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Hard rock and soft ground tunnel boring technology

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Introduction

Since its introduction only a few decades ago, TBM technology has made remarkable progress towards becoming a highly efficient and cost effective means of tunnel excavation. Given sufficient geotechnical information, TBMs can now be designed to handle any type of ground ranging from hard rock to soft ground/soils to mixed-face conditions. Compared to drill and blast and other conventional methods, TBMs are capable of achieving significantly higher advance rates, leading to faster construction schedules and reduced project costs. This paper is intended to provide a brief overview of current TBM technology together with future anticipated developments.

Historical Background

Hard Rock TBMs:

In 1851, Charles Wilson developed a tunneling machine, which is generally considered as the first successful continuous borer for rock. However, problems with disc cutter technology and other difficulties prevented it from being competitive with the developing techniques of drill and blast tunneling. Other famous attempts include the compressed air driven TBM developed by Colonel Beaumont in 1881 for an exploratory tunnel under the English Channel (Figure 1). This 2-m diameter machine bored a total of more than 1.8 km in the chalk with daily advances of 24.5 m from the British side.

Practically no serious attempts were made until 1952 when James S. Robbins designed a TBM to be used for four tunnels at Oahe Dam in South Dakota. This unit was 7.85 m (25.75 ft) in diameter. The cutterhead was fitted with radially arranged, carbide drag bits and disc cutters, which were protruding slightly less than the carbide drag bits. This machine was powered by two 150 kW motors and had a total weight of approximately 114 tonnes. The machine bored through soft shale at advance rates reaching 49 m/day.

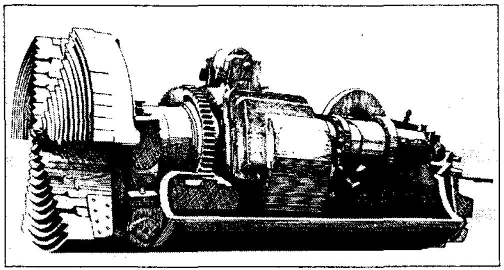


Figure 1. Full-face boring machine, 1881 version.

The first successful hard rock TBM (Figure 2) was built in 1956 by Robbins and used in the Humber Sewer Project in Toronto, Canada. This was a 3.3 m diameter Robbins TBM for boring a tunnel approximately 4.5 km long through sandstone, shale and crystalline limestone. The TBM was originally designed and equipped with drag bits and disc cutters, however, during the initial boring period it was decided to remove the high wearing drag bits, leaving only the disc cutters on the rotating head. This experiment turned out to be a success and became the main driver for introducing disc cutters in hard rock conditions.

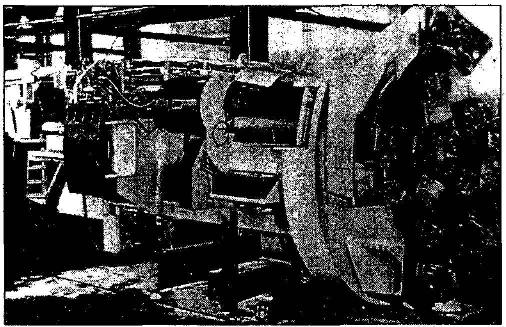


Figure 2. First successful hard rock machine, 1956.

Slurry TBMs:

In 1874, Greathead suggested that muck might be removed from the working face of a tunneling machine by pumping it out as slurry. Later, Prof. H. Lorenz proposed in a patent that a tunnel face could be stabilized by the application of bentonite clay and water under pressure. However, neither one of these ideas were ever tested in practice. In 1959, a machine designed by E. C. Gardner was put to work in a 3.35 m diameter storm water drain tunnel (Figure 3). The water was used as a transport medium, but not pressurized.

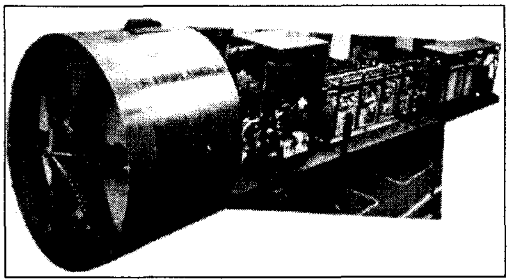


Figure 3. Gardner's slurry TBM.

In 1967, Mitsubishi manufactured their first trial shield with slurry face support. Figure 4 shows one of the earlier slurry shields with outside diameter of 5.05-m built in 1973.

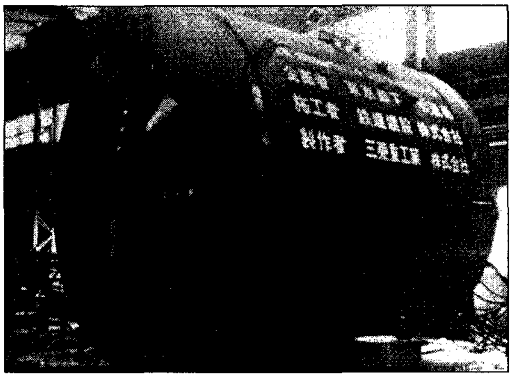


Figure 4. Mitsubishi slurry shield (1973)

J. V. Bartlett (1964) patented a process that a bentonite mixture could be maintained at a selected pressure in pressure chamber of a shield excavator in order to stabilize the tunnel face during excavation. Based on Bartlett patent, Robert L. Priestly manufactured the first bentonite-tunneling machine to be used in New Cross site in 1971 (Figure 5). E. Nuttall Sons & Co. Ltd. employed the machine on a 144 m test drive.

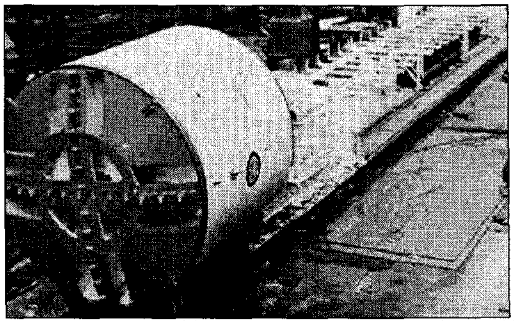


Figure 5. Bentonite shield (process patented by Bartlett in 1964).

Another important development of slurry TBMs was achieved by German contractor Wayss & Freytag in 1974 (Figure 6). The machine was employed to construct the Hamburg-Wilhelmburg collector beneath the Hamburg Port, which was 4.48 m in diameter.

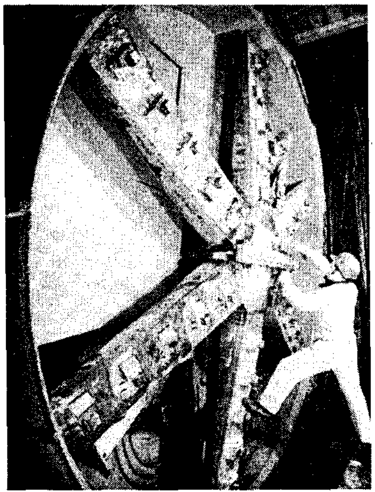
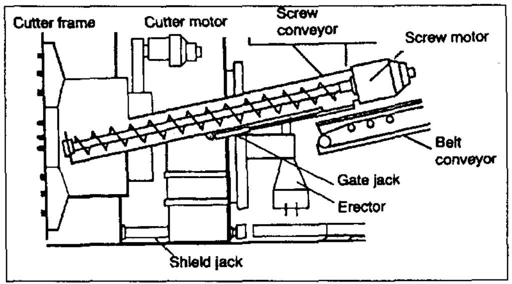


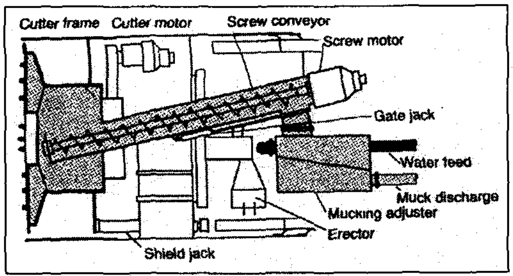
Figure 6. First German slurry shield by Wayss & Freytag (1974).

EPB TBMs:

Sato Kogyo Company started the first development work on Earth Pressure Balanced (EPB) shield in 1963. The first prototype was built by the Ishikawajima-Harima Heavy Industries in 1966 after considerable laboratory and field research (Figure 7).



(a)



(b)

Figure 7. Sato Kogyo (a) earth and (b) water pressure type shield machines.

Similar machines were also manufactured by Mitsubishi and other Japanese companies. The Mitsubishi machine (Figure 8), known as confined soil shield, operated in much the same manner as the shield developed by the Sato Kogyo Company.

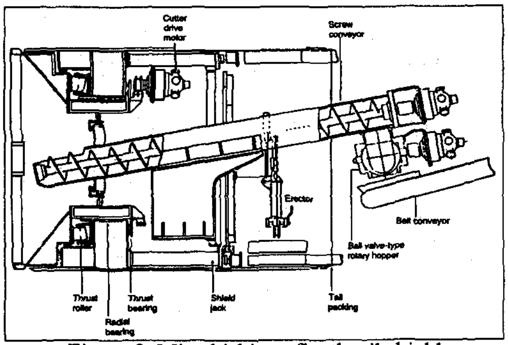


Figure 8. Mitsubishi confined soil shield

A further development to the earth-balancing concept was made possible by the Daiho Construction Company Ltd. As shown in Figure 9, the cutterhead on this machine did not include a faceplate. The first successful application of an EPB machine by the Daiho Construction Company in 1976 to excavate a 2.44 m diameter, 165 m long tunnel encouraged other contractors to make more use of this technology in future projects.

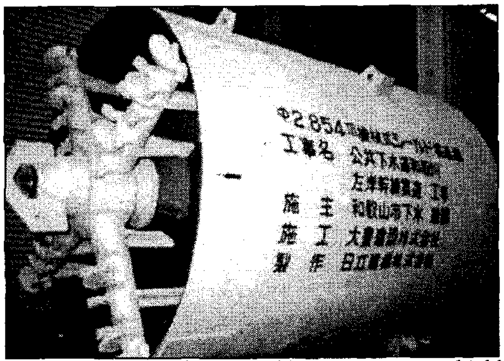


Figure 9. Daiho earth and mud balance pressure shield.

Present TBM Technology

Hard Rock Machines

TBM manufacturers have continually improved machine performance to cut into harder and harder rock since the first successful application in 1956. In the beginning, almost all the TBM development was the product of field trial and error. In the 70's and 80's, several universities and scientific organizations carried out research investigations to understand the mechanism behind the successful use of the disc cutter in rock. The knowledge developed from these efforts led to the ability to optimize designs, as well as reliably predict performance of TBMs in hard rock conditions. Since the mid 1950's the development of hard rock TBMs have progressed in two directions, open and shielded, based on the intact rock and rock mass conditions.

A. Open TBMs enable machines to bore tunnels in massive, hard and abrasive rock. This means more power and thrust capabilities on the machine

B. Shielded TBMs enable machines to bore tunnels in ground so unstable that the tunnel has to be lined concurrently with the excavation

A TBM fragments rock by action of an array of disc cutters installed on a cutterhead that rotates axially. While disc cutters are penetrated into the rock surface, the cutterhead rotates. This way each cutter cuts into new rock surface after each revolution of the cutterhead (Figure 10). This advance is defined as rate of penetration in mm/rev.

Figure 10. Cutting face of a TBM.

Figure 11 shows a typical hard rock TBM. The gripper assembly transmits the thrust and torque reaction of the cutterhead to the tunnel wall during boring, as well as carrying part of the machine weight. The anchoring force of the grippers is approximately 2.5 to 3 times the total forward thrust force. The front supports, support shoe and extendable side and roof supports provide ground contact immediately behind the rotating cutterhead in order to stabilize the TBM during tunneling.

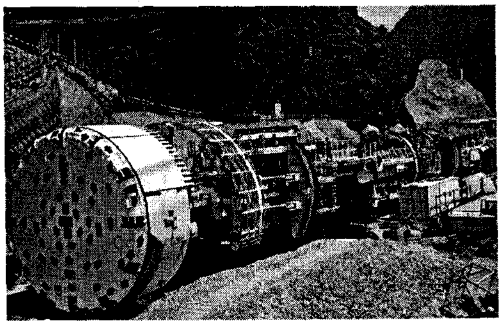


Figure 11. Main Beam TBM.

The muck generated by boring falls to the invert where it is scooped up by low profile buckets built into the head The buckets carry the muck to the overhead position, when it is dumped out onto the machine conveyor (Figure 12) The machine is provided with a troughed belt conveyor, which transfers the muck from inside the cutterhead back through the main beam to the rear of the machine. From this point, muck is transported by mine cars or belt conveyor through the tunnel.

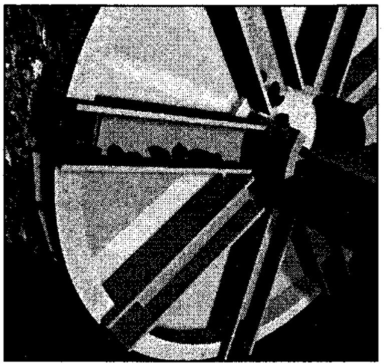


Figure 12. TBM buckets transferring muck to conveyor.

When the rock conditions are not suitable for an open type TBM, shielded TBMs are used in fractured rock conditions where the ground does not stay open after a certain time without any type of support.

With a single shield machine as shown in Figure 13, boring and lining installation takes place in sequence. This means after each boring cycle the machine has to stop and a new ring must be installed. The lining is used as an anchoring station to propel the machine forward during boring. Complete lining rings are installed inside the shield by a segment erector. After completion of each boring cycle, the last installed ring comes out from the rear end of the shield and the machine stops to install the next ring.

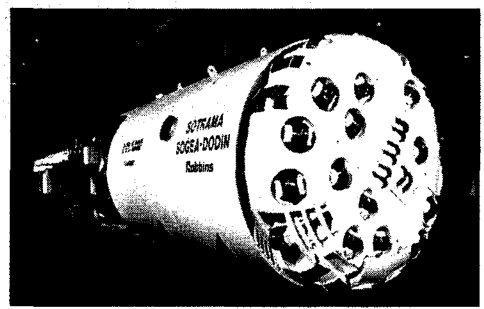


Figure 13. Single-shield TBM.

Another type of shielded machine is a double-shield one, as shown in Figure 14. In hard rock condition, the thrust cylinders push against the grippers, which are located in the rear shield. At the same time, a new ring installation can be performed inside the tail shield, if necessary. This allows the machine to be used in a continuous operation. If the tunnel walls fail to withstand the gripping pressures, such as in unstable ground conditions, the machine has the capability push off against the installed lining, instead. In this scenario, a double shield machine operates very much like a single-shield machine.

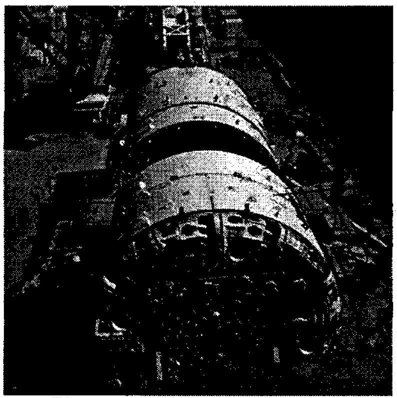
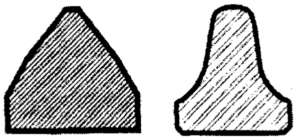


Figure 14. Double-shield TBM.

Disc cutters are almost exclusively used on hard rock TBMs. Until about two decades ago, disc cutters utilized on TBMs featured a V-shaped edge profile with an included angle varying from 60 to 120 degrees (Figure 15a). Although this profile provided for high rates of advance when the cutter was new, its performance was found to drop rapidly, as edge wear developed and the rock-cutter contact area became larger. To ensure a more consistent cutting performance with increasing edge wear, the so-called constant-cross section (CCS) cutters were developed (Figure 15b). The CCS cutters are designed to maintain a more or less constant profile as edge wear occurs. This means the machine performance does not decline as rapidly with cutter wear. These advantages have led to the CCS cutters becoming an industry standard in TBM tunneling.



(a) (b)

Figure 15. Disc cutter ring profiles (a) V-shaped (b) CCS.

Since their introduction, disc cutters have steadily grown in size from about 305 mm to 483 mm cutters (Figure 16). For the same thrust load on the cutter, increased diameter causes a reduction in the depth of cutter penetration into the rock because of larger cutter footprint area. However, larger cutters provide for higher bearing capacity, which more than offsets the performance loss brought about by the wider cutter-rock contact area. In addition, larger cutters rotate slower for a given machine rpm, which means less heat generation during boring. They also contain more cutter material to wear out before replacement becomes necessary, again contributing to longer ring life.

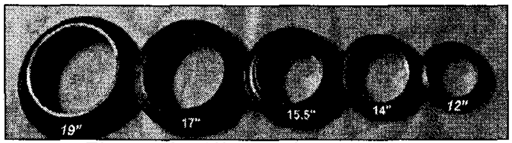


Figure 16. Different Ring Diameters.

Cutters are mounted on a TBM cutterhead at a steadily increasing distance from the center of rotation (Figure 17). The last cutter determines the radius of the tunnel cross section due to its high angled position. Cutter spacing is more or less constant in the face area and gradually decreases towards the gage.

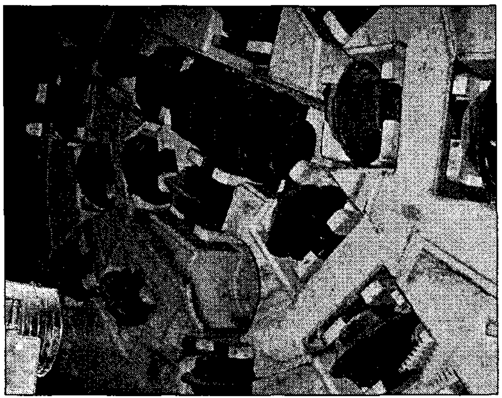


Figure 17. Allocation of disc cutter.

A shallow flat face profile is most commonly used on both new machines and modified older machines (Figure 18). The smaller radius at the gage area brings up the shielding very close to the excavated area. Flat shallow profile also requires lesser number of cutters compared to the other cutterhead profiles. Further, this profile is much more suitable for modification to other diameters. Disc cutters used in this type of cutterhead profile are backloading cutters; which provides a big safety advantage in unstable ground conditions.

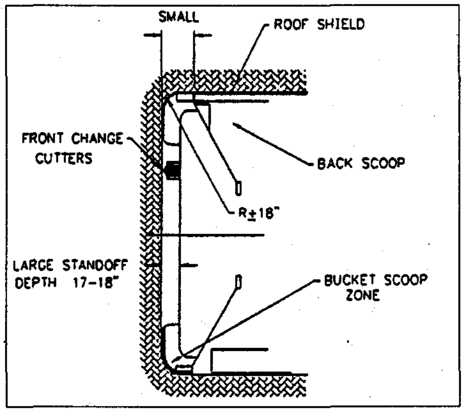


Figure 18. Shallow flat face cutterhead profile.

Slurry TBMs

In a slurry TBM, the face is supported by a clay suspension, which is usually a mixture of water and bentonite. The type of slurry mixture depends on the particular ground conditions in which the tunnel is to be excavated. Figure 19 illustrates the application range of slurry TBMs as a function of the particle size distribution of the ground. Slurry TBMs are mainly used in non-cohesive soil conditions. Bentonite serves both as a face support and conveying medium. In clay type soils, the use of bentonite is not necessary and water may be sufficient to provide the necessary face support, as well as transport the excavated material.

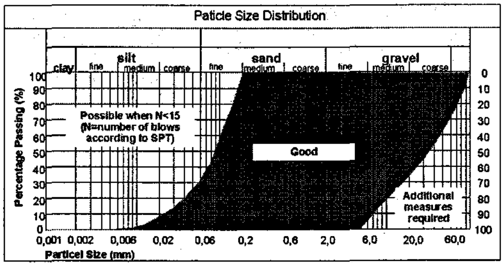


Figure 19. Application range of slurry TBMs.

As shown in Figure 20, the excavated material flows through the opening of the submerged wall into the rear chamber and through a centrifugal pump out of the tunnel and into the separation plant. In principle, the pressure at the tunnel face is determined by the volume balance between the supplying line and discharge line, as well as the excavated material at the tunnel face. The face pressure control can be achieved by an air bubble in the upper part of the working chamber, which is regulated by an automatic compressed air regulator. Thus, changes in the density of the suspension can be quickly compensated for in order to keep the face pressure more or less constant.

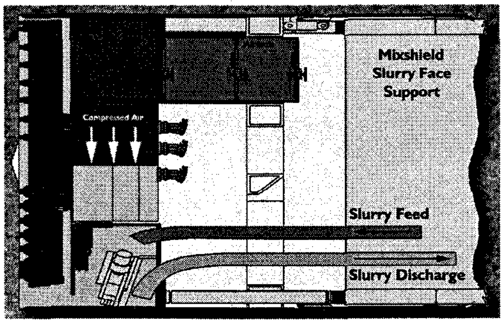


Figure 20. Operation of a slurry TBM.

A major advantage offered by a slurry TBM in comparison to the EPB TBM is the use of a stone-crusher at the invert area to crush the boulders before ingestion into the cutterhead chamber (Figure 21). This feature enables the slurry TBM for more effective operation in mixed geology and glacial soil formations.

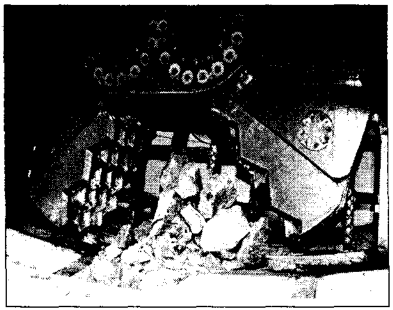


Figure 21. Slurry TBM crusher.

In sticky ground conditions, such as clayey soils, material accumulation can occur around the center area of the cutterhead. This problem can be remedied by the use of a micro machine at the center with high cutterhead speed and its own slurry circuit. This allows the shearing speed between cutterhead and excavated material to be significantly increased, which in turn, helps loosen up the sticky material. An added benefit of utilizing a micro machine in the center is the reduction in cutterhead torque requirements.

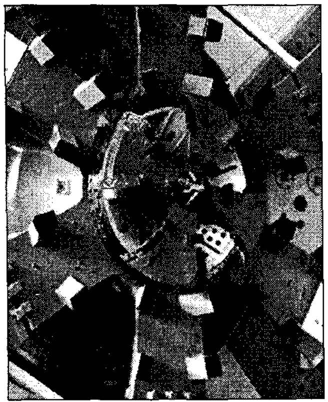
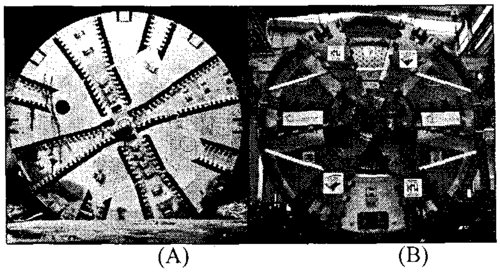


Figure 22. Micro machine at the center of a slurry TBM.

The cutterhead configurations used on slurry machines include closed and open types, as shown in Figure 23. Closed cutterhead generally works better in sandy ground due to its face support capability in case of personnel entry requirements into the cutterhead chamber. In ground containing boulders/cobbles, the open cutterhead allows the boulders to pass through the crusher located at the invert of the cutterhead. For personnel entry into the face area, the open type cutterhead can be equipped with additional mechanical face support devices to provide additional stability at the face during cutter changes or any other maintenance.



(A) (B)

Figure 23. Cutterhead types for slurry machines (A) closed (B) open.

One of the biggest disadvantages of slurry machines over EPB is the requirement of a separation plant on the surface for cleaning up of the mixture before pumping back into the slurry circuit. Especially in congested urban areas, lack of adequate space for slurry plant location may present difficulties for the planned use of a slurry TBM. The requirement of a slurry plant also adds to the cost of equipment. However, despite this advantage, in mixed and varying soil conditions, especially with the presence of large boulders, slurry TBM may emerge as the only option for successful tunneling.

EPB TBMs

EPB technology principally relies on the use of the excavated ground as the supporting medium in the excavation chamber (Figure 24). Under ideal conditions, the excavated material extrudes through the openings of the cutterhead towards the screw conveyor. The screw conveyor in turn discharges the material onto a belt conveyor located behind the machine (Figure 25).

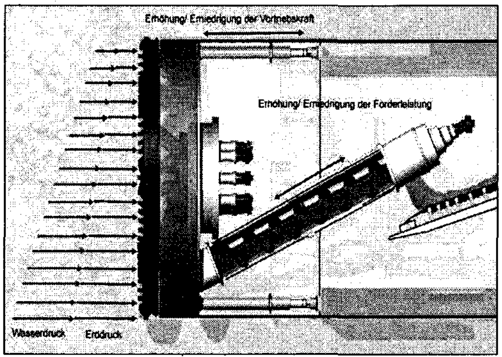


Figure 24. Operation principle of an EPB.

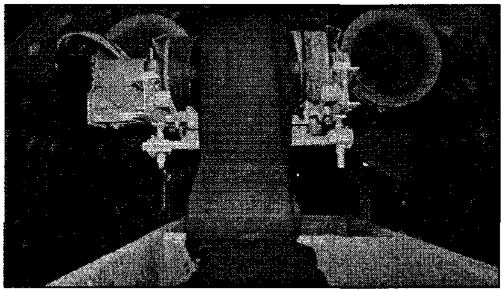


Figure 25. Excavated material being discharged by the conveyor.

In order to use an EPB machine most efficiently, the excavated material should have more or less the following properties to serve as support medium:

- Good plastic deformation
- Pulp to soft consistency
- Low inner friction
- Low permeability

Typically, no ground material possesses the characteristics to meet the properties described above. Thus, the material has to be conditioned. Soil can be conditioned with (1) water (2) bentonite, clay or polymer suspension or (3) foam. Especially the usage of foam has been proven to increase the application range of an EPB machine in non-cohesive ground, as shown in Figure 26.

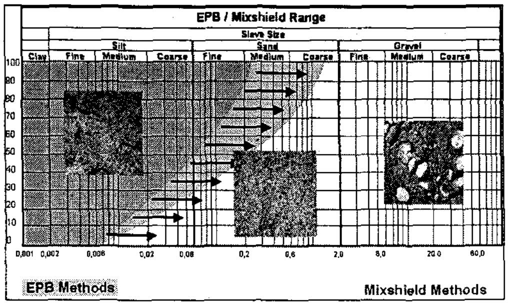


Figure 26. Application range of an EPB machine.

The application of foam creates artificial cohesion characteristics in non-cohesive, grainy materials and also reduces the permeability of the excavated material. Figure 27 shows the effect of foam in a non-cohesive material.

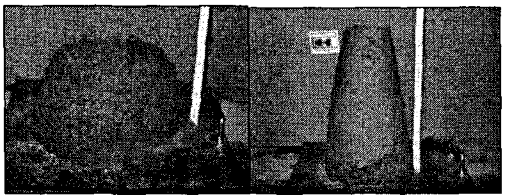


Figure 27. Soil conditioning left w/o - right with foam.

The foam on an EPB is simply applied through the cutterhead, as shown in Figure 28, in order to change the characteristics of the ground by filling the voids with foam bubbles.

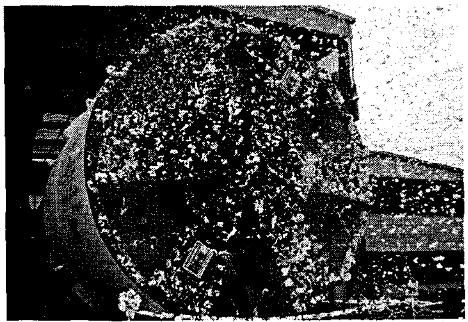


Figure 28. Application of foam through the cutterhead.

EPBs can be fitted with different cutting tools and cutterhead designs depending on the ground conditions and the existence of boulders. A cutterhead equipped with soft ground tools and hard rock disc cutters generally works well in boulder excavation if picks or chisel type cutters are recessed behind the disc cutters (Figure 29). Such a cutterhead design is also suitable for mixed-face conditions resulting from materials with significantly different properties and excavation characteristics. Figure 30 shows a good example of mixed-face conditions where boulders are present in a soft clay formation.

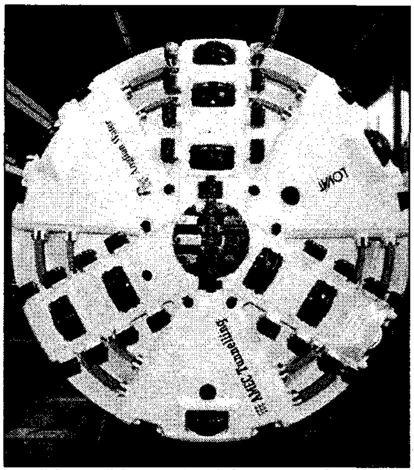


Figure 29. A mixed face cutterhead.

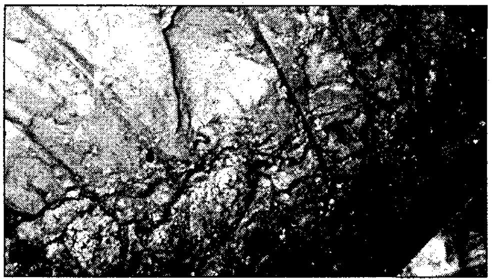


Figure 30. A mixed face condition.

If the tunnel is anticipated to be excavated in soft material with no boulders present, a cutterhead fitted only with chisels or blades may suffice.

Machine Operation and Control

Over the years, both the hard rock and soft ground TBMs have become highly automated with continuous monitoring of various machine functions and operational parameters. Today, the TBM operator is provided several screens displaying all machine and back-up system operating parameters in an environmentally controlled room (Figure 31). Through extensive diagnostic monitoring, any component malfunctions are readily recorded and displayed for easy trouble-shooting. Automatic control of various machine functions can be executed to increase operator efficiency and to achieve the most efficient machine operation. The recorded operational data can be readily analyzed to establish optimal machine operation so that higher advance rates can be realized. The recorded machine data can also serve as a basis for more efficient design of future TBMs

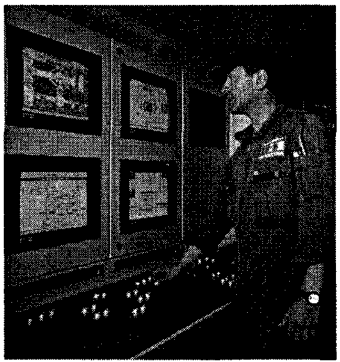


Figure 31. Modern TBM operating cabin.

Tunnel support

Roof bolting is mainly used on open type TBMs. The mechanized roof bolting takes place behind the cutterhead support. A typical roof bolting system consists of two drilling units for the drilling and installation of rock bolts during the boring cycle. These are mounted on either side of the TBM outer structure (Figure 32). The drills can be mounted on articulated positioners and slides, which allows bolts to be installed in the area between cutterhead support structure and the side grippers.

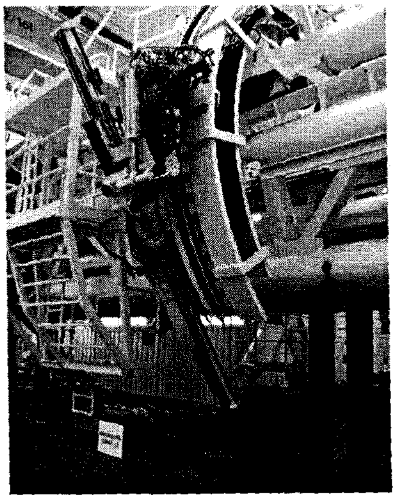


Figure 32. Roof bolters on TBMs.

Ring beams are often specified and required for temporary support of unstable ground in tunnels excavated by TBMs (Figure 33). Ring beam type (wide flange, U or channel profile) and spacing are usually specified by tunnel design and are generally placed in conjunction with rock bolts, mesh, lagging, and shotcrete. Installation of steel beams is performed by a mechanical erector, located behind the gripper assembly.

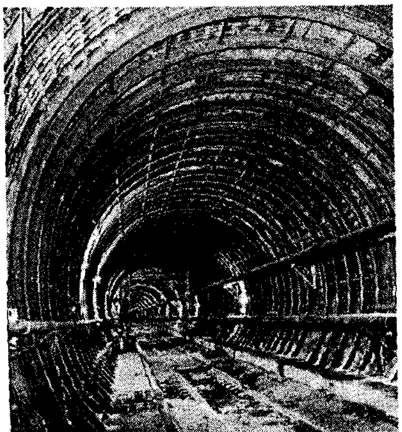


Figure 33. Ring beam support in TBM excavated tunnel.

Shotcrete application during TBM operation normally takes place behind the machine where space allows for proper implementation. In bad ground conditions where shotcrete may be required immediately for ground stabilization, the TBM is stopped and all the machine parts are covered with plastic covers for protection from rebound materials. Convenient work platforms on a TBM for men and equipment can enhance shotcrete quality while reducing rebound and machine downtime. On modern TBMs, shotcrete is applied by using a shotcrete robot (Figure 34) in order to provide more uniform thickness and less rebound.

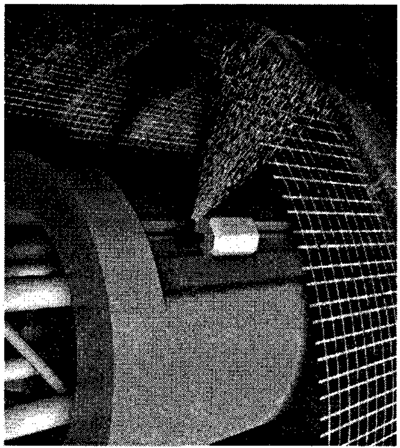


Figure 34. Shotcrete robot.

Conclusions

The TBM technology has experienced remarkable growth and improvements since the introduction of the first successful TBM in 1950's. Machine reliability and performance has continually improved with significant technological advancements in design and materials technology coupled with a better understanding of machine-ground interaction. The size of tunnels, which can be successfully excavated with TBMs, has dramatically increased. Today, TBMs are able to drive large diameter tunnels which were not considered technically feasible only a few years ago. Plans are currently underway to build TBMs to excavate tunnels in the 15-16 m range.