Chapter 54

TUNNEL BORING TECHNOLOGY - PRESENT AND FUTURE

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ABSTRACT

The science of mechanical underground tunnel excavation has developed at an increasing rate. From the feeble attempts late in the 19th Century to today's high speed tunneling systems, development has been a continual step by step series of events. In the past 15 years, the pace of development has picked up. Tunneling machines are successfully attacking ground and rock conditions deemed impossible just a decade ago. And the mechanical excavation industry is likely to continue its rapid pace of development in the years ahead. Machines will become more versatile, capable of boring through greatly varying geologic conditions with the same equipment; under great hydrostatic pressures, heat, cold, flowing soil and incredibly hard rock. The inevitable trend toward the safer and more rapid mechanical systems is sure to continue.

INTRODUCTION

The World's relatively stable and more liberal political and industrial environment has spawned many world shaping inventions. Some have undergone major technological improvement while maintaining basic operating principles. The one example well known by the general public is the airplane.

On December 17, 1903, Orville and Wilber Wright tested their aircraft. It managed an altitude of 10 feet and a speed of 9 mph that day. The plane had wing-like appendages that created lift, utilized a large fan-like apparatus which hurled gasses rearward for propulsion, burned liquid petroleum fuel, and used moveable wing and canard surfaces for attitude and directional control. Plus or minus a few details, that basic description still applies to the F-15 fighter.

Not nearly as obvious to the public are similar advances in commercial machinery, and the tunnel boring machine (TBM) or mole is one of these. The earliest attempt at a true TBM in the U.S.A. was in the Hoosac Tunnel (Western Massachusetts). This machine had a full diameter rotating cutterhead and picks arranged to cut concentric circles. It had grippers, thrust mechanisms and a conveyor for muck removal. However, this was 1856, and neither metallurgy nor structural design had advanced to the point where the machine could be successful in hard rock. The then renowned civil engineer, Herman Haupt, managed about a 10 foot advance before he was fired for innovation.

The concept languished for the next 100 years. TBMs, with picks for cutting tools, were applied in soft grounds and coal, but each attempt to use these machines in rock failed.

Finally, in 1956, an engineer by the name of James Robbins applied the idea of using a rolling disc cutter rather than a drag pick. On a sewer project in Toronto, a best day advance record of 115 feet was achieved. This project was the first to demonstrate economic feasibility of the full face TBM over a wide range of soft to moderately hard rocks.

From this project and for nearly 20 years, the technology grew slowly. By trial and error, manufacturers of TBMs were improving machine performance allowing the contractors to venture into harder and harder rock. In the late 70's and early 80's, several universities and scientific organizations in both North America and Europe carried out scientific investigations to understand the physics behind the successful use of the disc cutter in rock. These efforts and the information developed led to the ability to optimize designs, as well as reliably predict performance of TBMs in rock.

Similarly, technology in soft ground tunneling developed from the famous shield of Brunel which crossed under the Thames River from 1824 to 1840. Brunel's efforts were improved by Peter Barlow who patented a circular shield in 1864. This shield developed thrust by pushing off of lining segments placed within the shield, and featured gates at the front of the machine to control the inflow of muck. A version of this shield crossed the Thames River in one year, 1869. This machine was the predecessor of the Earth Pressure Balance (EPB) System.

The EPB and the somewhat more complex slurry pressure machines were initially European concepts, but were developed to a fine art by the Japanese. Several hundred of these shields were built during the 60's through the 80's as the Japanese expanded their essential underground transportation, water and sewer networks.

WHY A TBM?

Mechanical excavation of a tunnel offered numerous advantages over drill and blast methods, or pick, shovel and hand mucking, the prior options available. The machine was developed to its current state of technology, and will continue to be developed because it is in the best economic interest of the contractors. The more significant issues are discussed below.

<u>Excavation Rate</u> - The TBM applies power to the rock in a relatively constant operation, automatically gathers up the cuttings and conveys them to a haulage unit. Further, the cuttings tend to be relatively consistent in size, permitting easy handling by train, truck or belt. Even the ventilation requirements are constant; the large fume removal volumes are not required. These continuous techniques lead to advance rates ranging from now common 150 ft. days to record days exceeding 400 ft.

<u>Safety</u> - The fatalities and crippling injuries in tunneling operations are due primarily to rock falls, even in explosive operations. Ironically, the most hazardous of operations in drill and blast or hand operations is while installing roof support. All types of TBMs reduce these hazards by (1) cutting a more stable opening in the first place, and (2) by providing overhead protection during support operations. In the case of shield machines, full

linings can be installed from within the machine so that workers never even see the rock. The TBM work environment is more akin to a heavy industrial shop. While rarely described as comfortable, the machine environment attracts a large and skilled work force.

Other Features - In certain situations, the mechanically excavated tunnel offers other advantages.

a. Less vibration to disturb sensitive existing structures.
b. Smooth walls provide superior fluid flow in water or sewer tunnels. Any lined tunnel requires less roof support and concrete or grout.

MODERN MACHINE TYPES

After nearly 150 years of development, the TBM has come to the point where mechanical excavation can now be considered for virtually any tunneling conditions.

A machine type is available to construct a tunnel under circumstances where formerly only hand tunneling or drill and blast could be considered. In fact, in many environments today, only a TBM will meet the requirements and accomplish the job.

Figure 1 shows the type of TBM for various rock and soil conditions in which they are extensively used.

Since the degree of rock jointing and soil compaction has an impact on machine selection, both the competent and the unstable grounds are shown separately. The following paragraphs discuss each type of machinery.

Full Face Disc TBM

The TBM equipped with a full face cutterhead (Figure 2) and utilizing steel disc cutters for rock fragmentation was developed for use where drag picks had failed. The science of breaking rock with disc cutters has been studied and is now, perhaps better understood than any other excavation tool. The University of Trondheim, Norway, and the Colorado School of Mines are both well known for their work in this area.

Three basic factors which affect the performance of

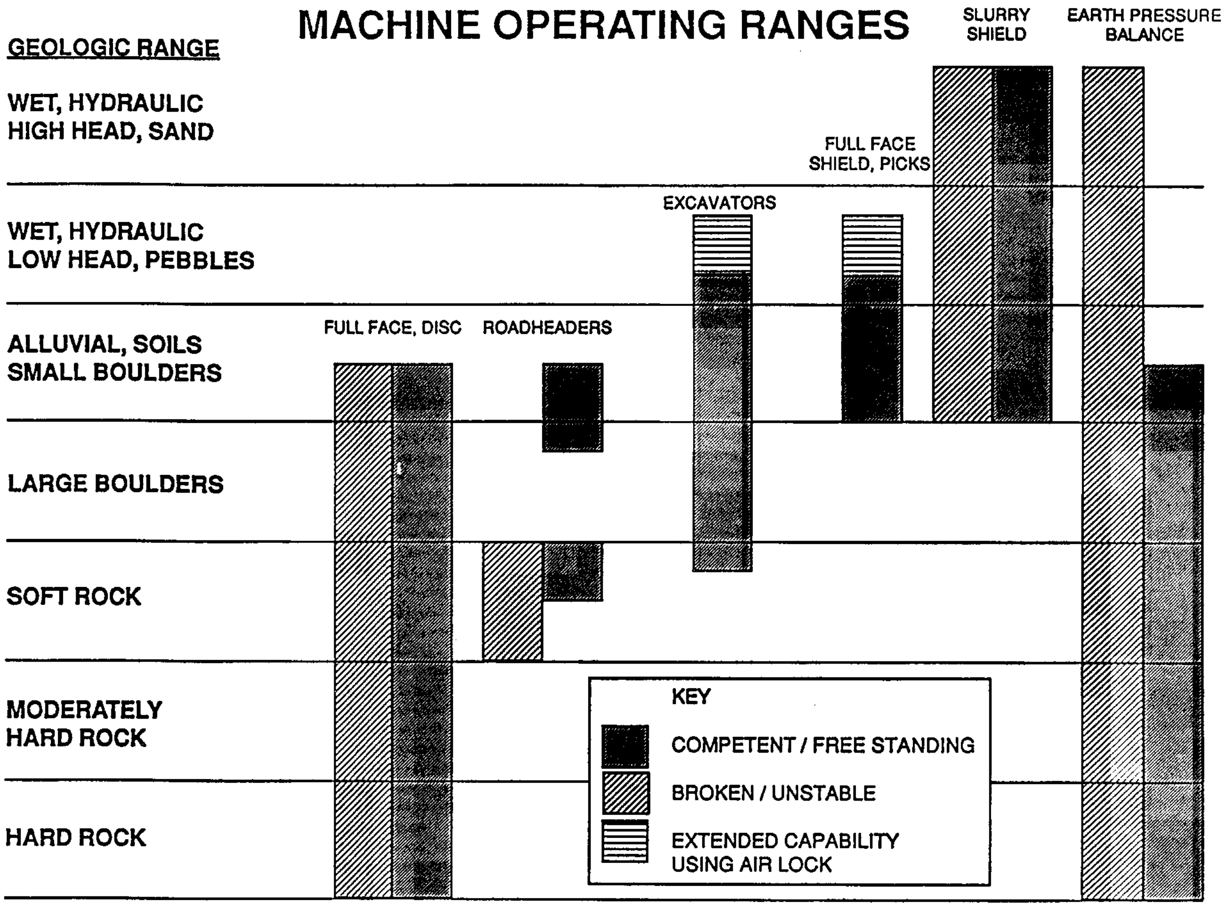

Figure 1. Machine Operating Range.

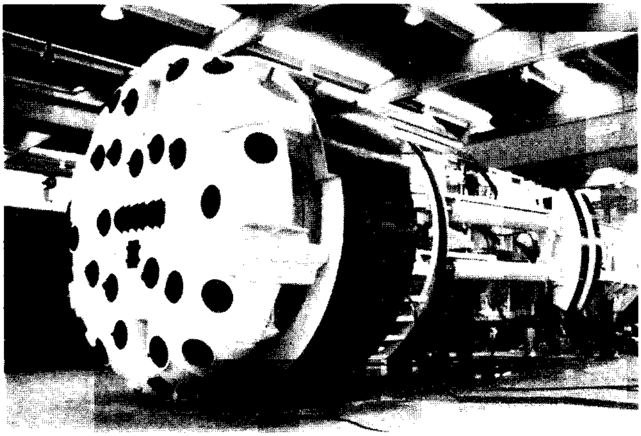

Figure 2.

hard rock TBMs are: the characteristics of the rock, geometry of the cutter and the design features and capabilities of the TBM. The significant elements of each are listed below.

Rock Characteristics

Unconfined compressive strength
Rock toughness
Fractures and joints

Geometry of the Cutter

Diameter
Blade width

TBM Features

Thrust per cutter available or structurally possible
Spacing between cutters
Power (torque and rpm) available

These are the variables considered in the most advanced predictive computer models.

The fundamental principle governing rock fragmentation efficiency of a hard rock TBM (or any excavator for that matter) is that system performance improves with the increasing size of cuttings produced. This means that the cutting tools should be arranged and used in the manner which produces the largest size cuttings. In a hard rock TBM this is accomplished by increasing individual cutter loads to attain deeper penetrations into the rock. Deeper penetration, in turn, allows wider cutter spacing. The combination of deep penetration and wide concentric cuts or kerfs produces the largest average chip size. With proper design,a hard rock TBM type can achieve an excavation efficiency of 3-6 HP-hr./ton.

Tests conducted at the Colorado School of Mines for a funded research program demonstrated that some 85 to 90% of the cutterhead power is absorbed by the rock crushing that takes place just beneath the cutters. The rock that spalls off the face between the cutters is almost "free".

This has the happy consequence that when cutters are properly spaced out, the TBM goes faster with a given amount of power. Wider spacing also means fewer cutters and thus lower cutter costs.

This phenomenon is now well understood by today's TBM manufacturers and explains the trend toward large diameter high thrust cutters (up to 20 in. diameter and 70,000 lbs.). It also explains the phenomenal rates achieved by hard rock TBMs in the last few years.

Within the category of hard rock TBM's, there are three major types:

<u>Open</u> - This is the most common type hard rock TBM. Its primary characteristic is a structural main beam aligned with the tunnel axis. At the forward end of the beam is a cutterhead support structure, housing a bearing, to which the rotating head is assembled. Off the beam, more or less toward its rear end, pairs of grippers are mounted. Of the four principal manufacturers, two use a single pair and two use a double pair.

All but one manufacturer uses the main beam to house a conveyor which accepts the muck at the cutterhead and routes it to the rear of the machine. Thus the beam forms the conveyor housing which enhances both safety (rocks can bounce off of a conveyor) and dust control.

Open main beam machines allow the most versatile rock support. Ring beams, lagging, straps, rock bolts, mesh, invert segments can all be installed just behind the cutterhead support. It is an excellent design to accommodate blocky or squeezing ground.

Single Shield - This type of machine features a complete circular shield, and is used when a tunnel is to be completely lined. Either ring beams and lagging or segments are placed directly behind or within the tail of the machine. It develops its thrust by pushing off the previously set lining.

Cutter arrangement, cutterhead, and cutterhead support structure of this type of machine can be built very similarly to a main beam machine. Steering, however, is quite different. Several methods have been used including:

a. The cutterhead can be moved a limited distance eccentrically to the shield. This cuts the hole off to one side and the body of the shield naturally follows the hole.

b. A "copy" or outside cutter is placed on the cutterhead. This cutter is capable of being moved in or out. Like the eccentric head technique, this biases the hole to one direction or another.

c. The cutterhead and cutterhead support are built as a short forward articulating shield. Thus the whole forward part of the shield is moved in the desired direction.

As is quite evident from the above, shield machines of any type are not known for their ability to execute sharp turns.

The single shield machine features a very low length-to-diameter ratio, making them less susceptible to getting stuck in squeezing ground. The single solid shield also lends itself to conditions that may require operation under a pressure head. Seals can be placed both at the tail shield and at the cutterhead bulkhead to prevent water inflow.

The overall advance rate of this machine type is affected substantially by the speed with which a segment or lining ring can be set. Therefore, recent development has concentrated on automating the lining installation process.

Double Shield - This machine is capable of working in two modes, as a single shield above, or by using a set of grippers in a second tail shield which telescopes into the head shield. Its advantage comes when operating in better ground conditions where lining placement in the stationary tail shield and boring ahead by pushing off grippers, can take place simultaneously.

A major breakthrough occurred in the early 80's when, on a double shield machine when a shielded cutter face, superior bucket designs and back loading or recessed cutters were introduced to provide a smooth cutterhead. Cutters and buckets were protected from damage when operating in broken rock.

In addition, discs with wide spacing were used with spectacular results in soft,(as little as 1,000 - 2,000 psi) non-welded tuff. Thus, the full face disc machine can be used from the hardest rock, whether massive or fractured, to soft rock and even in self supporting compact soils.

This technology is now shared by both the single and double shield types.

Roadheader

The roadheader (Figure 3) is a heavy mechanism which uses a drag pick laced cutterhead, much smaller in diameter than the tunnel. The cutterhead is mounted on the end of a boom which can swing up and down, left or right. The boom is most frequently tread mounted but can also be mounted within a shield.

When working in more massive formations, where all rock must be cut, the roadheader has an efficiency in the range of 15 - 20 HP hr./ton. In shales or rock with poor bonding between striations, the roadheader is plunged into the face near the bottom of the heading and rips upward. The rock slabs off in large chunks. Under these conditions the mass of rock cut per unit of energy improves dramatically.

The tread mounted machine is very mobile and versatile compared with a full face machine. It can cut a variety of cross sections, change diameters at will, change directions

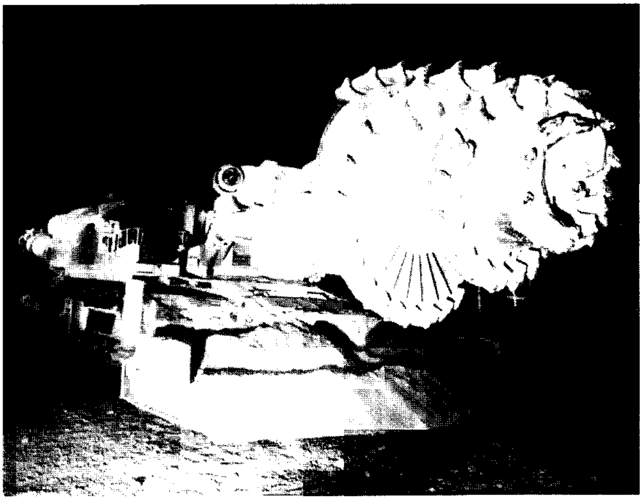

Figure 3.

quickly, and move to and from a face under its own power.

The machine usually incorporates gathering arms and a conveyor system to move the material cut from the face to a loading point at the rear of the machine. It can handle small boulders by breaking them loose from their matrix and picking them up with the muck. Large boulders are difficult to handle in two respects: (1) picks can break when they suddenly strike a large boulder, and (2) the muck handling system is usually unable to deal with large boulders and can get jammed.

Excavators

The excavator contains a powerful hoe, a pick or combination tool within a shield (Figure 4). The shield is thrust forward by pushing off the tunnel lining. It operates like a single shield, alternately thrusting forward and setting lining rings. The hoe is either tripod or swivel mounted and also serves the function to move the material from the face to the conveyor pickup point.

The excavators are generally limited to reasonably competent, but soft ground. Breasting plates or "orange peel" ground supports can partially control ground which would otherwise collapse. When truly hydraulic ground conditions are encountered, however, the excavator becomes

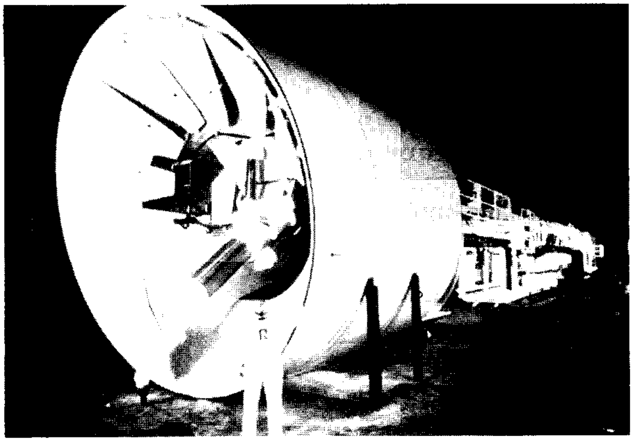

Figure 4.

unsatisfactory.

Despite the excavator's limited range of use, it is a popular choice due to its relatively low cost, the ability to handle large boulders, and visibility at the face. It is a high advance rate machine for compact talus, alluvium, or ancient flood plains, the types of soil on which the majority of urban areas have been developed.

Full Face Shield, Picks

This TBM is very similar to a hard rock, single shield machine, except that the cutterhead is dressed with drag picks rather than disc cutters. Almost by definition, picks limit the machine to softer, non-abrasive soils.

A frequent feature of these machines are the muck control gates and a semi-sealed bulkhead. By control of the gate opening and cutterhead speed, inflow of material is metered.

As in the case of the excavator, this machine is not suitable for use in truly hydraulic soils unless specially equipped. With the addition of tail seals and replacement of the belt conveyor with a screw conveyor, some manufacturers have devised a way to convert this type of machine into an Earth Pressure Balance machine (EPB). Thus, it is capable of going back and forth between the operating modes.

A significant operating factor in these machines, as well as with slurry or EPB machines is to meter the removal of material in proportion to the forward advance of the machine. These machines are always used at relatively shallow depths and if mining continues without forward motion, a funnel can form all the way to surface. This can and has caused devastating accidents on the surface; a road collapses or a building foundation shifts.

Slurry Shield

The slurry shield is designed for operating in true hydraulic soils or a mixed situation where the tunnel alignment goes in and out of these conditions. The design is also a full shield, developing thrust by pushing against the liners and with a variable rpm, full face cutterhead. Picks are generally used, but sometimes in combination with disc cutters. The discs are placed slightly forward of the picks in the theory that should boulders be encountered, the discs will break them up and minimize damage to the picks.

The machine differs from the full face pick shield in that the slurry shield always operates with a pressurized bulkhead.

A slurry fluid, frequently bentonite, is pumped into the volume between the face and the bulkhead. The slurry is mixed with the in situ material as it is scraped from the face. The combined or "pregnant" slurry is then removed by slurry pump from an outlet hole, usually near the bottom of the bulkhead. The slurry is generally pumped to surface where a separation plant removes the solids. Cleansed slurry is then returned to the face.

This machine is extensively used in both Japan and Western Europe where it is essential to pressurize the excavation face to prevent collapse. The critical operating parameters are (1) not to over pressurize, and thus cause a bubble to surface, and (2) to carefully meter output so as not to funnel to surface. This type machine is used at shallow depths and may be pressurized up to about 3 bars.

Earth Pressure Balance

Like the slurry shield, the EPB machine (Figure 5) is designed to seal and pressurize the face cavity to control water or ground inflows. These machines have been designed

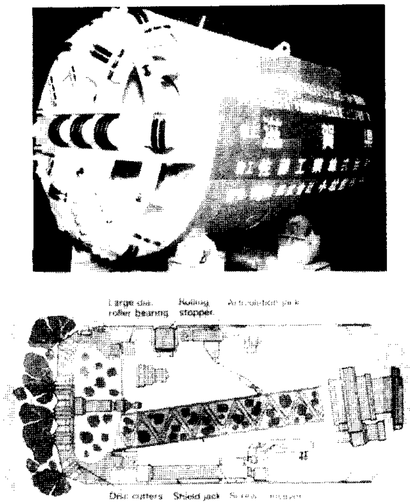

Figure 5.

to operate under pressures as high as 10 bar. The operational objective is to allow the pressure in the cutterhead and face cavity to buildup naturally by the pressure of the ground itself and the accompanying ground water. These machines operate best at ground moisture contents of 10 - 15% or less. Water, or a mud, is sometimes pumped into the bulkhead to maintain a desired moisture content.

Face pressure, however, is controlled by a gated outlet. Most frequently, a screw conveyor is used by itself or in conjunction with a piston discharger.

The EPB may be designed to operate on a wide range of rock and ground conditions, ranging from very hard (with discs) to soft ground (with picks). The use of slurry machines is declining in favor of the newer EPB concept because of its simpler control and versatility.

The machine is frequently built to allow operation in multiple modes. It may operate either as a single shield or as a double shield, switching back and forth as the need arises. It can also switch back and forth between a closed (sealed and pressurized mode) or an open (atmospheric pressure) depending upon the competency of the rock.

Thus, a deep undersea tunnel could operate in the open, double shield mode, unless it encounters a pressurized seam or fault. Then the machine must quickly seal and operate in the true EPB mode.

These machines have achieved some outstanding results, as demonstrated in the English Channel Tunnel (Figure 6), but are far too expensive a design to use unless absolutely necessary.

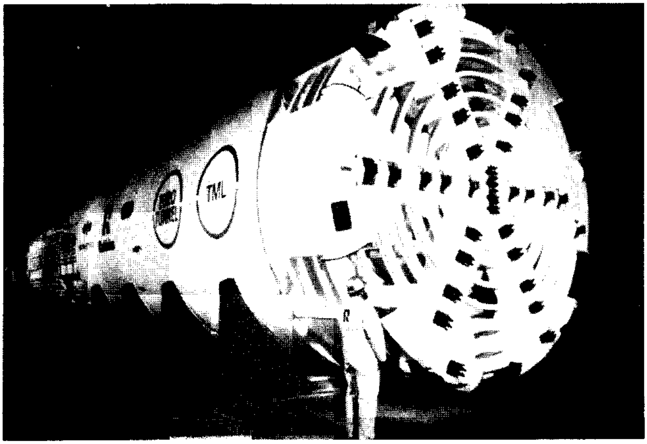

Figure 6.

Mobile Excavators

Especially in the underground mining industry, there is a great need for a mobile excavator in hard rock. This machine type should ideally excavate openings of various shapes and sizes while retaining sufficient mobility to move from one heading to another within the mine. Similarly, a need exists for civil underground construction where short tunnels or chambers could be excavated using a mobile piece of equipment. Such applications are not suited for TBMs because of the time needed for mobilizing and demobilizing and the circular cross section which they produce. To address these needs, extensive efforts have been underway worldwide to develop a suitable hard rock excavator. These efforts have resulted in the development of some promising concepts and equipment.

One of the developments in hard rock mobile excavators

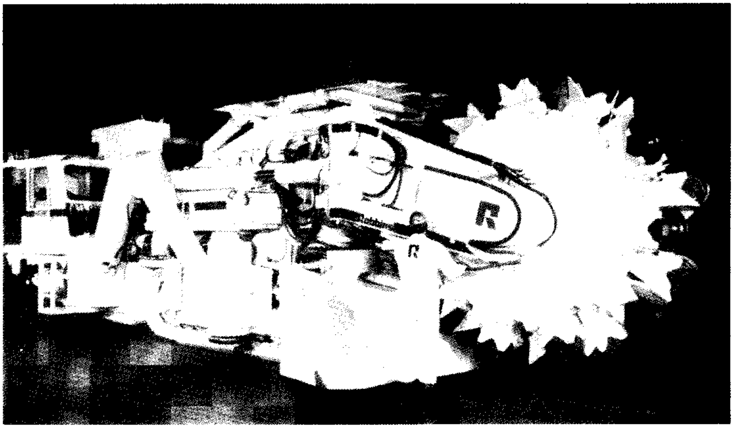

Figure 7.

is the Robbins Mobile Miner (Figure 7). This is a crawler-mounted excavator which features a rotating wheel fitted with disc roller cutters and mounted on a swinging boom. Rock excavation is accomplished by sumping the rotating cutterhead into the rock and slewing it sideways. The goal is to utilize the proven hard rock cutting capability of disc cutters to fragment the rock while maintaining system mobility. The present machine excavates a near rectangular opening with flat roof and floor with elliptical shaped walls. It is capable of making tight turns and working both inclines and declines.

Muck is removed from the face with gathering arms loading onto a conveyor which discharges behind the machine into mine cars or trucks. The first Mobile Miner was built in mid-1980s and tested at the Mt. Isa mine in Australia. The machine was used to drive a 1100 m. long conveyor decline and a 540 m. long horizontal drift. The rock types encountered consisted of greenstones and quartzites with compressive strengths ranging from 110 to 330 Mpa.

Despite some structural and mechanical problems experienced with this prototype machine, the trials have proven the concept and represented a major development step. The results from Mt. Isa were analyzed and evaluated in extensive detail and were used as input toward the development of the second-generation Mobile Miner, the MM130.

This machine, jointly developed by Robbins and Pasminco Mining, is currently excavating a 300 m. long horizontal drift at Pasminco"s Broken Hill mine in Australia. The rock types encountered in this drive are primarily metasediments, including gneiss and schist with quartzite bands. Rock strengths vary from 70 to 300 Mpa. The rock is highly abrasive with quartz contents ranging from 70 to 90 percent. The machine is excavating an opening size of 6.15 m. wide and 4.1 m. high. It has a maximum cutting width of 7.9 m.

This machine has several new features as compared to the first model used at Mt. Isa. All tramming, gripping and cutting functions of the MM130 are controlled by a Programmable Logic Control (PLC) system. Thus, the machine is capable of automated operation using PLC control. The PLC is also programmed with a cutting optimization algorithm whereby the wheel slewing speed is automatically adjusted as it encounters rock bands of different hardness during the cycle. This allows for maximum utilization of machine power by matching cutter spacing to geologic conditions encountered. The machine performance has continually improved since the start of operations with advance rates reaching 1.7 m/hr. Long term plans call for the use of this machine in the cut and fill stopes for ore production.

Based on the Mobile Miner cutting principle, a ranging unit capable of excavating a cross section of 50 to 80 m. in a variety of shapes is also under development by The Robbins Company. This machine, being developed for the Tasei Corp. of Japan will be used to drive road tunnels in areas where drill and blast excavations are not allowed due to the proximity to populations centers. This machine is being designed to operate in granites to 150 Mpa. strength.

The Wirth Company of Germany is also developing a hard rock mobile excavator, called the Continuous Miner. This is a joint development effort between Wirth and HDRK Mining Research Ltd. (a research consortium of three Canadian mining companies, Inco, Noranda and Falconbridge). This machine also uses the proven hard rock cutting capability of disc cutters for excavation. It is crawler mounted to provide the desired mobility.

The excavation process is accomplished by four hydraulically activated cutting arms fitted with large diameter disc cutters. The arms are hinge-mounted on a rotating support plate. As the plate rotates, the arms are swung out to create spiral cuts to break the rock. The center arm creates a "pilot" hole by slewing towards the center of the bore. Once this "free" face is created, the other three arms start cutting spiral tracks outward toward the gage. This provides an undercutting action which, if successful, is a highly efficient way of breaking rock. When the three arms reach the maximum inner circular profile of the tunnel, they can be extended and retracted hydraulically to cut the desired final shape of the opening. All is accomplished under computer control, allowing for excavation of different size and shape openings.

The Continuous Miner is in the final stages of assembly and will soon begin field trials at a quarry near Essen, Germany. Following these tests, the machine will be shipped to Sudbury, Canada where it is to undergo extensive underground trials at a nickel mine excavating hard, abrasive rocks.

Atlas-Copco of Sweden is also designing a hard rock mobile excavator called the Disc Boom Miner. Again, the intent is to build a machine which has mobility and can economically excavate different size and shape openings in hard rock. The machine features a rotating circular head fitted with disc cutters. The cutterhead is mounted on a swinging boom. After sumping into the rock to a prescribed depth, the cutterhead is swung in the vertical and horizontal directions. The extent of the swing angle determines the final shape and size of the opening created. The Miner is track-mounted to provide a high degree of mobility. This machine is still in the conceptual development and design stage and has not yet been built.

Also under development as a mobile hard rock excavator is a Tamrock-Eimco heavy-duty roadheader which recently completed initial field trials at the Inco's Birchtree nickel mine in Thompson, Canada. This machine features a turret-mounted boom with a large diameter in-line cutterhead fitted with drag type cutter bits. The cutterhead features a low-speed, high torque drive system designed to allow deep bit penetrations for efficient chipping of the rock. During the cutting cycle, the machine is firmly held in place with a series of roof and wall jacks to provide a rigid and stable platform for reacting to high loads generated from the cutting action. Thus, unlike typical roadheader operation, machine weight itself is not relied upon for producing and reacting to the cutting loads.

Once the roof and wall stakes are set, the boom is pushed forward hydraulically, similar to the cutterhead on a TBM. Because of this feature, high sumping and cutting loads can be generated, a prerequisite to achieving efficient and economic excavation of hard rock formations. The machine can excavate openings of different sizes and shapes within the reach of its boom. It features a profile guidance system to enable automated operation and boom movement to provide precise profile control. Tests performed to date have shown that the concept has potential for excavation in mining and civil construction applications.

SUMMARY

The present day tunnel boring technology has nearly reached the capability to excavate wherever a tunnel need exists. Within the last few years, the industry has witnessed feats considered impossible to achieve only a decade ago. Today's machines can bore through harder and more abrasive rock, through blocky ground, faults and shear zones, under high hydrostatic pressures and through hydraulic soils at depths ranging from a few meters to a kilometer or more. Steep slopes greater than 45 degrees, vertically downward or upward, under conditions requiring dry boring and with water inflows approaching 6000 gpm; all have been conquered. Tomorrow's machines will still look a lot like the machines of today. Changes will be more subtle to the eye, but substantially increase production through reliability, instrumentation, material changes and automation.

CONCLUSIONS - THE FUTURE

The use of the mechanical mole for tunnel construction in all types of rock and ground conditions has not seen the end of its development. TBMs will see increasing use in even more hostile environments.

Hard Rock TBMs - The basic disc cutter and full face cutter head will be with us for some time yet. In the laboratory, on a 2.0 m. diameter machine, a penetration rate of over 36.5 m./hr. was achieved using a cutter spacing of 236 mm. An amazing efficiency of 1.2 HP-hr./ton was achieved. This approaches the energy efficiency of explosives and is more than double the best of today's equipment.

Equally big improvements in overall advance rates will come from improving utilization. While a TBM is said to be "continuous", the fact is they are seldom utilized more than 50% of shift time. The record (so far as the authors know) is 63%. Non-boring time is regripping, cutter changes, repairs, and roof support under adverse conditions. There are some human factors too, but we are probably stuck with these for a few generations yet.

Sequential gripper TBMs to permit continuous boring are coming on the market. The objective is to improve overall machine utilization by eliminating the downtime to reset grippers.

A problem which is beginning to surface with the advent of high power, high thrust TBMs is the creation of very high stresses in the cutting disc. Plastic deformation and/or macro fracturing of the edge have both been observed. In fact, the cutter ring composition and metallurgy is now the limiting factor to transferring more power into the rock. As a result, a great deal of attention needs to be focused on seeking and developing new materials with the capability to sustain higher stress and acceptable wear resistance while reacting to the high cutter loads which the TBMs of tomorrow will generate.

<u>Soft Ground Machines</u> - The full face pick machine, slurry machine and EPB machines will improve their efficiency primarily through automation. Automation in operation, monitoring of pressures, amount of muck being removed, thrust control, and perhaps most significantly by automatic lining installation.

The authors' only controversial prediction for the future involves the above three machine types.

The machines will merge into a common more versatile combination machine, sort of an EPB which can use an injected slurry where needed but which could also completely depressurize when in competent ground. The pure slurry machine is a more tedious beast to control as it requires careful monitoring of slurry pressure, control of advance to match the amount of material removed and the necessary remote separation plants. The basic EPB unit or such a combination unit is likely to erode the pure slurry machine market.

General - Modern TBMs are being fitted with more electronic systems to provide early detection of impending component failures and wear on critical components. One of the more exciting new developments is the automatic steering of machines. Technology is now available to directly interface the laser guidance system with the machine steering circuit to enable fully automatic steering of the TBM. Electronic systems are also being installed on TBMs to provide automatic optimization of machine performance in response to changes in rock and ground conditions. In particular with the use of variable frequency AC drive systems, the cutterhead RPM and the thrust pressure can be continuously varied to allow maximum penetration at all times during the advance cycle. Electronics systems are also aiding in the scheduling and control of various operations at the tunnel heading and the back-up/transport system.

Not to be overlooked or minimized in their importance are improvements to TBM backup systems. Recent improvements in TBM performance can be attributed to the use of continuously advancing conveyor systems in place of the traditional rail haulage for muck removal. The mechanical reliability of the conveyor systems have improved dramatically over the last several years, as well the distance over which they can used effectively. Several tunnels are currently being bored with conveyor haulage systems extending over distances of several miles. For shaft hoisting of TBM muck, conveyors can also readily interface with the vertical belt hoisting systems, resulting in the most continuous muck handling system yet devised for TBMs.