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DEVELOPMENTS IN TUNNELLING MACHINES FOR HARD ROCK MINING

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ABSTRACT: In hardrock mining, breaking continues to be dominated by the traditional drill-blast-and-muck cycle, an intermittent process and slow, which is almost impossible to automate. Mining engineers and equipment manufacturers are making a concentrated effort to eliminate this cyclic operation in order to achieve some of the efficiencies presently being achieved by softrock mining. The alternatives are to develop continuous mechanical excavating machines. The paper describes these developments, the economic, mechanical and electrical criteria for such machines and the impact these machines would have on the hardrock mining industry.

For many years mining has contributed significantly to Canada's favourable foreign trade balance. In 1987, non-petroleum minerals, led by gold and followed by copper, zinc, nickel and iron, generated $17.1 billion in revenues. Unfortunately, because they are produced through hardrock mining, they do not share the production advantages of other commodities such as potash, coal and industrial minerals which occur in softrock formations: namely, automated equipment and methods for development production mining. For example, very sophisticated longwall mining and rapid drifting machines are available for use in both potash and coal mining. Similar equipment or methods do not presently exist for use in hardrock mines. The hardrock mining industry is still struggling to reach the productivity and efficiency levels that are now the accepted norms in soft rock mining operations.

Drifting or lateral development, either for production or exploration, is a major concern to mining engineers. The age old drill-blast-and-muck cycle is still the prevailing method used in hardrock mining. Although highly automated drilling jumbos and advanced explosives and blasting techniques are now available and used, development is still a cyclic operation. Major new efficiencies in development operations will only occur when automated continuous excavation machines are available to replace drilling and blasting. Their introduction and use will reduce the lead time required to bring new mines and stopes into production.

Most hardrock tunnelling (or drifting) machines in use are modified versions of units designed and developed to meet civil engineering project requirements. They are particularly effective in carrying out long drives, which are not common to hardrock mining. Civil engineering projects, in general, provide more opportunity to optimize tunnelling machine performance. This is because the tunnels are usually longer and straighter, hence less down time or set up time, and because there is usually more geotechnical information available for the shallower locations in which tunnels are driven. In addition the acceptable cost levels for a civil project are usually higher and not subject to world mineral market prices. As a result, a mining engineer is necessarily more conservative when introducing new technology to mining.

Although full-face tunnelling machines, or TBMs, have a long history of applicaation in civil engineering projects, they are far from replacing conventional drill and blast methods in hard rock mining. Records show that TBMs were first developed in Europe in the mid-1800s. The early machines used compressed air driven rotating discs to cut the rock.

Successive improvements introduced over the years have resulted in present day machines which use electric and/or hydraulic power to rotate the cutting heads and to activate thrust jacks. TBMs are presently used to mine potash and other softrock minerals but none, to date, has been successfully used to mine hardrock where the uniaxial compressive strength (ucs) of the rock formation exceeds 240 MPa (35 000 psi). Of the 450 tunnels driven world-wide with TBMs, reported in 1982, only 9% were associated with mining operations and, of those, only 2% were associated with hardrock mining operations. If TBMs are to have a significantly expanded role in Canadian mining, then, they will have to be able to compete both economically and technically with drill and blast developments in mining areas such as Sudbury, where the compressive strength of rock is above 240 MPa. It should be noted that a South African Gold mine was technically successful in driving a drift with a Wirth TBM in a 100-350 MPa rock formation. An advance rate of 1 m to 2 m per hour was achieved, but at an exorbitant cost (1). Ultimately, such experiments will provide the necessary information to develop a successful hard rock boring machine.

While technically possible, there are a number of factors which limit, if not exclude, the use of TBMs in hard rock mining. These are: high capital cost; the high cost of muck handling arrangements; high set-up and dismantling costs (short length of drivages); the required infrastructure for mammoth machines; excessive vibrations in fractured rock formations. Hopefully, by successfully addressing these problems through research and development, a suitable TBM for use in hard rock mines will become available.

The availability of a suitable hard rock TBM or a mechanical excavation machine can be expected to revolutionize hardrock mining. By providing predictable rock fragment sizes, unlike blasting, the succeeding haulage and loading-unloading operations will be amenable to full automation. In this regard it should be noted that the present production bottle-neck in Vertical Bulk Mining is the intermittent drawing, loading and hauling of ore. The lack of fragmentation product control with blasting in hardrock mining is preventing the achievement of the degree of automation that already exists in coal and softrock mining.

The minimum radius of curvature required for a TBM drifting operation is 40 - 80 m compared to 15 - 25 m for a non-TBM operation. Operational requirements in mining can often require much sharper curves. Once a commitment has been made to use a TBM for drifting, it is very difficult and expensive to change to another drivage method. Modification or abandonment of drill and blasting drifting is relatively easy because of the size and cost of the equipment involved.

TBMs produce openings of circular cross-section which have some advantages with respect to hanging vent tubes, air pipes and cables. However, additional cost is involved when a flat road service is required for mobile equipment and must be achieved by either reblasting or backfilling. It is an uncomfortable marriage of two incompatible methods. The backfill could be provided by TBM operation itself but, never-the-less, it constitutes an additional cost.

In some cases, the smooth surface generated by a TBM or a mechanical excavatoris an over riding factor (as compared to cost) in the selection of this excavation method. Hydro authorities in Norway are investigating the use of a Mobile Miner to smooth the rough surface of an unlined drill-and-blast tunnel in order to improve the tunnel's hydraulic and structural properties (2).

On a TBM tunnelling project with 10% bad ground, 50% of the delays of the whole project could result because of this (3). It is much more important to know the ground thoroughly when a TBM is being used. It is very expensive to abandon a decision to use a TBM once the initial financial commitment has been made.

In 1982, Mount Isa Mines Ltd. (MIM), in Australia collaborated with the Robbins Company (USA) in the development of a continuous mining machine, the Mobile Miner, for hardrock operations. The machine was intended to bore a 22 m^2 section tunnel, 1.2 km long, in an abrasive quartz formation with a compressive strength of 110 to 270 MPa.

The Mobile Miner had a cutting head consisting of roller disc cutters mounted on a large rotating wheel. Unlike the conventional TBM, the Mobile Miner was not designed as a full-face machine. The plane of the cutter head was designed to face the drift at an oblique angle to the axis of the drift. Only 3.67 of the disc cutters would be in contact with the face at any time (4). This arrangement made the machine lighter than an equivalent TBM. It was designed to initially penetrate the face and then sweep laterally, excavating a rectangular section.

This mode of operation has definite advantages in terms of mining, and air and water flow. The drift produced does not require back filling or blasting for use by mobile equipment as a flat floor and back is generated. As it is a mechanical excavating machine there is no over break or blast damage to the walls. The later was the prime consideration for MIM in considering mechanical excavation.

Boyd (4) has provided a performance analysis of the Mobile Miner. Some of his findings on the machine and its use are summarized below:

- As a prototype machine, mechanical and organizational delays were unavoidable;
- The machine utilization was only 17% of the total scheduled time;
- The average rate of advance was 42 m /month over a drift length of 842 m of 22 m^2 section;
- The best recorded single shift performance was a 3.66 m advance in 5.3 hours cutting time;
- As experience with the machine was gained, organizational and machine improvements were introduced, resulting in improved utilization.

Figure 1 provides availability and time delay data for the Mobile Miner for S60, 1156 m decline and R61, 587 m drift (5).

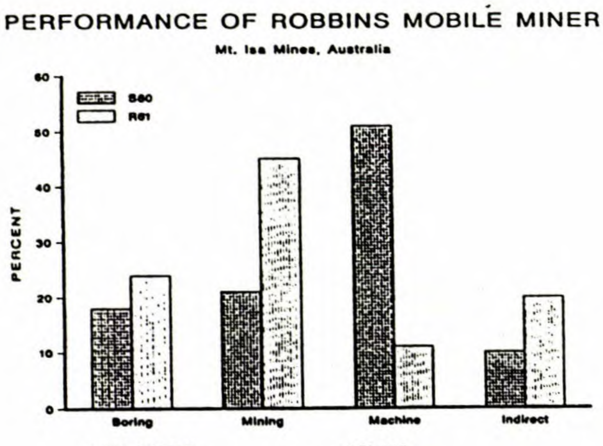

Figure 1. Availability and delay data for Mobile Miner for drifts S60 and R61 at Mount Isa Mines, Australia, (5)

Hard Rock Tunnelling Machines

TBM technology has not yet progressed to the point at which it can successfully replace conventional drill and blast drifting in hardrock formations. Cutter wear, and thrust and bearing limitations are the major technological barriers to their use in hardrock formations. TBM designers and mining engineers, however, are optimistic of the ultimate use of TBMs in hardrock mining.

In 1985, a bold attempt was made by Kiena Gold Mines Ltd. (Val d'Or, Canada), in collaboration with Redpath Ltd. of North Bay, to rehabilitate a 7 ft 6 in Jarva Mark 6, for use as a TBM to drive 2828 ft drift in peridotite and basalt formations intersected by hard diorite dykes. The uniaxial compressive strength of the formations encountered varied from 70 MPa to 255 MPa (10 000 to 37 000 psi).

The TBM performance, time delay data, and availability analysis are summarized in Figure 2 for South-East drifting, North-West drifting, and for the total project. The bar charts were developed from data in a paper by Vanin (6) modified to convert to same base parameters as for the Mobile Miner. (Although the geotechnical, cross-section and other parameters differ in these two cases).

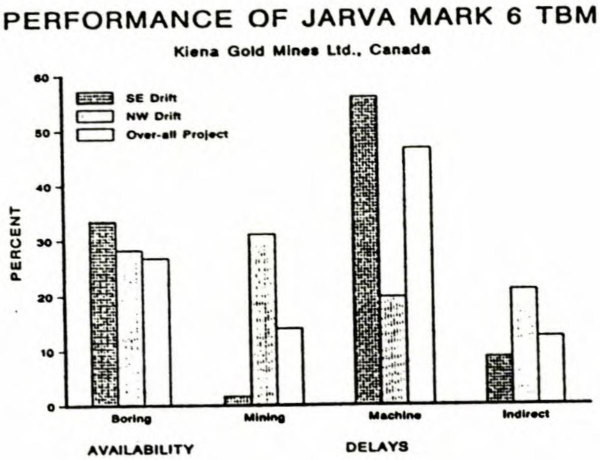

Figure 2. Availability and delay data for Jarva Mark 3 S-E Drift, N-W Drift and both Drifts at the Kiena Mine, Val d'Or, Quebec, Canada (6)

The intersection of rock formations having rock strengths exceeding that could be handled by the machine forced abandonment of the project. In the N-W drift 22.09% of the operational time was devoted to ground control, while no time for ground control was required in the S-E drift. Mechanical maintenance occupied 17.56% of the machine time in the S-Edrift and 2.14% in the N-W drift. These different machine time utilizations were mainly due to rock conditions. The cost of driving the S-E drift was $363.78/ft, excluding TBM depreciation and the contractors fees. Changes in support methods and organization prior to use in N-W drift decreased machine delays.

It is interesting to compare the forecast for the S-E drift and the actual performance as summarized by Vanin (6), Table 1.

	Forecast	Actual
Length	4700 ft	1685 ft
Rock type	basalt and diorite	basalt and quartz
RQD (+4 in.)	80% +	80% +
UCS basalt	20 000 - 26 000 psi	6000 - 37 000 psi
UCS andesite dykes	14 000 psi	non encountered
Scheduled operation per day	1st month, 1 shift/day remaining: 1 mtce shift 2 boring shifts	1½ months, 1 shift 1 month, 2 - 12-hr shifts remaining: 1 mtce shift 2 boring shifts
Performance		
1 shift/day	20 ft	9.9 ft
3 shifts/day	40 ft	21 ft 18.43 ft ave.
Ground support requirements	none	none

Table 1. Contract parameters - S-E drift, Kiena Mine

Compact Underground Borer, (CUB)

The Kiena Mine trials with the modified Jarva Mark 6 convinced the Company's mining staff that a truly hardrock TBM was feasible. In 1988, Falconbridge, the parent company of Kiena Mines, established a consortium with Boretec (USA) and Brown Boveri Howden (Canada) to design, build and test a machine. The Federal Government is providing partial financial support.

The consortium members are confident that the Kiena experience and recent advances in material and machine design will make the development of such a machine possible. Falconbridge will act as the Project Manager for the consortium based on its Kiena experience and as an operator with several hardrock mines suitable for field trials. Falconbridge has identified 17.5 km of drifts which must be driven in the next five years through 205 MPa - 310 MPa (30 000 to 45 000 psi) rock formations to meet operational requirements. It has made the commitment to driving 13 km using mechanical excavating machines if the development is successful. While the consortium members will be directly responsible for the design, development, construction and testing of the TBM, sub-contractors will be used for peripheral investigations such as, determinations of rock drillability and rockmass qualities, machine stress measurements, and lay out planning.

Because of its use as dedicated underground tunnelling machine and the designed compact features it has been named - the Compact Underground Borer (CUB).

The major design parameters for the CUB are (7):

- modular component design to facilitate assembly, disassembly, and transport within a mine;
- short turning radius;
- capable of excavating soft to very hard rock formations;
- more powerful than conventional TBMs for civil engineering projects;
- safe and comfortable environment for the operator, (with remote control capability);
- cutterhead with close cutter spacing to permit higher face loads;
- larger diameter cutters and bearings, permitting an increase in wearing surface and cutter/rock loading; and,
- new materials to extend cutter life.

Some of the features which distinguish the CUB from the Jarva Mark 6, used in earlier trials at Kiena Mine, are the following

Increased Horsepower and thrust capacity:

- The CUB will have 550 hp and 400 tonnes of thrust as compared to 200 hp and 250 tonnes for the Jarva Mark 6. The higher horsepower and thrust of the CUB should permit it to achieve higher advance rates.

Narrow, high capacity disc cutters:

- The CUB will be equipped with 18" diameter disc cutters, the largest commercially available, spaced at 2.5 inches. The Kiena Mark 6 has 12" diameter cutters spaced at 3.5 inches. The 18" diameter disc cutters can support axle loads of 25 tonnes. Combined with the 2.5 inches spacing this should result in higher penetration rates.

Double gripping system:

- A double gripping system will permit

continuous operation of the CUB as the machine is advanced. It will also permit the use of short boring strokes and reduced size of the structural components. Thus, the CUB will be lighter and shorter than a conventional TBM.

Shorter length boring machine:

- The CUB will be approximately half the length of the the Jarva Mark 6, which was originally designed for civil engineering projects. This feature will allow the CUB to negotiate a 100 ft radius curve, a requirement for a hard rock mine TBM. The modular design will permit components to pass through a 5.5 x 5.5 ft opening.

Continuous ground support:

- Because mechanical excavation reduces support is normally required. However, the CUB will have a 220 degree shield extending from the cutting face to the ground support chamber. The latter will be equipped with an articulating roof bolter and a local finger shield for operator protection. The CUB is also compatible with the use of ground support rings or arches where ground conditions will require their use.

Table 2. Summary performance characteristics

Table 2

Summary performance characteristics *

	CUB	JARVA MK6 (Kiena Mines Ltd.)
DIAMETER	8' 0"	7' 2"
HEAD POWER (hp)	500	250
HEAD SPEED (rpm)	14.1	12.4
TORQUE (ft. lb.)	186,000	103,000
PROPEL FORCE (Tons)		
(Running)	450	242
(Peak)	565	290
GRIPPING CLAMP FORCE (Tons)	1270	1360
GRIP PAD AREA (sq. ft.)	66	24.5
PAD PRESSURE (psi)	266	770
GRIP TO THRUST RATIO	2.25	4.6
STROKE (Continuous)	NO	NO
STROKE LENGHT (inches)	24	24
REGRIP TIME (min)	0.5	4
CONTINUOUS STEER	YES	NO
MAIN BEARING B.D.T.C. (lb)	2,085,500	362,000
CUTTER DISC SIZE (inches)	18	12
CUTTER SPACING NOM. (inches)	2.7	3.25
CUTTER BEARING CAPACITY (lb)	60,000	28,000
NUMBER OF CUTTERS	20	18
TOT. CUTTER BEARING CAPACITY (lb)	1,200,000	504,000
RATIO OF BRGS. TBM TO CUTTERS	1.74 : 1	0.72 : 1
HYDRAULIC SYSTEM PRESSURE		
(Peak psi)	5,000	3,000
(Running psi)	4,000	2,500
TOTAL KVa REQUIRED	600	300
T.B.M. WEIGHT (Tons)	48	37
POWER TRAILER WEIGHT	11	10
TURNING RADIUS (FLAT HEADINGS)	85 ft.	300 ft.

Table 2 permits comparison of the CUB and Jarva Mark 6 machine parameters. Although the CUB will be half of the length of Jarva Mark 6, it will be 30% heavier, with a weight of 48 tons. The weight increase is primarily due to the increased power capacity, the closer spacing of larger cutters, and the double gripper system essential for continuous operation. Based on these machine parameters, the designers have estimated the machine performance for comparison with conventional drifting, Table 3 (7).

Table 3. A comparison of performances of conventional drifting method and the CUB (estimated)*

	Conventional Method	CUB estimated performance
Minimum cross section	8' x 9' 72 sq. ft. 6.7 sq. m.	7' 6" dia 44 sq. ft. 4 sq. m.
Advance per day in first 1000 m.	5 - 6 m.	12 m.
Cost/m.	Same	Same
Advance per day from 1000 m. - 2000 m.	4.5 m.	12 m.
Cost/m.	20% premium	Same
Advance per day after 2000 m.	3 - 4 m.	12 m.
Cost/m.	30% premium	Same

* Source: T.F. Pugsley et al
Falconbridge Mines Ltd. Toronto (1988)

The Roger Continuous Mining Machine

In the period between 1983 and 1988, Machines Roger International Inc., of Val d'Or, Quebec, successfully developed a unique raise boring machine. The machine uses short head, 6.5 inch diameter, in-the-hole hammers for rock breakage attached to a header supplying compressed air. The V-30 borer, for driving 30 inch diameter raises, uses 2 hammers while, the V-50, for driving 50 inch diameter raises uses 3 hammers. The header, which rotates, allows the hammers to carve rings in the rock as upward thrust is applied. As in the case of conventional raise borers, the Roger raise borer requires a pilot hole to a lower drift for attachment of the reaming head and for cuttings removal. The machine is powered by 21 m^2/min of air at 2400 kPa

(750 cfm at 350 psig). The Roger machine is a simple machine which does not require an expensive and heavy concrete pad for installation. It is relatively portable and requires low capital cost to bring one into operation. Figure 3 illustrates the machine layout.

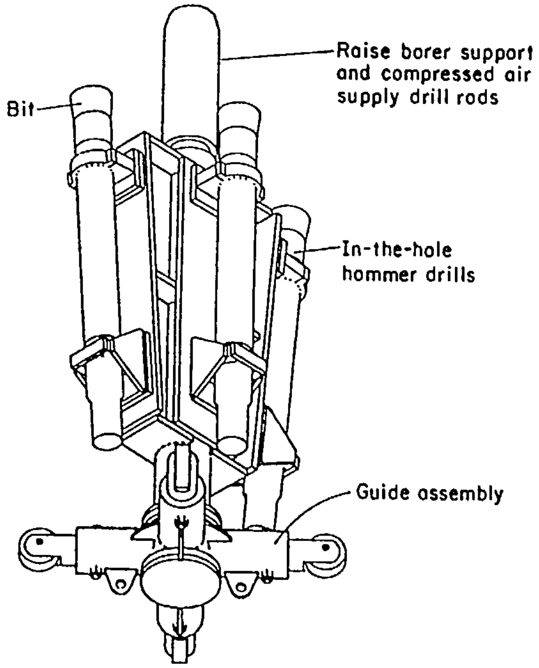

Figure 3. Roger raise borer

The Roger raise boring machine has been tried in several Canadian mines and is now in commercial production. The V-30 borer can back ream at rates up to 1.5 m (59 inches) per hour in rock of 207 MPa (30 000 psi) compressive strength (8). It has been very successfully used at LAC Mineral's Mines Bousquet, in Quebec, to drive raises in ground in which conventional methods were difficult. LAC can drive a 60-ft raise in two shifts with the V-50 Roger machine, a task which can take 15 shifts using conventional method (9).

The natural extension of the Roger raise boring machine is the development of a horizontal boring machine. For this extension of the technology, however, pneumatic drills will have to be replaced by hydraulic drills to achieve improved breaking efficiency and reduced noise levels. The horizontal machine will be mounted on an off-the-shelf mobile unit and will be combined with an armloader. The front end of the machine could have as many as 10 hammers operating simultaneously. Because of numerous small, narrow and irregular vein gold ore deposits in north-west Quebec, Roger Machine International is giving priority to developing a stoping machine to meet the requirements for this type of deposit. The machine will operate in a stope as a continuous mining machine. A conceptual drawing of the machine is shown in Figure 4. The machine is being designed to economically mine formations having compressive strengths up to 250 MPa.

Sufficient sponsors and financial resources are now in place to proceed with its design, development and construction. Both the Federal and Quebec Provincial Governments, and several universities, mining companies and research organizations are either contributing funding of the project or directly taking part in the machine's design and development.

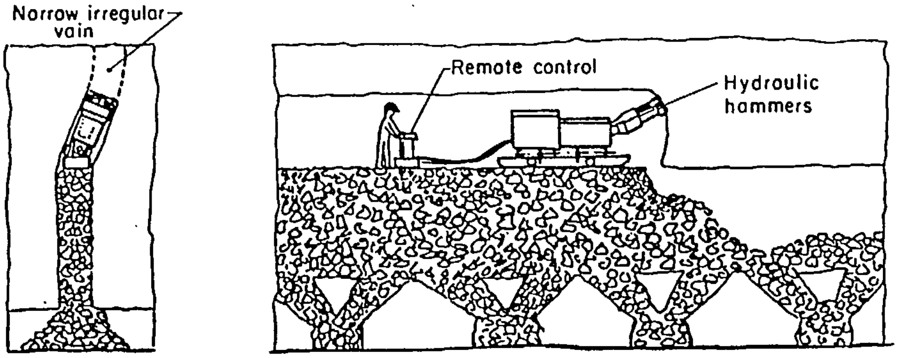

Figure 4. Roger continuous mining machine in a narrow vein stope

Conclusion

An economically viable continuous mining or tunnelling (drifting) machine for mining in rocks of over 250 MPa will be a major technologic of breakthrough for the Canadian mining industry. The predictable fragmentation would change present concepts as to material loading and handling. Automation of mining systems would be greatly assisted. Unless hardrock mining's dependence on drilling and blasting can be broken by the use of continuous mining machines the tull benefits of the automation being achieved in other industries will never be realized.

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