Tunneling Machines of Today and Tomorrow

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Current tunneling machines are competitive in making circular bores in rock as strong as 25,000 psi compressive strength and in diameters to 20 ft. These machines produce tunnels 50 to 100 percent faster than conventional ones, and show tremendous savings in permanent tunnel linings. Machines of the future will be able to cut other than circular bores and be competitive in many formations as strong as 35,000 psi strength and in sizes equivalent to 35 ft in diameter. Principal development is required in rock disintegration, material handling, and temporary roof supports.

• THE INCREASING public awareness that population concentrations demand more underground facilities has spurred a tremendous interest in tunnel boring by machine methods. The need for rapid transit systems, the desire to reduce the number of unsightly elevated freeways, the need for more parking facilities, the requirements of the civil defense, and the high cost of urban surface real estate all point to a greater demand for improvements in underground excavation technology.

The shallow or top few hundred feet of earth crust will contain many of the public works tunnels. This crust is not uniform so several methods of boring will be required, sometimes within the same tunnel. This discussion will deal principally with so-called "hard-rock" tunnels, a term loosely applied to any rock much stronger than well-prepared plaster of Paris. It will ignore that very important field of soft-ground tunnels where shield driving (Fig. 1) is a well-advanced art. More than 60 of these shields have been built in the United States.

Rock tunnels are driven by drill and blast and by tunnel-boring machines (TBM). The first successful TBM's in 1954 were for 26-ft diameter soft-ground tunnels at Oahe Dam in South Dakota. They remain the largest rock machines used to date in the United States. One larger, 36-ft, James S. Robbins' TBM was used on the Mangla Dam in Pakistan by the Guy F. Atkinson Company.

The South Dakota machines were developed from the technology borrowed from the developments of continuous coal-boring machines. The coal industry now has more than a thousand continuous miners in use, most of which have been developed since World War II. The first South Dakota machine was built by Robbins for the contractor, Mittry, and is frequently called the Mittry machine. This TBM used drag cutters to cut kerfs and discs to split the ridges between the kerfs after they had built up. This method is still used by some machines in coal boring. Even before the Mittry machine was built, the U. S. Army Corps of Engineers had supported the development of a coring or a gage kerf-cutting device for the Oahe shales. The gage kerf was cut with a coal-mining machine, which resembles a large chain saw.

While the Mittry TBM was being developed, independent developments for harder rock were being carried out in shaft sinking in West Virginia, Germany, and Holland and on a tunnel borer in England. The Dutch and Germans were boring 26-ft diameter coal-mine shafts (Fig. 2), and the Germans were developing the first raise drills to connect overlying coal-mine entries below ground. One German developer (Salzgitter) tried to build a shaft drill that cored from the bottom up. The German Bade made a

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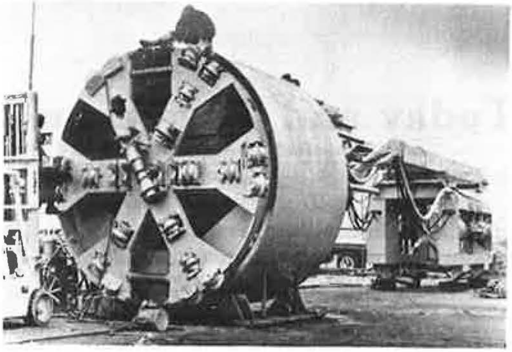

Figure 1. Soft-ground tunnel driving shield with 13 ft 4 in. diameter disc cutters.

Figure 2. Bit bodies for Dutch rotary reaming 26-ft diameter mine shafts.

drill for shaft sinking using a unique principle of rolling cutters turning in a planetary action about a central rotating shaft. This principle is being modified and tried in a new approach to tunnel boring machines in England, Germany, and Switzerland, as will be explained.

The Zenis in West Virginia, with assistance from Hughes Tool Company, developed 2 machines to drill 6-ft diameter mine shafts during the 1950's. These machines used rolling cutters, and the first of the two was a core drill.

Hughes built a horizontal test TBM in the late 1950's and with it proved that rock harder than 35,000 psi compressive strength could be drilled in rather large diameters, but on a laboratory scale. At about this time or in the early 1960's, Robbins put his discs closer together, eliminated his drag cutter, increased his thrust, streamlined his machine design, and successfully drilled some rock of about 12,000 psi strength. This was the first application of discs as the primary cutter to large diameter rock drilling. A little later, K. C. Cox of Dravo, with assistance from Hughes, showed that discs on a pointed or conical head could be made to break more of the rock in tension and thus reduce horsepower and thrust requirements.

Several machines were then built from 80 in. to 20 ft in diameter (Fig. 3). TBM's were applied progressively to harder rock and are now being used in 22,000-psi limestone in Chicago. Some of the layers of rock being bored at White Pine Copper exceed 30,000-psi compressive strength, but the TBM application in rock this strong must await a cutter cost reduction below that estimated today before it can be considered a complete commercial success in public works tunnels.

It should be pointed out that, while compressive strength is the best rock characteristic to use in estimating its borability, it is not conclusive. Compressive strength is difficult to measure precisely, partially because natural flaws exist even in apparently homogeneous rock. Rocks of equal compressive strength will bore differently depending on brittleness and other factors. Limestone of 20,000 psi generally will drill easier than a tougher (less brittle) schist of the same strength. Rock constituents also will affect cutter life and cost. Rock containing a large percentage of quartz will wear cutters faster than that having predominantly a less abrasive mineral such as calcite.

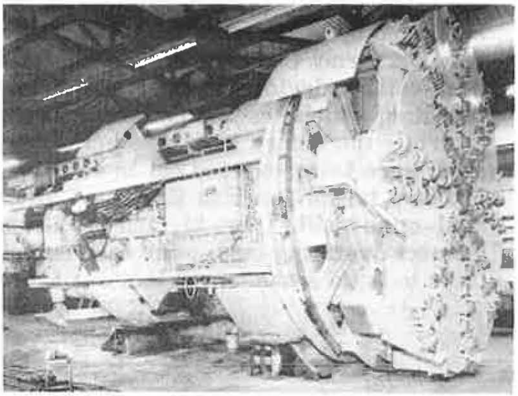

Figure 3. Hard rock boring machine 20 ft in diameter that bored 7,800 ft in BART Tunnel at 60 ft per day.

There are 4 manufacturers of rock TBM's in the United States and 3 in Europe. Most of them apply thrust of at least 50,000 lb per foot of diameter from wall anchors. The Lawrence Manufacturing Company machine gets a major portion of its thrust by pulling from an anchor set in a 24-in. predrilled pilot hole. Most of them use an essentially flat face on the cutter head, although the Robbins has a slight ovoidal or saucer shape. The cutter head is rotated at approximately 80 rpm divided by the diameter in feet. The rotary horsepower is approximately 50 times the diameter in feet, and most of them have 100 to 150 auxiliary horsepower. All use electric power, and all transfer some of this to hydraulic power for thrust; some use hydraulic motors for the rotary drive.

One British machine, the McAlpine, uses a planetary action on a movable cutter head and can thus cut a heading of any desired shape. This cutter head, like that of the old German Bade shaft-boring machine, has some drag action to the cutters and thus can be considered only with caution for strong, tough, abrasive rock because of rapid cutter wear and slowness of penetration. The Swiss Habegger and Wholmeyer machines have a similar action but have not been used in this country or elsewhere extensively because of this and also because of their mechanical complication. Krupp in Germany did some experimental work with this principle.

Some who analyze machines with planetary action point out that cutters are used in a chipping as well as a drag action. It is also suggested that some of them cut radially from a predrilled hole, that they require less thrust, or that they cut rock in tension rather than compression. On close examination none of the arguments can be substantiated. First of all, the pilot hole must be drilled, and this is time consuming. Then the rock under radial attack must be chipped under compression, and most of such rock being attacked responds similarly to attack from north or south as it would from east or west. The main difference is that the forces resisting the thrust on the rock must be taken by the machine in the radial attack, whereas in the frontal attack they are taken by the interface of the machine to the tunnel wall. This is a doubtful advantage and, if one exists, it is probably outweighed by the frontal attack covering more face area at one time with much less complication of machinery.

It may be overlooked that all rolling cutters that have teeth provide a chipping action. Those that rotate in a more usual, nonplanetary motion do not have as much self-destructive drag action as planetary cutters in hard rock. Some drag action is desirable only in very soft formations. The very good advantage of the Bade-McAlpine planetary approach is that it will cut a horseshoe shape so desirable for transportation tunnels.

Nearly all the TBM's that use rolling cutters offer one or more versions of the disc cutter. Some have single discs on a spindle. Some have 3 or 4 discs on each spindle, and the spindle diameters vary from 9 to 15 in. Some have steel edges, and some have sintered tungsten carbide inserts as teeth or wearing surfaces. Some have replaceable cutter shells so that either the bearing or the cutting surface can be replaced. The tooth type of cutters, which were used on the original Zeni rock-boring machines, are seldom used in rock tunnel boring today, but some form of tooth cutter may regain usage as machines move into stronger rock applications.

As previously mentioned, the Germans developed the raise drills early in the 1950's. They drilled holes of about 36 in. in diameter in sedimentary rock. Raise drills are drills normally used in deep mines to drive vertical or sloping shafts between vertically separated tunnels. They are mentioned in this discussion on tunneling because their development may influence hard formation tunneling. The raise drilling rig drills a small hole of 8 to 12 in. to connect the tunnels. A 60-in. bit is put on at the other end, and the hole is backreamed letting the cuttings fall into the lower tunnel. Hughes used the idea in the late 1950's and "beefed up" the European design to cut 60-in. holes in very hard rock at Cleveland Cliffs, Michigan, iron ore mines. Robbins and others subsequently built more than 50 of these machines (Fig. 4). These machines have proved that, by providing sufficient thrust and power, the hardest rock can be bored at the reasonably good penetration rates of 2 or 3 ft/hour. The cutter cost today is reported to be $8 to $12/cu yd or higher. This high cost, combined with the rather slow penetration, all but rules out TBM's for hard rock because drilling and blasting in this material is about as fast, perhaps slightly less costly, and more reliable. It may be interesting to note that in sandstone of about 10,000 psi TBM's have advanced at 17 ft/hour and at cutter costs reported to be less than $1/cu yd.

Today's TBM's differ only slightly in their guidance means. Some machines can change direction while they bore and others reset direction at the end of each stroke. In the latter method strokes may be shortened if necessary for a continuous curve. In any event, most TBM's have good guidance control, and one tunnel was bored within $^5/_8$ in. of the prescribed line and grade. The stroke length on different TBM's has ranged from 1.5 to 5 ft.

All TBM manufacturers offer mechanical aids for setting ring beam supports above or around the machine and within about 5 ft of the face. None of these is completely automatic, and most of them are quite awkward and leave considerable room for improvement.

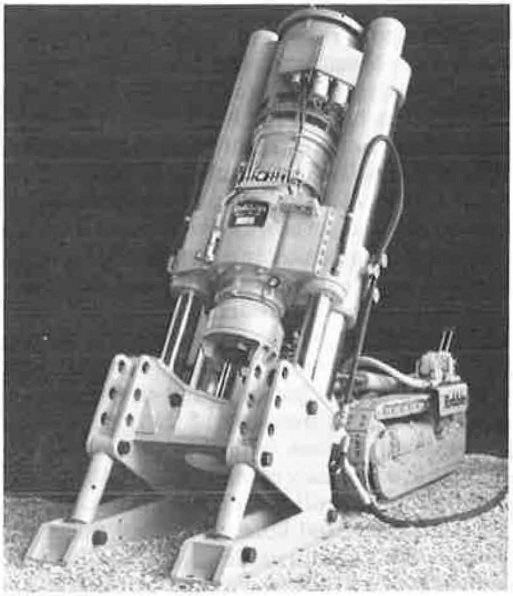

Figure 4. Raise drill for drilling small hole into a rock tunnel and pulling a 60-in. reaming bit up.

Muck is picked up by buckets on the outer edge of the cutter wheel and deposited onto a belt conveyor to be transported to tunnel cars in the rear of the TBM, except in a few machines such as the McAlpine. The muck in any multiple-head machine such as the McAlpine either is plowed onto transverse drag conveyors discharging at the center on a longitudinal belt conveyor that moves it to the rear or is gathered to the central conveyor by revolving arms like those on snowplows or coal-mining machines. Such gatherers will have high maintenance when required to handle sharp-edged, hard, abrasive materials. One of the Lawrence machines used a screw conveyor rather than a belt to move the material out. Where possible, the machine belt conveyor should be at least 30 in. wide to handle peak loads during very fast penetration and to handle large rock particles that fall off the face or roof.

The TBM manufacturers or the contractor must take considerable interest in seeing that the trailing conveyor is adequate and that there is a minimum delay in waiting for cars. More than half of the TBM applications to date have had less than adequate car supply facilities. Except in the very best jobs, delays of more than 40 percent of the available time have been caused by waiting for cars. Trailing conveyors of early tunnel borers were 60 to 150 ft long. Many of those being built today are 300 ft or longer and straddle a double track. Long thin cars are being designed for small tunnels so that a string of empties can be stored under the conveyor alongside that string being loaded to avoid car waiting delays.

No rock TBM manufacturer, or user, has developed a successfully proven method for concrete lining concurrently with the boring. The complication of having forms in the way in a congested tunnel, hauling concrete in without interfering with muck haulage out, and generating added heat so far have been insurmountable problems.

A study of patent files shows that for more than a century, man has dreamed of a tunnel-boring machine. Machines were used in the last century in England and the United States, but none prior to 1953 got much beyond the prototype stage. It has taken nearly 20 years for the current concept of a rock TBM to develop to the present state. There have been no significant innovations in the TBM's in the past decade, other than laser guidance. Backup facilities, such as conveyors and car changers, have been improved as has TBM reliability; but cutters, rpm, and thrust types and techniques generally are the same as were drawn up in 1960 and were in the concept stage in 1955. This is revealed in patents and in some of what appeared to be "visionary" technical papers of that period.

This indicates that with our existing approach it takes at least 15 years to get an idea from the drawing board to complete acceptance in the field. Much of the first 10 years is used convincing a broad segment of the users that the idea is feasible. They are the ones who have to gamble the money and make the ideas work. There are still some who are not convinced that the TBM has "arrived," even though they have lost profitable jobs to those who were convinced that the rock TBM would work. There are some of those who now believe in the TBM principle but have an unrealistic value of its limitations.

There are some limitations or restraints, and some of these are being erased or modified. Machines cannot be built for tunnels smaller than 80 in. today because they fill the hole too much for maintenance and roof support. TBM's are uneconomical in most tunnels larger than 30 ft in diameter because cost per cubic yard for conventional excavation decreases with diameter increase at a faster rate than it does with TBM's. No one really knows the exact effect of size on the cost or machine requirements for TBM's.

The Jarva Manufacturing Company proved that machines could compete commercially and bore rock stronger than 20,000 psi in St. Louis limestone, and Calweld Division is ready to try its machine in rock stronger than 30,000 psi. There were rules of thumb that a machine should not be considered for tunnels shorter than 2 miles in length because the high capital cost (which is about double that for conventional tunnel driving) could not be written off in less. With the greater availability of used machines, this restraint should not be applied automatically. The availability of used machines is helping to overcome the disadvantage of long lead time of about 10 months to build a tunnel-driving machine.

Much has been written about the advantages of TBM's. Where they can be used, there is good evidence that steel primary support can be cut almost in half. Because of elimination of overbreak, concrete for permanent lining often is reduced by 50 percent. These 2 savings to the owner and contractor in many cases will pay for most of the depreciation on the TBM. There are about 10 percent fewer lost-time accidents in TBM jobs than in conventional jobs; eventually this will be reflected in insurance savings.

Total labor savings for TBM to date have been less than was anticipated. The crew at the heading has been decreased by about 75 percent, but larger crews are required to lay track and handle the muck production at the higher rates. The net saving has been about 15 percent.

Predictions of machines in 20 or 30 years, of course, are impossible to make with any assurance of accuracy. It is a good exercise though if not taken too seriously. Some conclusion may be reached by evaluating announced research plans. The following estimates are made with these reservations in mind. It is hoped that they will stimulate manufacturers, contractors, or tunnel designers to similar thoughts that may help the progress of this technology in which there is such a large stake.

In tunnel drivers of tomorrow, "tomorrow" must be defined. If tomorrow is the next 2 decades, then the tomorrow TBM will be a greatly improved version of today's machine. If tomorrow is the year 2000, then the TBM will be one that destroys rock by a combination of mechanical, thermal, or more than likely high-pressure water erosion.

The 1990 machine will cut rock with rolling cutters. A convex or concave head will cut more of the rock in its weaker tensile mode, rather than compression as is done now. It will be able to set roof supports automatically, and this may be a spray-on concrete or plastic. The support may consist of ribbons of steel that are flexible in storage but are formed and applied in place. It will be completely dust free. It will sense bad rock or water trouble ahead. It will be operated remotely so that men are rarely exposed to unsupported roof. Most of the controls will be handled by a computer responding to a laser beam for guidance and other electronic devices for varying thrust, varying rpm, and avoiding obstacles. The permanent lining will be installed within a few feet of the rear of the machine.

Devices will be available to ream the round or circular openings, made by a machine, to moderately large rectangular sections, as are required for underground urban parking lots and rapid transit stations.

Solids pipelines to handle muck will not replace wheeled vehicles that will continue to be needed for supplies and men. Rail or vehicles or both are cheaper than belts and do not require crushing or the separating of cuttings from a slurry as is needed in a pipeline. Tunnel cars of 1990 will not look much like those of 1970. They will be long, slender, and flexible, and therefore adaptable to various shapes and sizes of tunnels. They may ride on pneumatic tires on a special prefabricated roadway at double or triple today's tunnel rail speed, which is 10 mph. Each may contain its own propulsion unit and operate manned or unmanned. The 1990 machine will be able to turn curves of a radius equal to 5 times the tunnel diameter as opposed to about 20 times the diameter limit of today's machine. It will be able to go down grades of 20 deg as opposed to today's of about 10.

The 3,000 ft per month or better progress rate of today's machines will be a low average production rate in 1990. Today's infrequent high record rates exceeding 6,000 ft per month will be achieved frequently in 1990, and 200 to 300 ft-days will be common in good ground.

The mechanical parts of 1990 machines will weigh about 60 percent of that of today's, which in tons is approximately 0.6 times diameter in feet squared; but weight of electronic controls, dust controls, temperature controls, and automatic roof support will offset the weight saving. Freight to the job will be about what it is today. Boring-machine business will have developed sufficient volume and highway- and water-tunnel designers will have standardized so that today's lead time for a machine will be 3 to 4 months rather than 10 to 12 as it is in 1970.

Tunnel-boring machines in 1990 still will be unable to penetrate heavy, broken, hard rock ground. Drilling and blasting will remain the standard method for such ground as well as hard rock tunnels larger than 35 ft in cross section.

The machine of 1990 will have cutters that will penetrate hard rock (35,000 psi) at 6 ft/hour at a cutter cost of less than $4/cu yd and that will penetrate rock weaker than 20,000 psi at 25 ft/hour and a cutter cost of less than 50 ¢/cu yd.

Time between cutter changes will be extended from its current 100-hr average (good performance) to 300 rotating hours. Machine reliability and backup equipment will have improved so that machine availability will increase from its present 60 to 85 percent. Cutters therefore will be replaced about twice a month. Part of the reduction in cutter cost will come from cost savings in mass production, reducing the list price, so that it will cost 20 percent less than the approximately $40,000 to $70,000 (depending on rock type) to dress or add a complete set of cutters to a 20-ft machine.

This will make tunnel-boring machines competitive in tunnels in any kind of reasonably competent rock to diameters of 35 ft. There will be a rock TBM for tunnels of 60 in., but not smaller.

A concentrated research effort could produce the 1990 machine by 1980 and move the year 2,000 TBM to 1990.

Some very rough guidelines for estimating machine-bored tunnels are given in Table 1.

TABLE 1

RULE-OF-THUMB GUIDELINES FOR ROUGH ESTIMATIONS OF MACHINE TUNNEL BORING

Item	Unit	Value 1970	1990 to 1970 Ratio
Horsepower	hp	50D	0.7
Machine weight	lb	$D^2 \times 10^3$	0.8
Minimum turning radius	ft	20D	0.25
Rotary speed	rpm	80/D	1
Thrust	lb	$5D \times 10^4$	0.6
Maximum penetration rate	ft/hr	$2/S \times 10^{-5} - 3 \leqslant 25$	1.5
Production	ft/shift	4 × max. pen. rate	1.5
Cutting cost/cu yd	$	$0.50 + (S \times 10^{-4})^2$	0.6
Machine cost	$	$5D \times 10^4$	1.2

Note: D = diameter in ft, and S = rock compressive strength in lb/sq in.

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