Seven roadheader manufacturers worldwide presently offer small (30 ton), midsize (70 ton) and large (up to 120 ton) roadheaders. These machines operate with an installed cutting motor power of 80 kW up to 300 kW and a maximum torque up to 2.5 times the running torque.

To increase torque and the ability to cut hard rock, a two speed gear box arrangement or motor change is required to reduce the rpm. On early machines, the motor change usually coincided with a reduced horsepower which to reduce the speed of the peripheral bit tips and to minimize bit damage while maintaining penetration. However, in some early designs where only a gear reduction had been used, the high input horse-power could be used only for a limited period of time without gear failure. Modern machines now use pole switchable motors, variable frequency motors, or a new hydraulic drive which converts from a 300 kW electric drive through a planetary gear to a high power hydraulic drive which operates at 25% of the speed of the standard electric drive but at higher torque. In addition, the slewing speed are reduced to accommodate the slower bit tip speed and penetration requirements. Meanwhile, the additional stiffness needed to sump into hard rock is provided by higher mass of the machines and a telescopic boom with

0.7 to 1.0 m (2 to 3 ft) stroke to direct reaction forces to the center of the machine. The latter reduces loss of energy caused by tractive inefficiencies. This is especially effective on transverse machines. Today we also see the cutter head power on some large high production machines has been increased to as much as 375 kW (500 hp).

Cutting Tools

Roadheader cutting heads laced with tungsten carbide tipped point attack bits have evolved into the state of the art in impact rock breakage for boom type mechanical excavators. However, high silica rocks limit their application for hard rock cutting due to the heat generated at impact and its effect on carbide. The cobalt content of tungsten carbide can be varied to improve the toughness and reduce heat effects on the bit tips. Also, the bit shape has changed to accommodate more efficient cutting with reduced amount of dust and heat generated during the cutting. Recently, a new wear material has been made available by the steel industry for use in bit shanks. This material has higher toughness and abrasive resistance to prevent the premature loss of carbide. The new generation of bits will have longer shanks with less material around the carbide tip, since the higher quality of the matrix material can support the forces acting on the carbide. Recent developments in layered carbides, shaped polycrystalline diamonds, and small diameter disc cutters offer a breakthrough in technology that will allow more effective cutting. The new cutters are gradually being used in new roadheader designs. They will allow more effective use of cutting head power, and will significantly improve roadheader application in siliceous rocks.

Pricipal of Rock Fragmentation with Bits

When cutting, the bit tip strikes the rock at a set penetration angle. As the tool penetrates into the rock, a zone of crushed material is developed under cutter which transfers the load to the surrounding rock. In this zone, a pressure bubble is formed and the hydraulic effects of the fines propagate fractures in the rock fabric. These fractures are not very deep due to the limited forces available on the tool which creates a relatively small crushed zone with low pressure created. Succeeding passes of following bits at a set spacing take advantage of these fractures to form chips and relieve the rock from the face.

Unfortunately, due to lack of stiffness and the nature of the cutting operation with boom type machines, cutter tracking is very difficult. The result is criss-crossing of the bit paths and inefficient cutting due to ineffective use the fracture pattern developed by previous cuts.

The spacing between the cuts has a significant effect on the cutting forces. Short spacing between the cuts means very inefficient cutting and excessive over-crushing and dust generation. As the spacing is increased, the cutting gets more efficient up to a certain point where the interaction between the fractures from neighboring cuts ceases. Specific energy of cutting, defined as the energy required to cut a unit volume of rock, is the main indicator of cutting efficiency. The lower the specific energy, the more efficient the cutting. There is a range of spacing to penetration (S/P) ratios for which the specific energy of cutting is minimized. This range is unique to each rock type and critical to the roadheader cutting head design and selection of cutter geometry. For conical point attack bits the optimum S/P ratio usually is 2-4 times penetration. For brittle rocks, this ratio can be greater than four (Ozdemir 1978). Bit geometry also effects the penetration and the ability of cut material to egress from the point of contact into the muck stream.

For silica rocks, an index has been proposed by Schimazek (1987) as a value of abrasivity related to the volume of quartz as a percentage of the total volume. This index indicates the feasibility of cutting rock with roadheaders featuring point attack cutters and has been described by Schimazek to be:

$$I_c = \frac{VT_d\sigma_t}{100} \quad (1)$$

Where: I_c = Index of Cutting
T_d = Ave. dia. of quartz grain
σ_t = Tensile strength (MPa)
V = Volume hard minerals as % of quartz

Force Estimation

For situations where direct measurement of cutter forces is not available, several methods have been proposed to estimate the cutting forces needed to achieve a certain penetration depth. One of the most common methods, developed by Evans (1984), predicts the drag force on a conical bit by:

$$F_c = \frac{16\sigma_t^2 d^2}{Cos\alpha.\sigma_c} \quad (2)$$

Where;
F_C = Mean peak drag force
d = Depth of cut
α = Half of tip angle
σ_t = Rock tensile strength
σ_c = Compressive strength

The ratio of drag force to normal force on a bit depends on the rock type, rock fabric, bit shape, attack angle, and depth of penetration. For most point attack cutters, this ratio (known as cutting or drag coefficient) is approximately 0.5-1.0. The normal force can be obtained either from direct measurement with a LCM , or from the estimated drag force using the above mentioned or other formulas. Most heavy duty point attack cutters are now designed to withstand a maximum cutting force of 15 ton (30,000 lbs.), generated by a typical large roadheader.

The total thrust requirement for the cutting head is the sum of all the bit normal forces. This total force requirement is estimated by calculating the number of bits in contact, times the average (estimated or measured from the LCM) normal force requirement. Force requirements are then compared to the forces available on the machine being evaluated.

Estimating Roadheader Performance

Step 1: To evaluate existing cutter head designs submitted by suppliers or to design a site specific cutter head lacing requires an understanding of the energy requirements of the rock types to be excavated. The optimum bit spacing and the S/P ratios that give the lowest specific energy of cutting are best determined by laboratory testing. The optimum spacing to penetration ratio usually occurs in a range from 2 to 4 for road-headers, with the higher value normally associated with more brittle rock.

Step 2: Determine the cutter head rotational speed from the maximum allowable bit tip speed:

$$RPM = \frac{V_b}{\pi D} \quad (3)$$

Where: V_b = Max. bit tip velocity
D = Cutterhead diameter

Bit tip speed is limited by the heat dissipation characteristics of the bit. This can be a significant contributing factor in bit failure on some high RPM transverse cutting machines in high silica or massive rocks.

Step 3: Determine the number of bits needed on the cutting head:

$$N = \left(\frac{L_c}{S}\right) \cdot N_s + C$$

(4)

Where: N = Number of cutters

L_c = Length of cutting profile on head

S = Spacing between the bits

C = A constant accounting for nose and back trimming bits

N_s = Number of starts on the head

L_c is the arc length of the curvature of the cutterhead. C represents the number of extra cutters at the nose and back trimming area, where the spacing is reduced due to more severe cutting conditions. The number of extra bits depends on the type of cutterhead and the condition of the rock. For axial type roadheaders this empirical formula gives the required number of bits within 10%, taking into account trimming and sumping bits. However, a ripper type roadheader carries two heads laced in a pattern to cut in compression rather than shear and may require up to 10% more bits per head than axial machines.

The estimated number of bits in contact at any one time is influenced by the Rock Quality Designation (RQD) and UCS:T, compressive to tensile strength ratio of the rock. High RQD and UCS:T values above 7.5 will result in the operator intuitively cutting with only a partial area of the available cutting head surface.

For cutting intact rock the number of cutters in contact can be estimated by using depth of sump as follows:

$$N_c = \frac{N}{180} \cdot \cos^{-1}\left(\frac{R - D_{sump}}{R}\right)$$

(5)

where: N_c = Cutters in contact per head (multiply by 2 when sumping)

N = Total number of cutters

R = Cutting head radius

D_{sump} = Sumping depth

(Note: $\cos^{-1}$ in degrees)

For axial type machines, however, N_c is a func-tion of the ratio of sumping depth to the length of cutting head. Therefore, during the sumping mode, this number can be estimated by:

$$N_c = \left(\frac{D_{sump}}{N}\right) \cdot N$$

(6)

Where: L = length of cutting head measured along the boom axis

While arcing, the above number should be divided by two since only half of head is cutting the rock.

For the cutting action of a transverse roadheader in a rock mass, an empirical factor can be used to account for the rock quality effects on cutting as well as the operators intuitive selection of a cutting depth. In order to estimate the number of bits in contact this factor, "f", is used in the formula as below:

$$N_c = \frac{N}{2} f$$

(7)

Where: f = Cutting Efficiency Factor calculated by:

$$f = 1.0 - 0.06 \cdot \left(\frac{UCS}{T} - 7\right) - \left(0.5 \cdot \frac{RQD - 25}{25}\right)^{B1} - 0.1 \cdot \left(\frac{\sigma_c - 5000}{5000}\right)^{B2}$$

(8)

B1 and B2 are empirical coefficients 0.4, and 2, respectively. This equation is valid for English units. For metric units, the coefficients must be recalculated or parameters converted to English system. In essence, "f" is the ratio of sumping depth to the cutterhead radius, below 1 if the depth of sump is less than a full radius, above 1 for sumping, passed the rotation axis of the cutterhead.

Step 4: Evaluate the available forces on the cutter head. During sumping, the tractive effort (thrust) of the machine is combined with the torque needed by the drag forces to break the rock. The sum of the two would be:

$$F_{ts} = (T_h + T_r /R)\eta_m \quad (9)$$

Where: F_{ts} = Total sumping force (max.)
T_h = Thrust or tractive effort
T_r = Torque
R = Radius
η_m = Mechanical efficiency

T_h is a function of cutting head design and is usually in the range of 20-60 tons. When cutting in arcing mode, the machine is held in a fixed position by its mass (and is often aided by stelling jacks to improve system stiffness) and a lateral force is applied to push the head into the rock. The total available lateral forces can be estimated as:

$$F_l = F_a.\eta_m \quad (10)$$

Where: F_l = Maximum lateral force available
F_a = Available arcing force

The machine efficiency can be influenced by cutting on a decline or incline, slick or wet floors, and other factors that may influence machine stiffness or cutting efficiency, including dull or inefficient bits.

Step 5: Estimate the cutterhead force, torque, and power requirements by multiplication of the number of cutters in contact times the estimated forces for the given penetration:

$$T_{hr} = \sum_{1}^{Nc} F_{ni} \approx N_c.F_n \quad (11)$$

and $$F_{ar} \approx 0.5T_{hr} \quad (12)$$

and $$T_q = \sum_{1}^{Nc} T_{qi} = \sum_{1}^{Nc} F_{ni}.C_d.R_i \quad (13a)$$

or for a gross estimate:

$$T_q = N_c.F_d.R_{avg} = T_{hr}.R_{avg}.C_d \quad (13b)$$

and

$$Power = T_q.RPM.C_p \quad (14)$$

Where: T_{hr} = Thrust or sumping force required
F_{ar} = Arcing force requirement
T_q = Torque
F_n = Normal force
F_d = Drag force = $F_n.C_d$
C_d = Drag coefficient.
R_{avg}= Average radius of active cutting area
$R_{avg} = R - D_{sump}/2$
R_i = Individual bit position radius
C_p = Conversion factor for power (i.e. $1.9x10^{-4}$ for ft-lbs/min to hp)

For a transverse roadheader, the calculated value of T_h must be multiplied by two to account for both heads. The drag coefficient for medium rock is within the range of 0.5-1.0 (average 0.7) for point attack bits depending on tip shape and bit penetration angle. Estimated torque must be lower than the installed torque on the machine. Overall, the estimated total force and power requirement of the head, must be below the available capacities of the proposed machine .

Step 6: Calculate the tons per foot of advance in the drift as:

$$V_{pl} = \frac{A}{C_v} \quad \text{or} \quad W_{pl} = \frac{A.\rho}{C_w} \quad (15)$$

Where: V_{pl} = Volume of rock per unit length.
W_{pl} = Weight in tons per unit length.
A = Cross Sectional area of the tunnel
ρ = Rock Density (lbs/ft^3 or gr/cm^3)
C_v = Conversion factor for volume
C_w = Conversion factor for weight

Step 7: When the general specification of the machine and specific energy of cutting for a particular rock type are known, the theoretical maximum advance rate for given opening size can be estimated using the following formulas:

$$V_{ph} = \frac{HP.\eta}{S_E} \quad \text{and} \quad W_{ph} = \frac{V_{ph}.\rho}{C_w} \quad (16)$$

Where: V_{ph} = Production rate in m^3/hr, yd^3/hr

HP = Cutting head power (kW/hp)
S_E = Specific Energy (hp-r/yd^3)
η = Efficiency of the system (as a whole)
W_{ph} = Production rate in tons per hour
ρ = Rock density (i.e. gr/cc, lbs/ft^3)
Cw = Conversion factor for weight,

Hence, the maximum achievable advance rate "A_r"(in ft/hr or m/hr etc.) would be:

$$A_r = \frac{V_{ph}}{V_{pl}} = \frac{W_{ph}}{W_{pl}} \qquad (17)$$

Step 8: Estimation of the advance rate can be done in various ways. On a full face machine, when the penetration rate is known, the advance rate can simply be calculated by:

$$A_r^* = C_s.p.RPM \qquad (18)$$

Where: A_r^* = Advance rate (of full face machines, or cutterhead speed) in m/hr, ft/hr
p = Penetration (mm/rev, in/rev)
C_s = Conversion factor (0.06 for metric and 5 for English system)
RPM = Rotational speed in "rev/min".

The penetration "p" must be adjusted for the cutting condition and used in above mentioned formula as follows:

$$p_{adj} = p.f \qquad (19)$$

Where: p = Nominal penetration
f = Cutting Efficiency Factor

For a partial face machine such as a road-header cutterhead speed can be revised to estimate the advance rate by using the distance a head must travel per unit length of tunnel. This figure, in turn is calculated from the sumping width which is influenced by the RQD, UCS:T, factor *f*, and the sumping depth of the cutting head. Consequently, the advance rate is determined from the following equation which is adjusted for the "*f*" factor:

$$A_r = \frac{A_r^*.\ D_{Sump}\ .W_{sump}.\ f^2}{A} \qquad (20)$$

Where: A_r = Advance rate (i.e. m/hr or ft/hr)
W_{sump}= Width of sump, determined from head diameter and depth of sump as:

$$W_{sump} = \sqrt{D^2 - (D - 2.D_{sump})^2}$$

D_{sump} = Depth of sump (mm or in)

Step 9: Utilization can be calculated as a percentage of the available cutting time per shift using a machine mechanical availability and normal and mandatory delays (such as maintenance, support installation, etc.) as:

$$U = \frac{T_t - T_d}{T_t} \qquad (21)$$

Where: T_t = Total time per shift (minutes)
T_d = Total delay time (minutes)

$$T_d = (D_n + D_m + D_u)$$

D_n = Normal delays
D_m = Mandatory delays
D_u = Delays to install utilities or support.

Step 10: The face advance per shift and tons produced per shift can be calculated by:

$$A_s = A_r.T_t.U \quad \text{and} \quad W_{ps} = A_s \times W_{pl} \qquad (22)$$

Where: A_s = Advance rate per shift (m or ft/shift)
W_{ps} = Production rate (tons/shift)

Example

In this section, an example of performance prediction using the suggested method will be presented. Assume a project including excavation of a 3 by 5 m (10x15 ft) tunnel using a medium size roadheader with 200 kW (260 hp) installed cutting head power. The machine has 35 ton sumping force with 17 ton lowering and lifting, and 7 ton arcing force capacity. The machine is a transverse type with head diameter of 1000 mm (40 in), laced with 44 point attack picks (tip angle 100°, α =50°), and the rotational speed of 58 RPM. The compressive strength of the rock is 100 MPa with a tensile strength of 10 MPa (14000 and 1400 psi respectively), density of 2.25 gr/cm^3, and 70% RQD. The maximum line spacing between the bits is 30 mm (1.2 in).

The optimum spacing to penetration is selected to be 3, which is within the range of 2-4 S/P ratio. Thus, the nominal penetration is selected to be 10 mm (0.4 in). Cutting forces grow with penetration as follows (the cutting forces are measured and a curve is fitted to the resulting forces):

$$F_n = a.p^b$$

Where "a" and "b" are constants, 2000, and 0.3 respectively. This would estimate the normal force in terms of pounds, given that penetration rate is provided in inches. The estimated forces can then be converted to the appropriate units (i.e. metric etc.) The drag force can be estimated using a drag coefficient of 0.5. Hence the forces for the nominal penetration will be:

F_n = 1520 lbs = 6.75 kN

and using C_d=0.5;

F_c = 760 lbs = 3.4 kN

If the cutting force measurement was not available, then Evans formula (Eqn. 2) could be used, which yields:

F_c = 570 lbs = 2.5 kN

and using C_d=0.5, the normal force would be;

F_n = 1150 lbs = 5.0 kN

The specific energy of cutting was measured at 9 kW-hr/m^3 (~hp-hr/Cyd). With the rock cutting charac-teristics defined, the next step is to evaluate the machine capabilities. Since the prospective roadheader is already designed, there is no need to estimate the number of bits on the head and RPM. The number of bits in contact can be found as follows. For the nominal sumping depth of 400 mm (16 in) in intact rock (Eqn. 4):

N_c = 20.6 (or 21)

Or for rock mass with discontinuities (Eqn. 6,7):

f = 0.893
N_c = 20

The estimated total sumping and arcing force requirements are (Eqn.10,11) :

T_{hr} = 2x21x6.75 = 283.4 kN ~ 28 ton (sumping)
F_{ar} = 21x6.75x0.5 = 70 kN ~ 7.2 ton

Note that "T_{hr}" or sumping force is multiplied by 2 to account for both cutting heads while sumping, however, since operators use subsequent sumping when machine runs out of sumping force, this limit is often automatic-ally by passed. However, if the difference between the required and available sumping forces is an order of magnitude, it means that an efficient cutting may not be achieved.

Using a 90% mechanical efficiency factor the available machine capacities are (Eqn. 8,9):

F_{ts} = 31.9 kN
F_l = 5.6 kN

This means that the sumping force requirement is met but the machine is likely to run arcing force limited and must be checked in more detail. The torque requirement of the cutting head is (Eqn. 12):

T_q = 21x3.4x(0.5-0.225)=20 kN-m=15000 ft-lbs

This figure, combined with 58 rpm head speed, gives (Eqn.13):

Head Power requirement 166 hp = 125 kW

This is within the range of installed power of the cutting head even if the installed power were to be reduced by 10% to account for the mechanical efficiency of the system. Production and advance rate can be estimated as follows (Eqn. 14):

V_{pl} = 15 m^3/m = 5.56 Cyd/ft

W_{pl} = 33.7 ton/m = 10.3 ton/ft

Production rate from specific energy and machines power can be estimated at (Eqn. 15):

V_{ph} = 15.5 m^3/hr = 20.6 Cyd/hr
W_{ph} = 34.8 ton/hr

Advance rate from specific energy method (Eqn. 16):

A_r = 1.0 m/hr = 3.4 ft/hr

The boom speed could be estimated at (Eqn. 17,18):

A_r*= 34.8 m /hr = 116 ft/hr

and advance rate from boom speed (Eqn. 19):

A_r = 1. m/hr = 3.3 ft/hr

Using a 55% utilization factor over an 8 hour shift the advance rate per shift (of excavation) would be (Eqn. 21):

A_s = 4.4 m/shift = 14.42 ft/shift
W_s = 148 ton/shift

Conclusions

Project estimating and selection of the proper machine for the job requires a knowledge of the rock physical properties as well as job site conditions. By using the geotechnical and rock physical properties information as well as the measured specific energy, the project engineers can develop a suitable machine specification to maximize the efficiency of the cutting operation and production rate. The methodology proposed in this paper accommodates the capability to evaluate and select the proper roadheader for the project, while providing a reasonably close estimate of advance and production rates.

A roadheader capable of cutting rocks harder than 100 MPa (15,000 psi) effectively is needed by the mining and tunneling industry. Various methods for improving the cutting ability of roadheaders are being developed to move these machines into the next level of capability. Already several methods of increasing torque and thrust are available. Utilizing the effects of high pressure water jets through the head sprays, to clean the crushed zone while lubricating and cooling the bits, has been used to show a marked improvement in cutting ability. The next logical step in this progression is to combine the cutting technology of hard rock TBM's to the flexibility of the modern roadheader design with the use of minidisc cutters recently developed at the Colorado School of Mines. At present, design of a roadheader cutting head utilizing minidisc cutters for hard rock application is underway at CSM. Plans call for laboratory testing of the disc cutterhead in near future.

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