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MECHANICAL BORING OF TUNNELS AND RAISES

by

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ABSTRACT

Lateral or inclined tunnels may be driven by conventional methods that involve drilling and blasting or by means of boring machines. Within the mineral industry, most lateral driving is done conventionally whereas within the civil engineering field, an increasing number of tunnels are driven by mechanical devices.

Inclined tunnels (raises) are, to an increasing extent, driven with raise boring machines which are gradually becoming more competitive as compared with conventional methods.

Machines for lateral tunnel driving generally operate by exerting a high thrust against rotary or disc cutters which are brought to bear against the rock face as the head of the machine rotates. Performance on machine driving is rapidly gaining on conventional methods but some problems such as high cutter wear and machine inflexibility must be overcome. Thus far, lateral tunnels have been economically driven in rock with a compressive strength of 25,000 lb/in^2.

Raises are usually bored by first completing a pilot hole then reaming to full size which may be 5 to 7 ft. in diameter. In rocks of up to 35,000 lb/in^2 compressive strength which have been successfully bored, conventional methods of driving would probably show more favourable costs. However, the superiority of bored raises for many purposes continues to favourably affect the spread of the technique.

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The superior types of openings which result from boring machines and the efforts being expended on improvements, including steps towards automation, will probably further increase the applications for the new technology.

RESUME

Des tunnels horizontaux ou inclinés peuvent être percés selon des méthodes conventionnelles impliquant le forage et le sautage ou bien à l'aide de machines de fonçcage. Les tunnels horizontaux sont pour la plupart percés de façon conventionnelle dans l'industrie minéerale tandis que, dans le domaine du génie civil, ils sont de plus en plus percés par des moyens mécaniques.

Les tunnels inclinés (montées) sont d'une façon croissante percés avec des foreuses de montées qui, comparées aux méthodes conventionnelles, deviennent graduellement plus compétitives.

Le principe de fonctionnement des machines pour le percement des tunnels horizontaux consiste généralement en l'application d'une forte poussée sur les taillants rotatifs ou à disques qui sont mis en contact avec le front rocheux lorsque la tête de la machine tourne. Le rendement du fonçage mécanisé gagne rapidement du terrain sur les méthodes conventionnelles mais certains problémes, tels que l'usure élevée des taillants ainsi que le manque de flexibilité, doivent être surmontés. Jusqui'ici, des tunnels horizontaux ont été percés de façon économique dans des roches ayant une résistance en compression uniaxiale de 25,000 lb/po^2.

Les montées sont habituellement foncées grâce au forage initial d'un trou-pilote, suivi d'un alésage à un diamètre final de 5 à 7 pieds. Dans des roches ayant jusqu'à 35,000 lb/po^2 de résistance en compression uniaxiale et qui ont été percées avec succès, les méthodes conventionnelles de fonçage montreraient probablement des coûts plus favorables. Toutefois, sur plusieurs points, la supériorité des montées fonçées mécaniquement continue d'affecter favorablement la diffusion de la technique.

La supériorité des ouvertures réalisées par les machines de fonçage et les efforts apportés aux améliorations, y compris les étapes vers l'automatisation, augmenteront probablement davantage les applications futures de cette nouvelle technologie.

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1. INTRODUCTION

The driving of openings which are long as compared to their diameters occurs frequently in civil engineering works as well as in underground mining. Although much of the driving of these openings is pursued by use of conventional methods of drilling and blasting, many sophisticated machines have appeared on the market in the last twenty years to perform the tasks. The introduction of tunnelling machines resulted partly because of the need to do things faster and partly because of the lack of qualified personnel to do the driving by drilling and blasting. Most of the machines are similar, in that they grind or cut the rock face into pieces, thereby advancing the openings by mechanical methods.

Two broad categories of mechanical driving are found, that is, the driving of essentially horizontal tunnels (1) used in civil engineering works and mines and the driving of inclined openings (raises) used more often in underground mines. As these two types of underground openings are most conveniently considered separately owing to differences in driving technique, the report is divided into two sections: the first discusses the driving of essentially horizontal openings while the second discusses the driving of raises. The information presented was compiled from a detailed literature survey, from observation of operations in the field and from the Tunnelling Office of Canada (TOC). An agency of the Mining Research Centre, Department of Energy, Mines and Resources, Ottawa, TOC assembles and distributes free of charge, information pertaining to tunnelling.

The present report covers in each of the two sections the operating principles as well as the design of the boring machines, with particular emphasis on the cutting tools. The different uses are then

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(1) The OECD definition of a tunnel is: "Any underground opening which has a cross sectional area of 2 square meters or greater". Some of the openings which will be considered in this publication do not meet the definition.

discussed as well as the limitations in using mechanical methods. Performances and costs of driving by the mechanical methods are analysed for a variety of Canadian jobs. The gathering of geological information which is necessary previous to the use of mechanical driving is discussed, stressing its importance. Brief comparisons are made with the performances and the costs of conventional methods. The advantages and disadvantages of mechanical driving methods are summarized. Problem areas during field work are noted and finally, the future prospects of mechanical driving are considered.

2. LATERAL TUNNEL DRIVING

2.1 Tunnel driving methods

Tunnels can be divided into three groups according to the method of excavation as follows:

1) the conventional method of driving by drilling and blasting,
2) the driving in soils or in unconsolidated rocks using machines with a protective shield, and,
3) the driving by the full face boring method in rocks of variable strength.

The conventional method will be discussed only to establish comparisons.

2.1.1 Protective shield machines

Protective shield machines are used in soft materials which must be supported until the time when a permanent lining can be installed directly behind the machine. The entire machine is usually pushed toward the front with the use of hydraulic jacks which bear against the last installed section of lining. Driving is thus intermittent with stops for the installation of lining sections which among others can be sections of cast iron, welded steel, or segments of concrete with a length of 2 to 4 feet.

On the face side, the machines are equipped with tools such as rotating or oscillating arms with picks to break the material to be penetrated.

One of these machines is illustrated in Figure 1 which clearly shows the picks. Many soft ground machines are equipped with a unit to hoist and put lining sections in place. One of the largest manufacturers of soft ground machines has recently developed machines using disc cutters to work in slightly stronger materials such as chalks and hard clays. Protective shield machines are known to have been built to diameters varying between 7 and 33 feet. An indication of driving performance with soft ground machines is given by the progress in the Victoria line of the London Subway which was 14 feet in diameter and was advanced an average of 410 feet per week.

2.1.2 Full face driving machines in hard rock

Full face machines can be divided into two completely different types according to their method of operation, as follows:

1) Machines which work the entire face at a time while continually advancing. These machines are usually called full face boring machines; an example is shown in Figure 2.

2) Machines with a cutter-equipped head which is substantially smaller than the cross sectional area of the tunnel. These machines can only work the face with a sweeping motion as is indicated in Figure 3.

The latter machines advance intermittently in the longitudinal direction of the tunnel. These machines were developed for driving haulageways in the coal mines, and have been used principally in Germany, Great Britain and the U.S.A. As machines of the second type above are not used in Canada, this report will cover only the full face boring machines in greater detail.

Full face boring machines can be sub-divided according to the method by which the tools break the rock. Figure 4 shows the three types

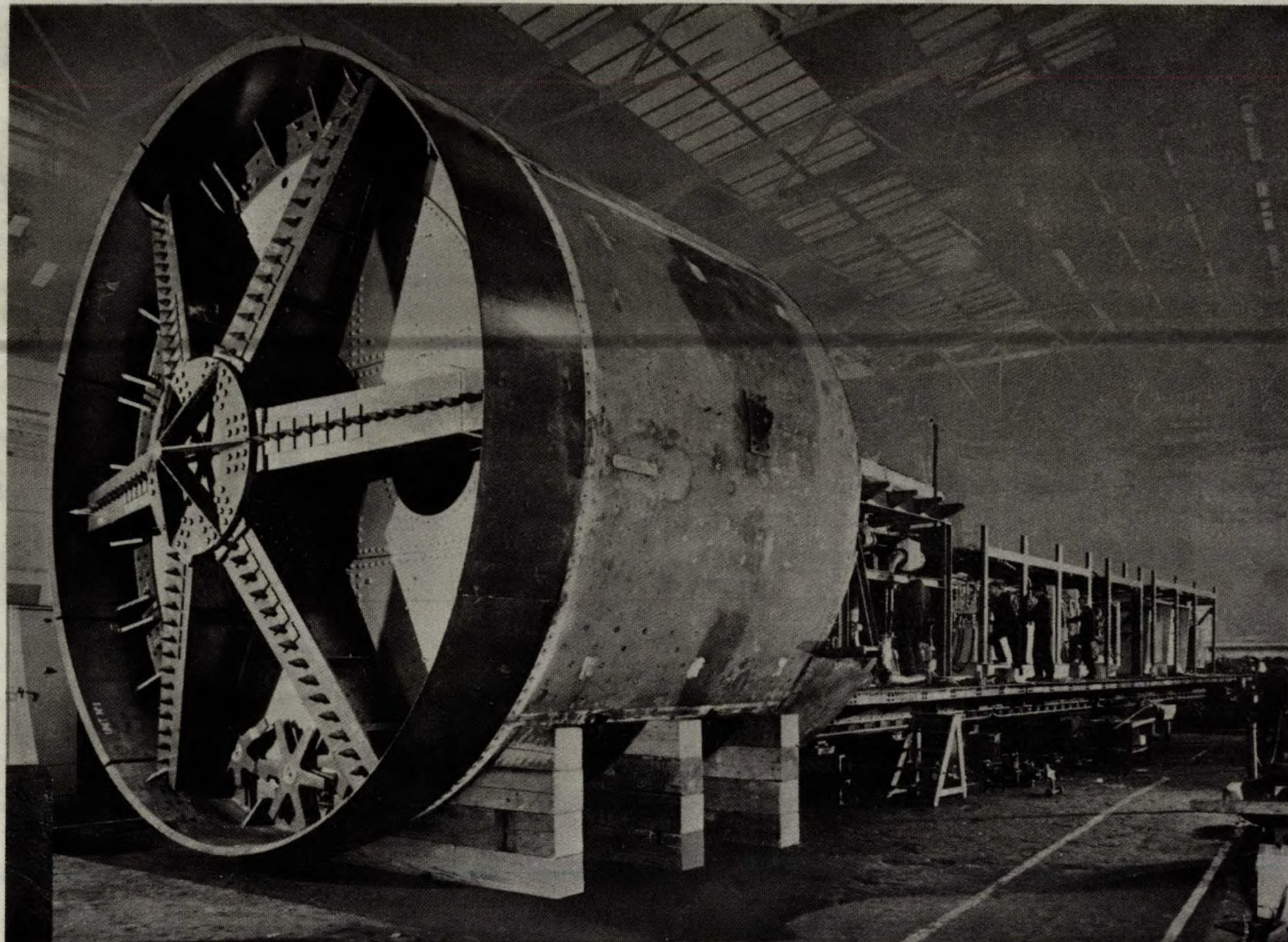


Figure 1 - Tunnel boring machine with a protective shield produced by K. M. Tunnelling Machines Limited.

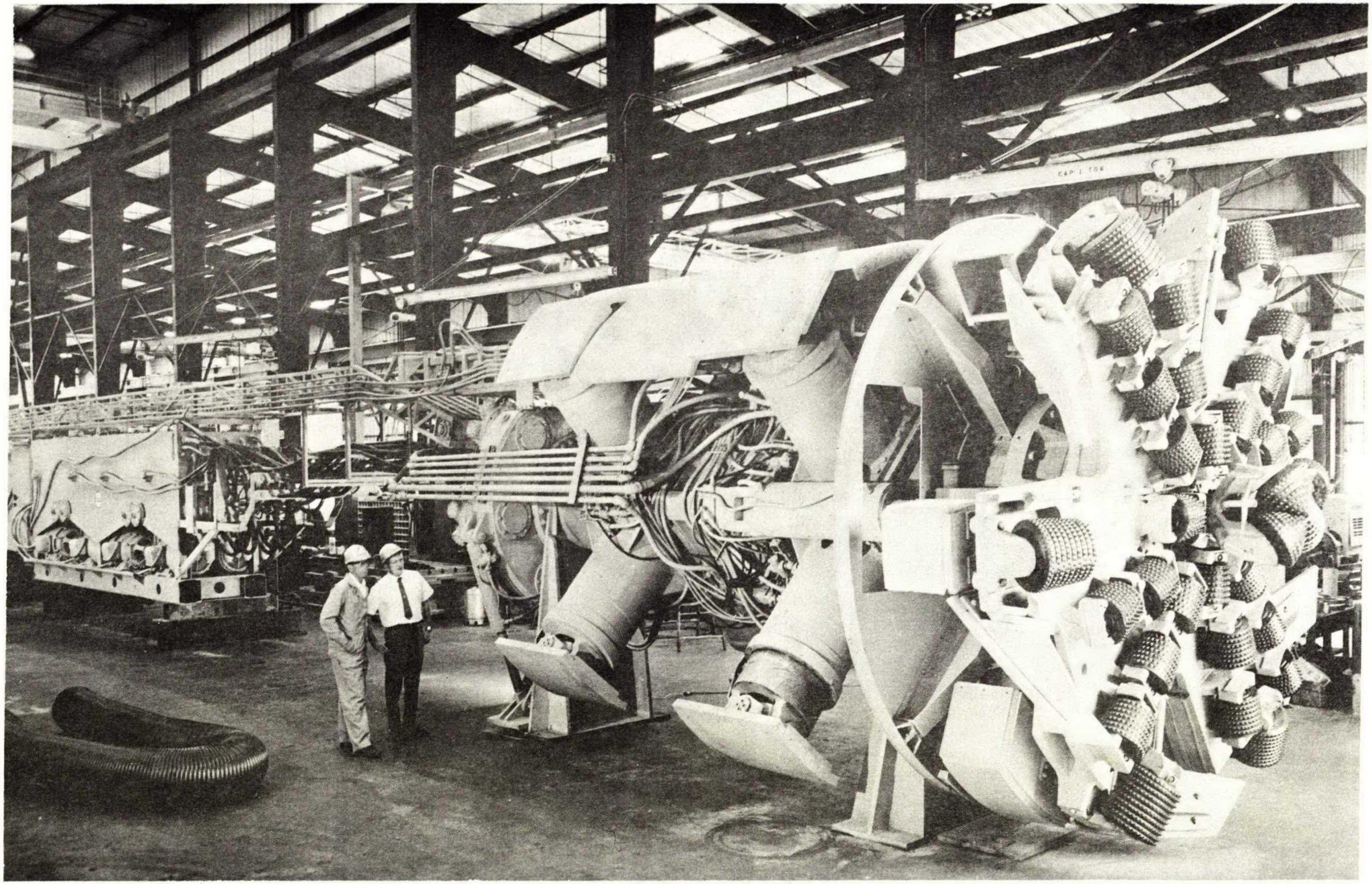


Figure 2 - Full face tunnel boring machines produced by Caldweld

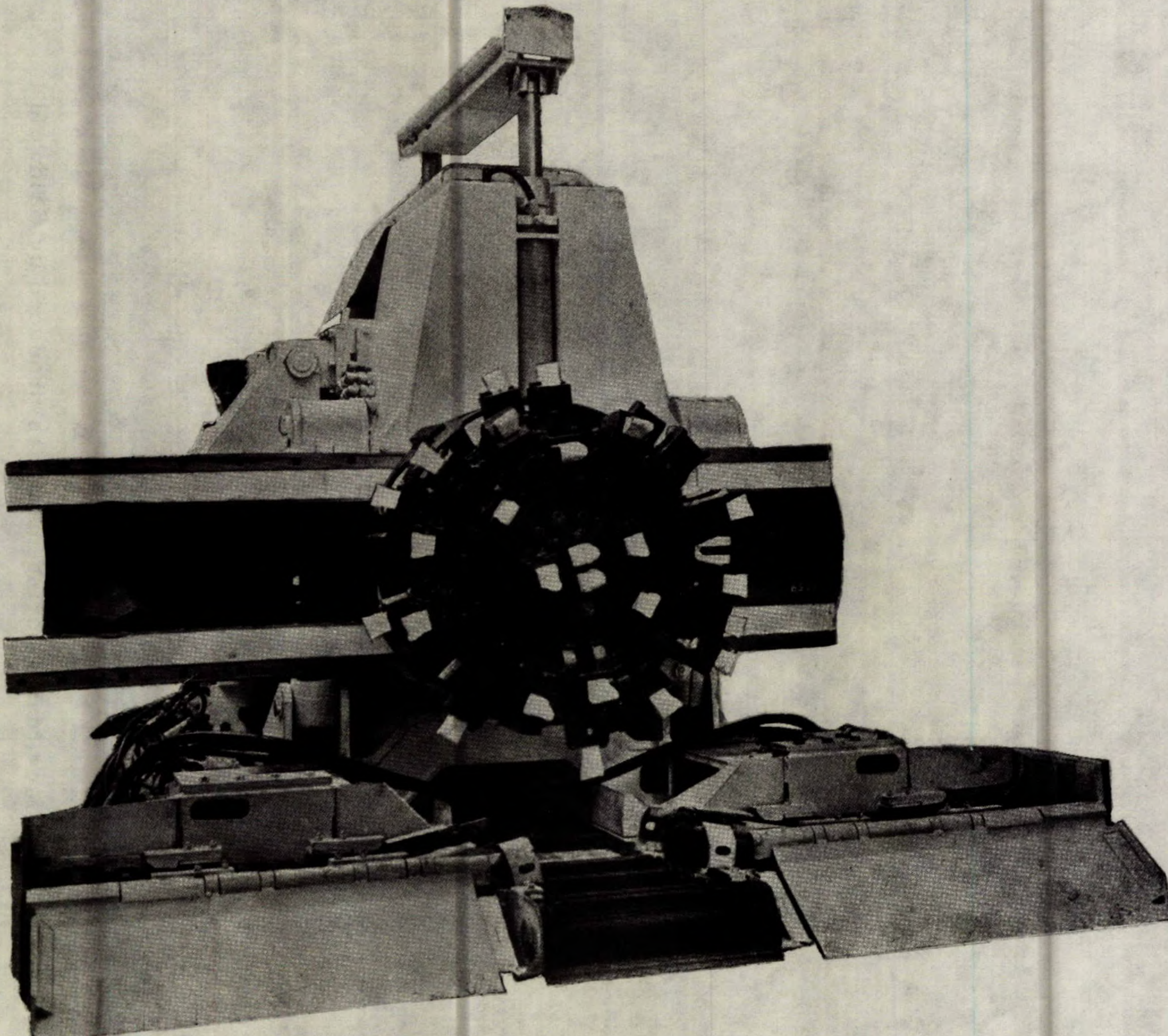
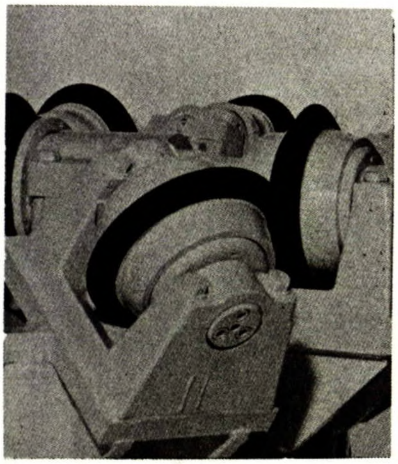


Figure 3 - Tunnel boring machine with a boring head operating by a sweeping action for use in coal mines produced by Greenside - McAlpine.

Rotating cutters with tungsten carbide buttons



Disc cutters

Tungsten carbide picks

Figure 4 - Types of cutters for tunnel boring machines

of tools; rotating cutters with teeth or tungsten carbide buttons, disc cutters, and, picks of tungsten carbide. Machines with rotating cutters or disc cutters are generally similar and have usually the same performance at comparable installed capacity. They constitute by far the greatest number of machines which have been put into operation. Full face boring machines with tungsten carbide picks and those that break the rock by undercutting are in some aspects different from the rotating machines with rotating or disc cutters. Thus far, machines with cutting picks have been used in Europe preferably in soft to medium hard rocks.

2.2 General design of a full face boring machine

All the full face boring machines have the following components:

1) A boring head, supporting the cutters,
2) a machine which supports the boring head,
3) a propulsion unit,
4) a steering unit, and,
5) a complete auxiliary system.

The various manufacturers have used several approaches to the mechanical design of the components and the means by which they are interconnected. Evidently, it is impossible to describe the various configurations in detail, therefore further discussion will be confined to particular characteristics.

2.2.1 The boring head

The machines which operate by grinding (i.e. those which use rotating cutters or disc cutters) employ the same engineering principles. A construction of welded steel, in most cases having the shape of a saucer, supports rotating cutters which are free to turn. The rotating head is usually equipped with buckets at the periphery for transferring broken rock to a conveyor, usually a belt along the length above the body of the machine. The head is rotated by electrical motors at approximately 10 rpm in the case of a machine with a diameter between 10 and 13 feet. A machine of this type is illustrated in Figure 2. The machines which operate by undercutting have a head which carries several cutting picks which tear out the rock instead of grinding it. A machine of this type is shown in Figure 5. For the latter machines, rock is transported toward the rear with a chain conveyor passing underneath the body of the machine.

2.2.2 The body of the machine

Aside from supporting the head, the body of the machine has the task of connecting the principal components together and of housing the driving motors, the electrical and hydraulic equipment, the auxiliary equipment and the steering unit. This equipment can also be mounted on a supply trailer at the rear of the machine.

2.2.3 The propulsion unit

With the exception of the German Krupp machine, which has continuous propulsion with the help of tractor chains and which for this reason is only acceptable for soft rock requiring little thrust, all the machines have an intermittent propulsion system using hydraulic jacks. However, the Alkirk machine is an exception as it pulls itself towards the face with the use of an expansion anchor which locks in a previously-drilled pilot hole. Most machines are anchored with the aid of a clamping unit against the walls of the tunnel.

2.2.4 The steering unit

When the steering unit is attached to the propulsion unit, there is normally little chance of modifying the alignment of the machine during an actual stroke of boring, therefore a correction of alignment can only be made when the propulsion unit is readjusted. Most of the machines use a laser beam to guide them. The reading of the target is made directly, or with the help of closed circuit television. A television camera mounted on the wall of the tunnel or an ordinary theodolite have also been used to control the alignment instead of a laser beam.

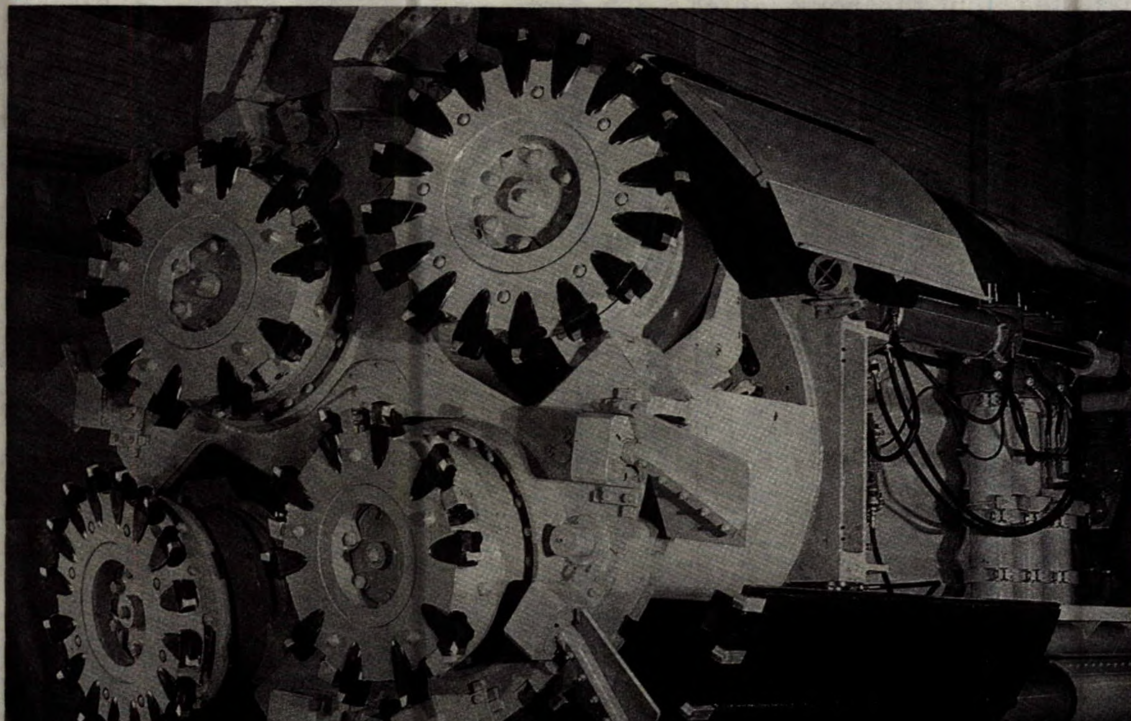


Figure 5 - Tunnel boring machine operating by undercutting produced by Atlas Copco.

2.2.5 The auxiliary system for mechanical boring

The use of mechanical boring machines requires an elaborate servicing system. Aside from supplying the source of electrical power, the machine must also be equipped with a dust evacuation system and with a transportation system for the broken rock. Trains of cars, or conveyor systems are usually used for rock disposal. In certain situations, a pumping system must be supplied to remove the ground water from the face.

2.3 Uses

The increasing use of mechanical boring methods directly reflects the pressing need to place more services underground with the increase in population density. More and more town planners look towards tunnels as being the most adequate and the most economical method for water supply, sewage disposal, transportation and other services. In countries like Japan and certain European countries, there will be intensive programs of tunnel driving almost exclusively in civil engineering works.

Canada, on the other hand, is different for while performing 9% of the total tunnel driving of the world, the greatest part of these are in mining areas and are pursued by conventional methods. In 1957, an attempt was made to introduce mechanical tunnel boring at the Steep Rock Iron Mine in Ontario. However, the experience lasted only for a very limited time period. The Potash mines in Canada use boring machines in their mining method but the conditions in these mines are very special with respect to the method of extraction and the hardness of the rock. Even today, such machines are not used in Canadian salt mines, the principal reason for this being the non-uniformity of the deposits. Mining machines used for extraction of coal in underground mines are to some extent boring machines without appearing to be. The use of boring machines in civil engineering works in Canada is limited to less than ten projects.

Recently, certain boring machines were tested in underground mines in the U.S.A. at White Pine in Michigan and at Climax Molybdenum in the West. The results of these trials are not known. It can be said that if success had been achieved, the results would have been more widely publicized.

The use of tunnel boring machines in the world indicates that they can be used with success in tunnels for civil engineering works with rocks having compressive strengths up to 25,000 lb/in^2. Presently, it can be said that if a tunnel can have a circular section of less than 11 metres in diameter with a length of more than two kilometres there are possibilities for economical boring with a machine.[(2)] The lack of manoeuvrability of the boring machines seems to be the important factor which excludes them from most mining applications.

2.4 Cost of tunnel boring machines

In 1970, the cost of a tunnel boring machine could be estimated at \$4,000 x (feet of diameter)^2 or about \$1,000/HP. Certain statistics on tunnel boring machines have been reproduced in Table 1.

TABLE I

Manufacturer	Model	Diameter (ft)	Total HP	Cost
Jarva	Mark 8	8	330	\$330,000.
Robbins	81-118	8.5	200	222,000.
Jarva	Mark 11	10	440	440,000.
Lawrence	HRT-12	12	600	500,000.
Robbins	121	13.25	400	400,000.
Jarva	Mark 14	13.67	540	540,000.
Hughes	Betti I	19.83	1,000	1,000,000.

(2) Sometimes referred to an a "mole".

The above data were obtained from an article by Norman and Stier dating back to 1967 and thus it can only be used as indicative of present day prices.

2.5 Performance of full face tunnel boring machines

After considerable world experience concerning the use of full face machines, the performances that are possible are relatively well known. These performances have increased through the years and reliability has improved owing to accumulated experience and development of better cutters. While no precise model has been developed to predict performance, it is known that the nature of the ground penetrated with all its geological, hydrological and mechanical characteristics has the greatest effect. The best performance is in general obtained in ground with rocks of medium hardness where the excavation can support itself and for long tunnels of small diameter. In very hard rocks, problems are to be expected, whereas in soft ground, the tunnel will require early lining installation. These two conditions reduce the performance more or less up to a point where mechanical boring may become less attractive. The performance obtained during the driving of some two hundred major tunnels which have been completed cannot be discussed owing to the repetition which would be involved. Therefore, some Canadian experience as well as the performance obtained by two manufacturers, Jarva and Demag during a few of their projects will be discussed.

A good part of the Canadian experience in mechanical tunnel boring in civil engineering works has been summarized by Verity of the Department of Energy, Mines and Resources in a detailed report on the subject. He reported the results obtained during four important projects for which certain statistics have been summarized in Table II. The first project was carried out in Toronto during 1958-59 for the boring of a sewer; this was followed by the boring of five diversion tunnels by the Prairie Farm Rehabilitation Administration in Saskatchewan during 1961-63.

Later, two projects were undertaken in British Columbia; one in Vancouver during 1963-64 and the other in Victoria during 1964-66. Only the project in Victoria encountered serious difficulties and it was necessary to complete the greatest part of it by conventional methods. The main reason was that the ground was too hard for the machine and its cutters. Since that time, other projects have been undertaken and completed successfully in the cities of Ottawa for a sewer and in Toronto for the extension of subway lines. Complete results regarding these projects are not yet available. Even if the economic advantages have not been of overriding importance, certain contractors have commented that much time had been spent to acquire knowledge of machine operation and that this acquired experience would produce better results on future work.

Jarva Tunneling Machines has claimed that during four projects, in which a Jarva Machine Mark 8 was used for tunnels of 8 to 10 feet in diameter in rocks having a compressive strength between 10,000 and 20,000 lb/in^2, rates of penetration of about 5 ft/hr were obtained. Considering machine utilization, this becomes an advance of about 15 feet per shift. The cost of cutters amounted to approximately \$6.50/ft of boring. For other projects, extreme rates of penetration of 4 to 10 ft/hr were reported with advances per shift between 8 and 35 feet and cutter costs between \$5.00 and \$35.00 per foot. The cost of cutters increases rapidly with the diameter of the tunnel; the last cost mentioned being for a tunnel 16 ft in diameter.

During the 8th Canadian Symposium on rock mechanics in Toronto, a representative of Demag presented a series of performance figures for boring of various rock formations in Europe. These results are given in Table III with the compressive strengths of the rocks as well as the costs of the cutters per ft^3 excavated. To obtain the advance per shift, the results must be corrected by a utilization factor which can vary between 50 and 80% depending on the machine and the particular conditions encountered.

TABLE II

SUMMARY OF CERTAIN CANADIAN RESULTS IN TUNNEL BORING AS REPORTED BY VERITY

ITEM	PROJECT: TORONTO	VANCOUVER	VICTORIA	PFRA
Purpose	Sewer	Sewer	Water supply	Hydro-power Electricity
Diameter (ft)	10.75	8 to 11	8.5	25.67
Total length (ft)	12700	26700	29000	19700
Work period	11/58-11/59	7/63-9/64	11/64-4/66	2/61-1/63
Ft/hour	4.8	n.a.	2.5	n.a.
Ft/shift	10.6	n.a.	8.6	15
Rock	Schist limestone	Sandstone, schist lens	Schist, quartz lens	Soft schist/rock concretions
Hardness (Moh)	2.5 to 5	2.5 to 4	4 to 7	1.5
Strength (lb/in^2)	6,000 to 14,000	6,000 to 12,000	12,000 to 25,000	150 to 400
Cost ($/ft)	$105.00	$110.00	$98.00	$415.00
Cost ($\$/yd^3$)	$ 31.00	$ 52.00	$35.00	$ 21.50
% Mech. boring	77	79	12	93

Other performance data are available in a recent article on tunnel boring by Muirhead and Glossop. However, the Jarva and Demag data presented above illustrate how the rate of advance is affected by the nature of the formation traversed.

2.6 Cost of tunnel driving with full face tunnel boring machines

The cost of mechanical tunnel driving is influenced by: the capital cost of the machine, manpower costs, cost of consumables such as cutters, power and maintenance. Of these elements of cost, capital outlay and cutter replacement generally overshadow the others.

In many cases, users of tunnelling machines have chosen to amortize the total capital cost over a certain footage. In other instances, the amortization is expressed on a cost per linear foot with some value assigned to the equipment upon completion of the project. Owing to lack of standardization in tunnel sizes, a machine may not be transferable to other projects even if its useful life could be 100,000 hours of operation.

The importance of the cutter cost in the total cost of the excavation is illustrated by analysis of the Demag data in Table III. The highest cost shown for the cutters alone makes the mechanical method uncompetitive with conventional driving in very hard rock. A cost of $70.00 per cu. ft. is greater than the total for most conventional driving.

Of the other costs, manpower can vary inversely with the rate of penetration. Maintenance and repair costs are strongly influenced by the difficulty of driving. Power varies directly with operating time. Finally, there are the cost of auxiliary equipment and services made necessary by mechanical driving, including extensive geological evaluation.

In general, the actual costs of tunnel boring are not readily available owing to the competitive nature of contracting for tunnel boring. The only accurate cost figures which are presently available are those calculated by Verity while writing his report which has been referred to previously. These costs do not necessarily represent the costs on similar

TABLE III

PARAMETERS FOR DRIVING PROJECTS WITH FULL FACE MACHINES

Rock Type	Compressive strength (lb/in^2)	Cost of cutters ($ U.S. $/ft^3$)	Rate of penetration (ft/hr)
Clay schist	1400-7000	3.5-7	10.0-16.5
Calcarous limestone and schist	2800-8600	4.5-9	8.0-13.0
Sandstone schist	4300-11500	6-10	5.0-8.5
"Molasses"	1400-5700	6-10	10.0-16.5
Limestone and dolomite	14300-26000	9-22	6.0-10.0
Siliceous limestone	26000-36000	13-35	4.0-5.0
quartz	14300-28600	9-26	2.5-5.0
sandstone			
calcarous limestone	7000-21500	7-10	5.0-12.0
Granite	21500-50000	70 and more	2.5-4.0
Gneiss	17000-40000	26-70	3.0-5.0
Slaty gneiss	13000-21500	9-26	5.0-8.5

tasks today, owing to inflation and to improvements in machines and cutters. The costs of tunnel boring in Canada are quoted per linear foot or per cu. yd. They average around $100 per foot for the three tunnels in the medium hard rock or between $31 and $52 per cu. yd. The costs for the tunnel in very soft rock amounted to $415 per foot including the lining and $21.50 per cu. yd. excavated. This cost is presently somewhat below that with conventional methods for driving in rocks of medium hardness. And owing to a more rapid increase in the costs for conventional driving, the increased use of boring machines appears assured.

2.7 Geological Investigation

Contrary to what is required for conventional tunnel driving, the mechanical method requires the gathering of extensive geological data and tests on rock samples. This amount of information is required, initially to verify the economic viability of using a boring machine. Also, the production schedule must be predicted to a certain accuracy by taking all of the foreseeable delays into account. The recommendation of Handewith for the study of a machine boring site are reproduced in Table IV (Handewith is with Ingersoll-Rand Lawrence Division, an important manufacturer and contractor). In this detailed table, the geological data required, the methods to gather this data and the use of this data are given.

Geological studies are made as complete as possible for they are vital to the success of mechanical tunnelling. However, all of the studies discussed in Table IV are rarely made for a given project. Usually, at least some core drilling is done at strategic points to establish the geology. Using rock cores, the investigator usually determines the compressive strength, performs penetration tests and analyses the rocks for SiO_2 to evaluate the abrasion problems which may be encountered.

TABLE IV

STUDIES TO BE PERFORMED PRIOR TO THE BORING OF A TUNNEL WITH A FULL FACE MACHINE

REQUIRED GEOLOGICAL DATA	METHODS TO GATHER THE DATA	USE OF THE DATA
1) General geological map of the area	. Surface mapping . Core drilling . Test trench . Exploration drift . Published geological maps	. To perform preliminary predictions of boring rate . To determine the major zone of slowdown due to unfavorable geological conditions . To compare with boring jobs under similar geological conditions and make a judgement on the economic success of the project.
2) Estimates of ground pressures and hold-up time	. Exploration drift . Previous experience in the same ground under similar cover conditions . Wells, or core drilling . Plate test or jack test in above hole or a test chamber	. To determine the safe displacement and the stationary temporary support requirements . To estimate the requirements for permanent support (could be modified after the boring) . To estimate the production delays due to excessive ground pressures . To evaluate the anchoring of the mole (thrust and torque)
3) Strength properties of the rock	In the field: . Estimate with fresh cores . Estimate with the Schmidt hammer on outcrops	. To estimate the rate of production boring . To estimate the cost of cutters for the rock.

TABLE IV (cont'd)

	. Seismic velocities . Moh hardness on fresh samples In the laboratory: . ASTM-D2490-71 . Normalized IR Lawrence penetration test . Triaxial test	
4) Abrasive properties of the rock	. % S_iO_2/compressive strength/depth of cut . By comparing with wear under similar conditions . Tabor test or Tabor modified test . Saw test . Los Angeles abrasion test.	. To determine the life and the costs of elements of the boring system in contact with the rock including the cutters
5) Detection of explosives, corrosives and dangerous gases:	. Drilling log . Study of history in similar rock . Geophysical sounding . Advance probe drilling	. Safety and protection of personnel . Choice of ventilation and monitoring system . Protection of components of the machine
6) Systems of joints and bedding (extent, dip, strike and integrity)	. Surface mapping of outcrops and quarries . Drilling of core (lost core)	. To estimate boring delays due to unfavorable rock conditions . To determine the requirements of temporary support Note : (Primary and secondary joint systems with a spacing smaller than 1/3 m help the boring - greater than 1/3 m they cause hang-ups in the broken muck handling system).

TABLE IV (cont'd)

7) Faults - Trends, thrust, throw and integrity. Water - Head and quantity.	. Surface mapping . Core drilling - lost and inflow of water in a bore hole . Study for the localisation of water wells . SONAR or RADAR for rock . Drilling with sensing ahead at the face . Geophysical sounding.	. To determine the water pumping requirements . To determine the requirements for grout curtains . To determine the requirements for ground support.

2.8 Comparison of performance and costs obtained with mechanical and conventional methods.

Few opportunities have presented themselves where a comparison of costs between mechanical boring and the conventional drill-and-blast method could be made under identical conditions. However, S & M Contractors completed a 23,500 ft tunnel 8 feet in diameter for the St. Louis Metropolitan Sewer District. The first 13,000 feet of the tunnel were driven by conventional methods. The last 10,000 feet were mined using a Jarva Mark 8 boring machine. The statistics kept by S & M Contractors show that even if the rock excavation methods are relatively different, they have basic costs which are common to each and can thus be compared. The cost categories are for manpower, maintenance, production, equipment, and the consumables aside from the costs of concrete lining, where it applies.

In almost all the cost categories, the cost of excavation with the machine is less expensive. The exception being the cost of the equipment where the initial cost of the boring machine is several times greater than that for conventional driving. However, the mechanical method required 43% less manpower than the conventional method. Another area closely related to the cost of manpower is the production; it was determined that the production with the machine was approximately 20% faster than with the conventional method. The supply of consumables was shown to be 26% less expensive with conventional driving. It is believed that when all factors are considered, present day maintenance costs would be about the same for both methods. Furthermore, the excavation with the machine saved approximately 0.33 cu. yd. of concrete per linear foot of tunnel. It was also noted that mining with the machine eliminated the need to survey lines and it was much easier to clean up the tunnel driven with the machine. The data given above are for a particular case dating back to 1967; they do not represent the average nor the conditions of 1973. It should be noted that the data relate to a machine boring a medium-hard limestone having a compressive strength of approximately 18,000 lb/in^2. The penetration of the machine in the limestone was approximately 4.8 ft/hr while the cutter cost was about $7.50/ft. According to S & M Contractors, during that particular project, mechanical driving was shown to be the most economical.

It is important to note that presently the performances obtained with conventional methods vary between 40 and 60 ft/day on most of the projects. On the other hand, none of the conventional methods of driving exceed 4 ft/hr. This is very close to the minimum obtained with boring machines in rocks up to 20,000 lb/in^2.

2.9 Advantages - Disadvantages

With suitable geological conditions, rocks with up to medium hardness, and an adequate length of tunnel of uniform diameter to be driven, mechanical methods can produce a more rapid advance at a lower cost than drilling and blasting owing to the continuous nature of mechanical driving. The circular section requires less permanent support and there is less chance of rock falls during the driving. Breakage beyond the pay-line is significantly less unless controlled blasting is used. The transportation of the broken rock is facilitated by its uniform fragmentation which permits the selection of a continuous system of conveyors for its removal.

On the other hand, there are several disadvantages connected with the use of boring machines. First of all, they are very expensive. Aside from that there is the disadvantage that the boring machines are usually made for a particular job where the design of the cutters, the power, the thrust and the speed of rotation are specified to meet unique conditions. Adjustments are very expensive to make and the present lack of standardization concerning the diameters of the tunnels does not make the development of "off the shelf" machines attractive. This produces important delivery delays in the order of 9 to 18 months. Driving with a machine is inflexible. For example, it is usually not possible to make dimensional changes along the tunnel. The machines cannot take curves with a radius less than 300 feet and their ability to bore at an angle is restricted to 45° going up to 27° going down and this with several important additional difficulties. Much more geological information is required than with the method of drilling and blasting because the results depend to a much greater extent upon the changes in conditions. Further, the mechanical method is comparatively new and the number of breakdowns in hard rock is particularly high.

2.10 Problems while driving tunnels with boring machines

The Canadian sub-committee on exploration in rock mechanics has made a literature survey to establish the frequency of typical problems encountered during the driving of tunnels with full face boring machines. It was determined that the three principal sources of problems are:

(i) hard layers and hard concretions in a soft matrice; the maintenance of proper anchoring and proper orientation are difficult to obtain,

(ii) caving ground; rock falls from the back or the face generally associated with structural geology features; and

(iii) inflow of water and/or gases.

As a result of this study, the sub-committee has proposed a system of sensing based on the use of small diameter diamond drill holes along the axis of the boring machine and comprising a visual analysis of the core, geophysical sounding in the hole and sensing with appropriate detectors.

An important group of problems relative to the design of the machine and the auxiliary equipment center around the structural design of the machine and the control of the direction of advance.

The driving of tunnels with a machine is composed of several phases requiring the judicious use of specialists. For a particular project, it is often difficult to assemble such a team and this is invariably followed by reductions in performance. To avoid these problems, the customers attach a great importance to the experience of the total boring team aside from the cost of the quotation.

2.11 Future prospects

In the future, it is to be expected that a greater use of tunnels will be made for civil engineering needs. Some experts suggest that within five years, 80 percent of the tunnels used in these works in the United States of America will be driven by mechanical methods. The more rapid increase in the costs of driving by conventional methods is cited to justify this projection. Further, fewer people are interested in working under the difficult conditions encountered in conventional driving, even at a high salary.

Technically, it is possible that in the future mechanical boring in hard rock will be economically possible. Three avenues could lead to this situation. First by developing combined methods of mechanical, thermal and hydraulic boring. Mechanical boring could for example be made easier by the application of a source of intense heat at the rock face which would reduce the resistance of the rock to the mechanical attack. A rapid cooling with water could reduce this resistance even more. There would be also the possibility of producing failure planes in the rock face. with the help of powerful water jets. All of these methods are being studied and could lead to some useful development in the future. Some of the methods which are under investigation will produce new problems requiring solutions.

Another possibility is the improvement of cutters from both the point of view of the cutting surface and the cutter bearings. During the last few years, there have been important developments in this area. Because the market for these cutters is developing rapidly, it is probable that considerable sums of money will be invested to improve them. Improvement would reduce the cost of boring in rocks of medium hardness and would make possible the boring of very hard rocks.

Some time ago, the U.S. Bureau of Mines called for tenders for the development of an automatic control system for a tunnel boring machine at a cost of several millions dollars. It can then be expected that within a few years an assembly of sensors, actuators and mini-computers will appear to control boring machines automatically. This should permit increased use of mechanical driving and lead to cost reduction as the system will certainly attempt to maintain optimum operating conditions. Where conditions are hazardous, such a system could be used to avoid endangering the lives of personnel.

The lack of flexibility of full face tunnel boring machines will hinder their application to mining of minerals. On the other hand, there is a possibility that machines with a cutting head which works with a sweeping action can be modified for hard rock and use in mines.

Because of the importance of tunnel driving in the U.S.A., the U.S. Bureau of Reclamation has initiated an important research program covering many aspects related to tunnel driving by the mechanical method. This research is combined to a great extent with the construction of the Stillwater tunnel. It is probable that much information and perhaps innovations will be reported in relation with this project in the years to come. The cost of the research program is valued at five million dollars, which is equivalent to a little more than one quarter of the cost of the driving alone. Unfortunately the Stillwater project has been temporarily suspended.

3. RAISE DRIVING

3.1 Raise driving methods

Raises, used mostly in mineral mines are driven by four major methods:

1. The conventional method of driving by drilling and blasting with or without a system of protection of the Alimak type for the workers.

2. the coring method of driving which can be used in relatively soft rocks;
3. the driving by boring a full size face around a pilot hole in rocks of variable hardness; and
4. the driving by boring a full face without a pilot hole in rocks of variable hardness.

Certain methods are available for driving in soils or unconsolidated rocks but these are beyond the scope of this report. The conventional method will be discussed only for comparison. The full face method without a pilot hole is new and it is not yet possible to discuss it.

3.1.1 Coring machine

Machines which produce a core can be used in soft rocks like anhydrite, salt and potash. With this method of driving, which is illustrated in Figure 6, first a pilot hole is drilled then with a drill bit the rock is ground in a crown which has the effect of producing a core much like that obtained in exploration diamond drilling. Sections of the core can be easily broken off; they fall to the bottom as the hole is of slightly larger diameter. It is believed the method is not in use in Canada therefore it will not be discussed. The manufacturer of the equipment suggests that holes up to 5 feet in diameter can be bored at speeds between 5 and 40 ft/hr depending on rock hardness.

3.1.2 Full face boring machines with a pilot hole

This group can be divided in two slightly different types according to the method of operation, that is:

1. machines which drill a pilot hole upwards, then ream this hole downwards, and
2. machines which drill a pilot hole downwards, and ream this hole upwards.

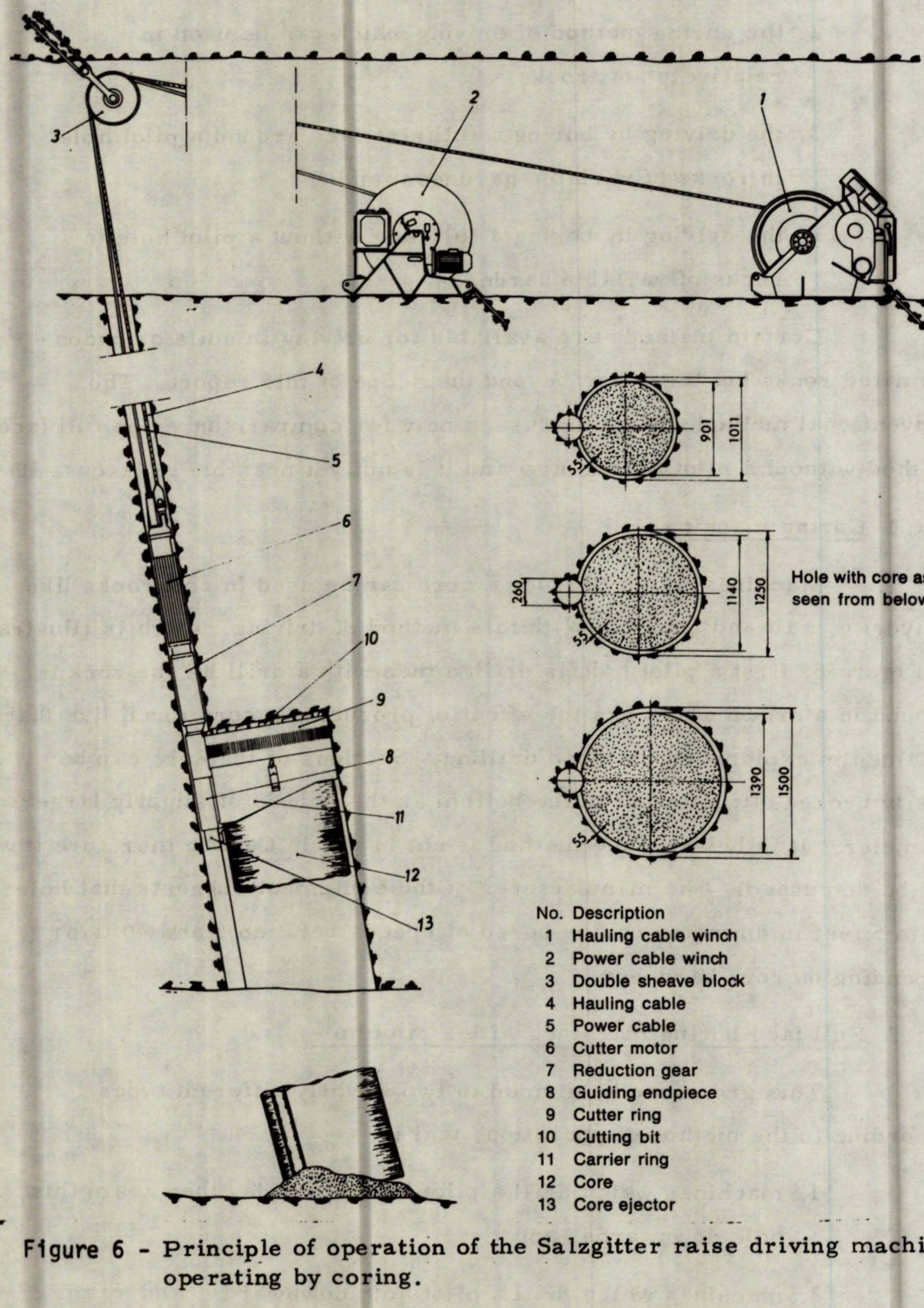


Figure 6 - Principle of operation of the Salzgitter raise driving machine operating by coring.

These two methods are illustrated schematically in Figure 7; the second method is the most widely used. The tools used for the boring with this method are pilot drill bits similar to the ones used for the drilling of blast holes in open pit mines, and reaming heads of various configurations. The drill bits are usually referred to as tricone bits. Bits for soft rocks have hardened steel teeth of variable shapes whereas for very hard rocks, the cones are impregnated with tungsten carbide buttons; between these two extremes can be found a series of compositions and shapes of cutting elements. The reaming head used to enlarge the pilot hole is composed of an array of rotary or disc cutters of the same type as those on tunnel boring machines. Figure 9 illustrates a typical mounting of cutters on a reamer. Originally, the reamer had the shape of a christmas tree with cutters on two or three levels, today however, the cutters are usually mounted on a flat head.

3.2 General design of a raise boring machine used in Canadian mines

All boring machines of this type include the following components:

1. a drill string with tools,
2. a drill of the rotary type with accessory equipment, and
3. a moving unit.

The principal manufacturers of these machines are Robbins, Dresser, Subterranean and Koken; there are no Canadian manufacturers. Space does not permit a full description of all the machines available therefore the main comments will be limited to the widely-used Robbins 61-R unit and some of the differences in other machines will be noted.

3.2.1 The drill string

The drill string is comprised of 5 foot rod sections screwed end to end. It is used for drilling the pilot hole and for the reaming. The string is very strong and permits a push on the drill bit or pull on the

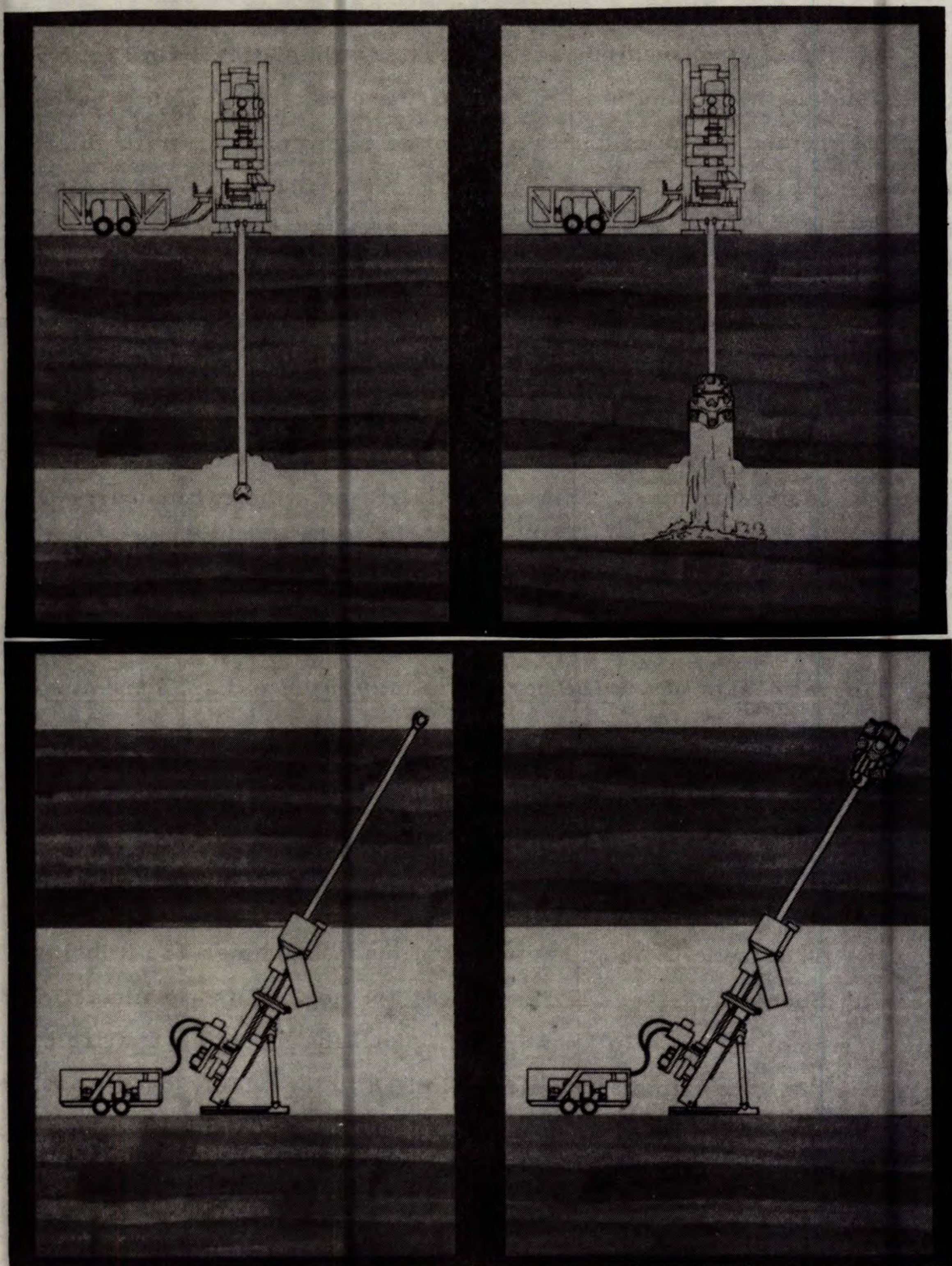


Figure 7 - Two methods of raise boring by the full face method with a pilot hole.

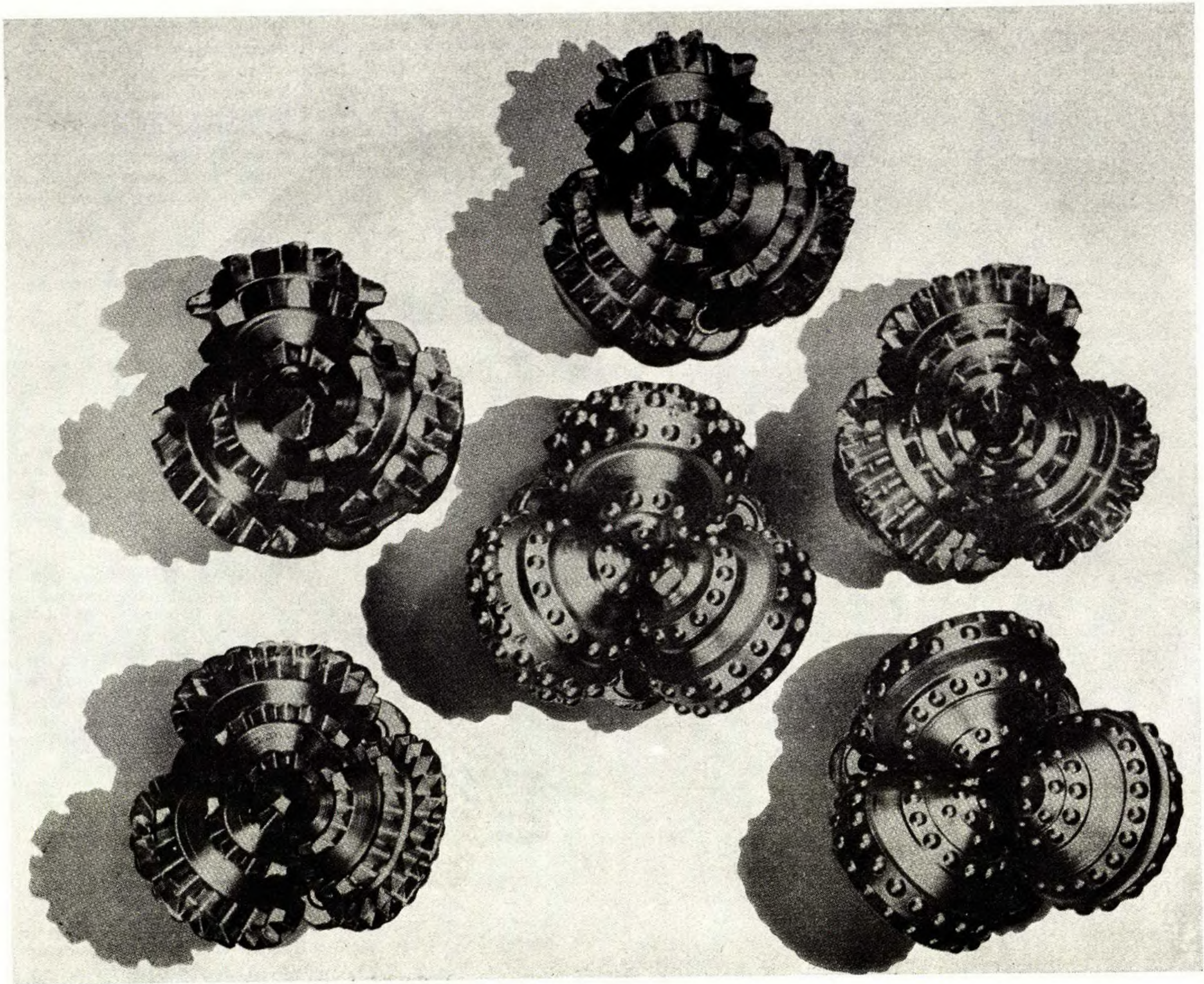


Figure 8 - Tricone bits for use with rocks of various hardness.

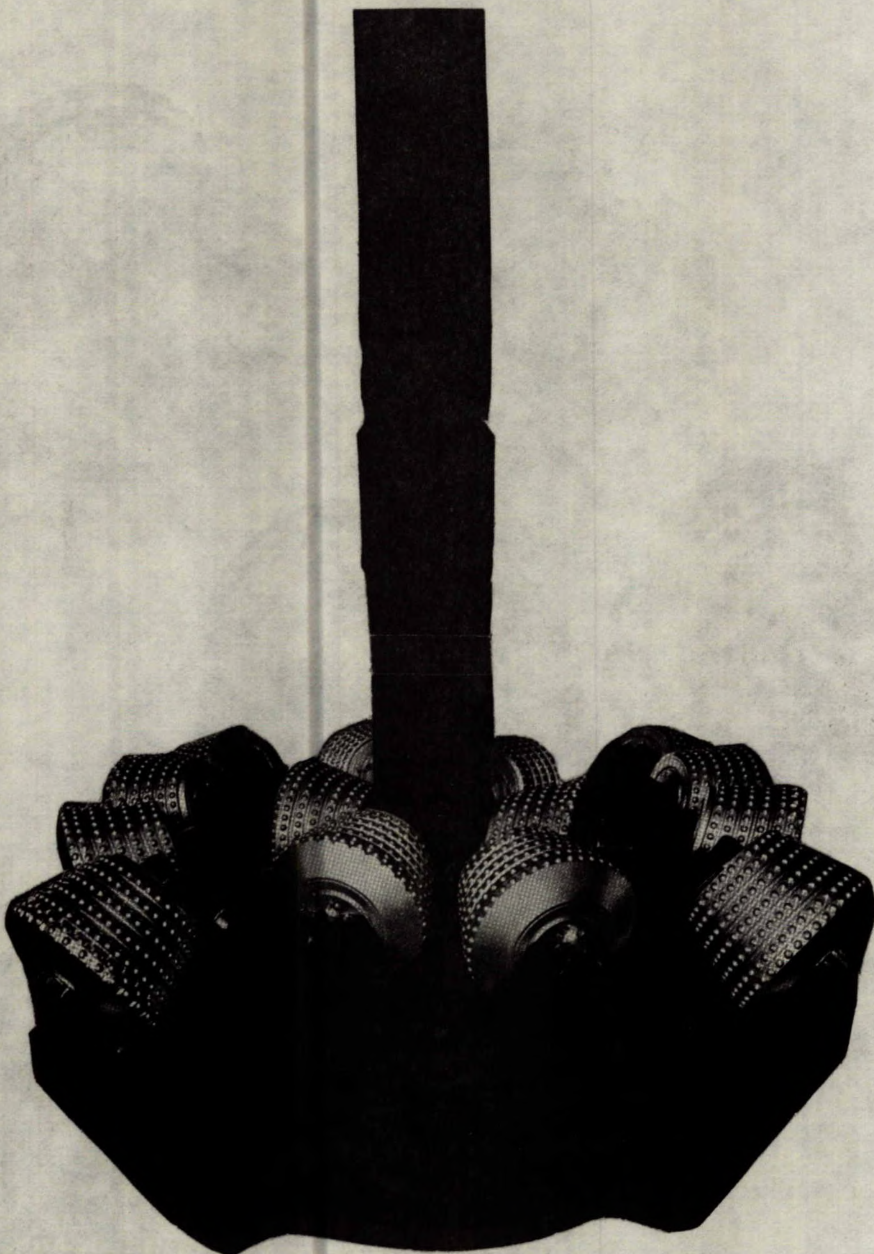


Figure 9 - Reamer used with the full face raise boring method with a pilot hole.

reamer while applying forces of up to about 500,000 lb in the case of a 61-R. The careful alignment of the initial section of this string, before beginning with the pilot hole, insures the proper orientation of the raise. This alignment is usually made by the mine surveyors. When the machine is used in a normal manner, the target is usually reached to close accuracy. If the pilot hole deviates to an unacceptable extent, the hole is redrilled. If the pilot hole deviates to such a large extent that it does not meet its target on the lower level, low frequency electronic equipment is used to locate the hole. The string is furthermore equipped with stabilizers which aid in maintaining good alignment. As the hole is deepened, the addition of successive rod sections can be performed with the assistance of the raise borer operator helper or by using a remotely controlled hydraulic system.

3.2.2 The drill

Figure 10 shows a Robbins 61-R raise borer with its accessories. It is composed of a main frame which permits the anchoring of the machine to the rock floor during the boring. On this frame is mounted the drill itself which supplies the rotary motion to the drill string. The drive section moves up or down according to the direction of penetration. This penetration is made possible by the thrust supplied by one or several hydraulic cylinders. On the 61-R machine, two rotation speeds are available for drilling the pilot hole, 36 and 72 rpm, and two for the reaming operation, 10 and 20 rpm; other machines offer a continuous variation of speeds between, for example, respectively 0 and 70 rpm and 0 and 25 rpm. The construction of the machine permits the drilling of holes more or less inclined with respect to the vertical, however, the drilling of holes at an angle less than 50° is often the source of additional problems. The borer operator operates the machine from a remote console and the supply of electrical/or hydraulic power is produced and modified using transportable units. During the drilling of the pilot hole, the drilling chips are flushed

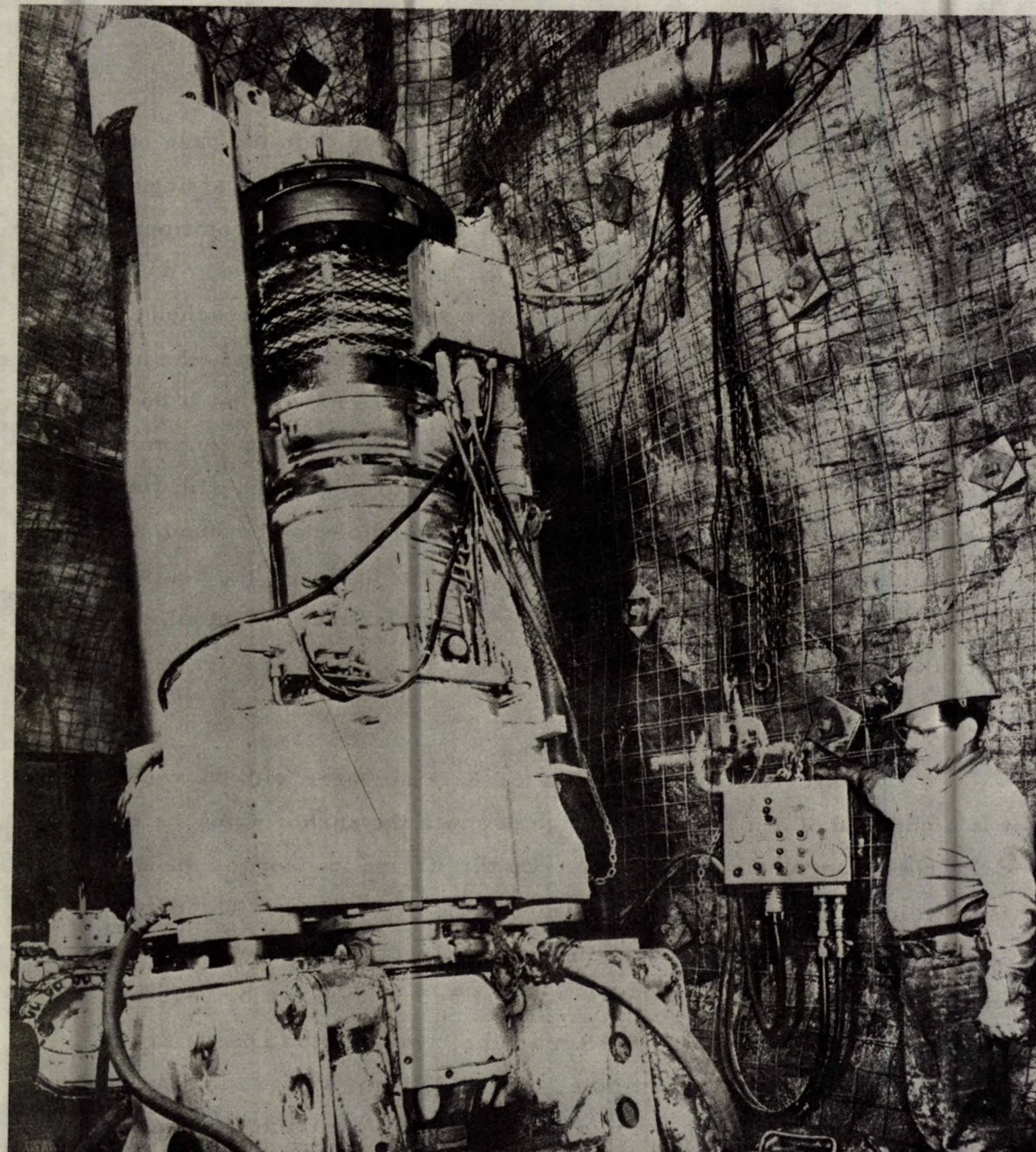


Figure 10 - Full face raise boring machine using a pilot hole produced by Robbins - model 61-R.

to the surface by a mixture of air and water. The reaming cuttings which are much more voluminous are removed from the bottom of the raise by the mine haulage system. The drive motors for rotation are operated on A-C power in the case of the Robbins 61-R; for other machines, they are hydraulic motors or D-C motors. Contrary to most of the tunnel boring machines, the raise borers are stationary in the great majority of cases during the boring of the opening. However, a certain German manufacturer offers machines which move in the hole toward the lower level and which do not require the drilling of a pilot hole; however, such machines are not found in Canada. Each boring site must be prepared prior to the arrival of the boring machine; usually a concrete pad from which extend several anchor bolts is provided.

3.2.3 The moving unit

A tractor permits the moving of the borer to another location on the same horizon. This move is made relatively slowly owing to the bulkiness of the machine and the relatively low power of the tractors. The rod sections are usually moved with scooptrams or by rail cars.

3.3. Uses

Many Canadian mining companies have adopted raise boring for some part of their work. In an important mining complex such as the one of INCO in Sudbury, over ten machines are in use; for smaller organizations, one machine is often all that is required. Where the required amount of raise driving is limited, the service of contractors can be used. Bored raises in mines are used for ventilation, for ore and waste passes and for services. Recently, some mining companies have used bored raises as openings from which drilling is done to mine large stopes.

Contrary to lateral tunnel boring machines, raiseborers are used in very hard ground, often much above a compressive strength of 25,000 lb/in^2. Recently, it was announced that a mining group in South Africa was making serious studies with a view to using raise boring machines in the gold mines located in quartzites. The economics of using raise borers in very hard rocks is open to discussion; however, factors like the necessity to do the work rapidly and with safety promotes the use of such machines even though for a given raise, it can be more economical to do the work by conventional methods. In certain Canadian mines with very hard rocks and a limited use for raises, raise boring machines are not used. Mechanical raise boring is rarely used for distances less than 100 feet, but has been used for raises up to two thousand feet. The common diameter in mines averages about 5 feet. However, several mines use openings of 4 feet while in some of the large mines, the method of mining requires raises up to 7 feet or more in diameter. When the power of the machine is not sufficient to ream the pilot hole to a required final size, this may be done in two stages. In the INCO mines in Sudbury, more than 100,000 feet of raises have been driven since 1964 using mechanical raise boring. Substantial footages have been bored in other mines so that the total completed in Canada exceeds that which has been done elsewhere.

3.4 Cost of raise boring machines

The cost of raise boring machines with accessories varies between $100,000 and $400,000 depending on the capacity of the machine. The reamer constitutes an important part of the cost, and may account for about $30,000, for one of 5 feet in diameter.

3.5 Performance of raise boring machines using the full face method with a pilot hole

The performance in driving raises by the mechanical method depends on: the mechanical properties of the rocks, the geology, the operating conditions, the angle of drilling, the diameter of the raise and the length of driving. The performance during the pilot hole drilling is often an indication of the performance which will be obtained during the reaming to obtain the final raise diameter. The quality of the cutters at a given instant is also a factor which cannot be ignored. Further, the overall performance of the operation is affected by delays caused by failures in the supply of electrical power, water, air or by delays in the removal of cuttings during the reaming operation. All the methods of predicting performance require the introduction of a factor to take into account the strength of the rock, commonly related to the uniaxial compressive strength of the rock and/or an index determined by indentation tests.

Among the performance data which are found in the literature, pilot hole advance varies between 4 and 17 ft/hr while reaming speed may be between 1 and 8 ft/hr. These results are for values of compressive strengths of the rock, which vary between 8,000 and 50,000 lb/in^2. In a given rock, the performances are in a first approximation and for a limited zone, directly proportional to the speed of rotation and to the thrust applied to the tools.

3.6 Cost of raise driving with raise boring machines using the full face method with a pilot hole

The cost of raise driving is influenced by several factors which are almost identical to those which affect performance. Amortization of the boring machine does not seem an important problem for most of the users. A relatively extensive literature review on mechanical raise boring has established that the costs of driving have varied between \$30.00 and \$300.00 per foot. In addition to the factors which affect the cost and were discussed in the preceeding section 3.5, the experience of the users must be added.

The relation between the strength index of the rock and the rate of penetration or the cost is somewhat uncertain. However, during a recent conference on boring, Bauer presented a graph showing the cost of driving as a function of the compressive strength for raises of two different diameters. Figure 11 reproduces this graph which is applicable to driving lengths between 200 and 600 feet. The costs shown are average operating costs only and do not include an allocation for depreciation.

The life of the cutters directly affects the cost of driving. As an indication, it can be said that with a rock of about 30,000 lb/in^2 a cutter

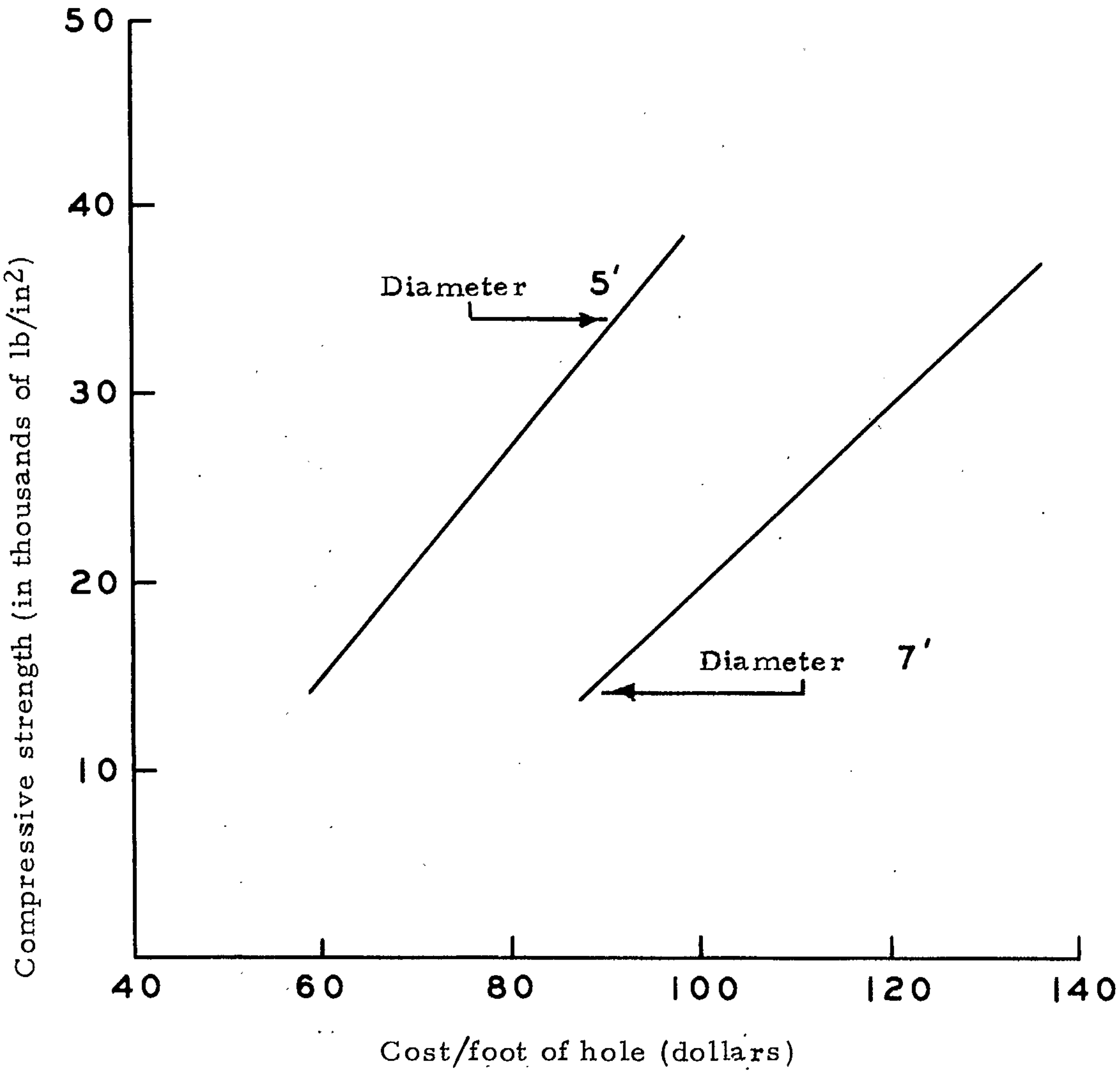


FIGURE 11: Cost of raise driving as a function of the rock strength, when using the mechanical method.

life of about 800 feet is obtained. Theoretically, the pilot hole bit life should be approximately the same. However, due to frequent excessive loading of pilot bits by the weight of the rods or by the hydraulic system, this life is often appreciably reduced.

In a recent article (3) from INCO in Sudbury, average costs were presented as being equal to $100.00 per foot for mechanical boring of a raise in hard rock (25,000-35,000 lb/in^2) having a diameter of 5 feet. These costs were distributed as shown in Table V. The importance of the cost of the reamers and cutters in this distribution is noticeable as it represents 35% of the operating costs. The other costs which appear in this table will be discussed later in the text.

3.7 Geological information

The geological studies prior to the use of raise boring machines are much more rudimentary than for the use of tunnel boring machines. First, because the machines are used in mines, the ground to be traversed is relatively well known. Therefore studies are often limited to the execution of penetration (indentation) tests and to the determination of compressive strengths by the manufacturer who estimates the expected performance in the mine. The suppliers also use the tests to establish the choice of cutters which they will recommend and to estimate cutter life.

Some contractors who bid on raise boring work often limit their investigation to a visual inspection of the ground whereas others complete their analysis by indentation tests on rock samples. The evaluation of the strength of the rock will also permit the manufacturer to recommend operating conditions for the boring machine. Once this method of driving has been selected by a mine no additional geological investigation is performed until particular problems are faced. However, it is only very rarely that attention is paid to the possibility of broken ground, caving ground, bedding planes, underground water, zones of rock bursts and of

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TABLE V

COST DISTRIBUTION

DRIVING A VENTILATION RAISE AT INCO

	5 foot diameter raise driven mechanically ($)	Raise 9' x 7' with timber ($)
Cost of manpower	19.00	69.45
Timbering	-	24.54
Drill steel, drill repairs, explosives	5.77	11.03
Supplies (machine)	3.57	-
Repairs (machine)	11.83	-
Pilot bits	7.32	-
Reamer and cutters	34.90	-
Dismantling the timber in the raise	-	13.10
Boring station	18.38	-
Total cost per foot	100.77	118.12

a variable composition at the face. The limited geological investigations are certainly a consequence of the relatively short lengths of bored raises, which average about 400 feet. As the lengths of bored raises increase, geological conditions may be less well known so more preliminary investigation may be necessary.

3.8 Comparison of performance and costs obtained with the mechanical method and with the conventional method

As for tunnel boring, results comparing the two methods under identical conditions are rarely available. In a recent article, representatives of INCO suggested that the comparisons cannot necessarily be made at equal diameters of openings. They supply an example of a ventilation raise where the alternative is often to drive a raise of 5 feet in diameter using the mechanical method or a raise of 7' or 9' conventionally with timbering, then dismantling the timber to obtain the same final product. The data for the two methods are given in Table V which was introduced previously, wherein the conventional method shows higher operating costs per foot. It is reasonable to believe that the capital costs are higher for driving with a machine. Thus, it becomes evident that the mechanical boring per cu. yd. is much more expensive in this mine than when the conventional method is used. However, the work is accomplished more rapidly, the opening is more stable and offers better flow characteristics. Furthermore, the training period for the crew is very much reduced, as it takes only about 6 months to train a mechanical borer operator whereas several years must be considered for training a conventional miner. This indicates that the data do not give the complete answer by themselves and care must be exercised when making comparisons.

In mines where the rocks are much weaker than the rocks at INCO, the cost per cu. yd. can become lower when using the mechanical method. When all the advantages of the mechanical method are considered, many of them could be translated into reduced costs. Such would be the case for boring in the schists of the copper mines of the Eastern Townships of Quebec as well as for other mines in grounds of medium hardness.

3.9 Advantages and disadvantages

The following reasons are often mentioned to support the use of raise boring machines:

1) safety with regard to rock falls,
2) elimination of explosives,
3) faster completion time,
4) better characteristics for the hole,
5) reduction in manpower (also the work is less arduous), and
6) reduction of costs under favourable conditions.

This method can, however, be more expensive than the older methods when:

7) extremely hard and abrasive rock is encountered, and
8) small raises are required.

3.10 Problems

The principal problems encountered during the boring of raises are a result of the geology traversed. In broken ground, some stoppages of the machine will occur because of depressions which can develop in the boring face, or collapsing of the holes can occur. Some difficulties can be encountered in the evacuation of the chips resulting from the drilling of the pilot hole and this can lead to wedging the rod string in place. Ground which has a tendency to yield after an opening has been driven can produce wedging in place of the drill string with the pilot bit or the reamer and require expensive procedures to retrieve the equipment. Ground with bedding planes can encourage deviation of the pilot hole, however, this deviation can also be produced by a number of other factors. The thrust on the drill string during the drilling of the pilot hole appears to have a great influence on deviation. If too much ground water invades the pilot hole, this can cause difficulties in the evacuation of the drill chips and require the use of a completely water based evacuation system; this produces more delays than with air evacuation. Rock bursts in pilot holes or in raises in the process of being reamed can produce mechanical damage to the string and the bit or reamer and require the partial cementation of the hole followed by redrilling. A variable composition at the face has the same effect as when boring into broken ground; this can require a closer control of the thrust on the bit or the reamer.

3.11 Future prospects

As for tunnel boring, the amount of raise driving by the mechanical method is expected to increase during the next few years. This will probably be brought about by improvements parallel with those expected in lateral tunnel boring. Economic factors and safety are and will remain the two most important justifications. Technical improvements will, particularly in the next few years, favour the economics. The availability of better cutters, the introduction of combined methods and the use of control systems will certainly be at the base of the principal future cost reductions.

To improve the control system for raise boring machines, a group in the Mining Research Centre is performing an in-depth research and development study in cooperation with a mining company. Numerous sensors have been selected and a data logging program has been initiated in the field. After this period, it is intended to establish a control strategy and to complete the assembly of the control system by installing control actuators and a unit which will make control decisions. It is anticipated that this system will attempt to maintain a maximum penetration speed while remaining within acceptable limits from the point of view of the overall economics. The system will also prevent abuse of these machines and thereby increase the life of the cutters and reduce maintenance and repairs. A. Bauer of Queen's University at Kingston, Ontario has agreed with predictions in this area during a recent symposium on rocks mechanics and tunnels held in Toronto. He considers as we do that improvements in costs could result more from increased cutter and bits life than from an increased penetration rate. He suggests that an automatic control package would be an efficient way to improve the results.

Until an automatic control system becomes available private industry will probably give greater attention to the choice and training of the principal raise borer operator. During a recent study in South Africa, this choice was shown to be extremely important, particularly as it affects raise boring economics.

In recent years, the construction industry has discovered the advantages of raise boring machines, therefore, a greatly increased use in this area is expected. Contractors are beginning to use raise boring for tunnel ventilation shafts, water supply systems, hydroelectric works and for sewer systems. Another new use which is beginning to appear in mines is for driving of short, slightly inclined tunnels. This latter application is likely to further develop.

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