Tunnel Boring Machines

Tunnel boring machines (TBMs) are used to excavate tunnels in virtually all types of ground and under widely different physical conditions. This chapter covers hard and soft rock TBMs with full-face rotating heads and their development from soft ground shields. Roadheaders (boom headers) are also discussed here because of their growing role in the softer rock tunnels and caverns. The innovative Ranging Mobile Miner, which combines some of the advantages of the roadheader and the TBM and can be used in harder rocks, is also covered.

The functions of a TBM are simple enough:

- To excavate the ground
- To remove the material excavated
- To maintain line and grade of the excavation
- To support the excavated tunnel temporarily until permanent support can be provided
- To handle adverse ground conditions

These five simple requirements become less simple when the necessary qualifying conditions are added. The functions must be performed:

- Safely
- Reliably
- Continuously for many months
- Through any and all ground conditions
- Quickly
- Economically

Throughout the development of TBMs, a term which implies a rotary action, designers have built on the successes and the failures of their predecessors. In recent years, there has been a great deal of healthy cross-fertilization between designs of machines for hard rock and those for soft ground. Today’s TBM is likely to have been designed specifically for the anticipated ground conditions and is likely to use technology from both hard rock and soft ground machines.

A TBM is subjected to heavy stress and much abuse during its service life. It is worth reflecting that a typical hard rock TBM may be called upon to cut through a wall of rock considerably larger in area than the wall of an average room, the wall being made up of rock of up to 10 times the strength of normal concrete. It must do this steadily, day and night, for many months, perhaps under corrosively saline water inflows, and almost certainly, at some point, through uncooperative ground. Only the state of the art in metallurgy and mechanical design can create a machine that can accomplish this.

HISTORICAL DEVELOPMENT

Like many other technical developments, the TBM was designed in concept by men of genius long before the technologies of metallurgy and motive power were advanced sufficiently to meet the challenges the designs imposed. In the period starting in the early 19th century, numerous tunneling machines were built, largely in the United States and Great Britain, many of them with features that can be recognized in the modern TBM. Before that time, soft ground was excavated and supported by hand mining methods, then from the protection of a shield, then from increasingly mechanized shields. The rock tunnels were excavated by explosives set in holes drilled into the face. Subaqueous tunnels in both rock and soft ground were not attempted until the early 19th century, and the poor success rate led to the development of the shield, and its subsequent mechanization into a TBM.

The history of TBMs started with soft ground shields of the type developed by Marc I. Brunel (the senior Brunel) and J.H. Greathead in England. These shields progressed by breaking the excavation into small compartments excavated by hand. The first Brunel shield, patented in 1818, excavated these compartments and advanced the shield in a spiral pattern, with lining segments following in the same spiral. The shield did not rotate, but the spiral arrangement of...
the head meant that the miner excavated along a spiral path at right angles to the direction of the tunnel. Since the miner was the cutterhead, a case could be made that this was a rotating head "machine," but the verdict is best left to the reader. The first subaqueous tunnel under the Thames at Rotherhithe may have been started in 1827 using one of two Brunel designs patented in 1818, but it was completed nine years later by a newer Brunel-designed compartmented shield, and one with no hint of rotary action in its operation. The completed tunnel lay idle for many years until the dawn of the railway age put it to work, a function it still performs well 160 years later.

The coming of the railway age was a great stimulant to tunnelers. The next two shield tunnels were both successes, at least in execution, and were built concurrently in New York and London in 1869. In New York, A.S. Beach, editor of the Scientific American, drove a length of 8-ft diameter tunnel to promote a pneumatic railway. Beach used a circular shield that advanced in one piece, shoved forward by hydraulic jacks thrusting against a brick lining. The shield operation was a success, but the project did not go further. The hydraulic jacks, used here for the first time, proved their worth. In London, a second crossing under the Thames, in clay, was driven in 1869 by a shield patented by P.W. Barlow in 1866 and 1868; J.H. Greathead was the engineer in charge. This shield, like Beach's in New York, was circular and segmented to offer greater protection to the miners against face collapse. The shield was moved forward by screw jacks, but this time thrusting against cast iron liners erected behind the shield. A lime slurry was used to grout behind the liner segments, another first. These shields gradually became more mechanized and exchanged features with the developing rock TBMs. But the first machine to incorporate a full-face rotating head was not to appear until 1882 in either soft ground or rock machines, and then in a rock that is softer than most rocks, and softer than some soft ground.

The first, and almost the only successful rock machine of the period, a machine that embodied many of the features of a modern TBM, operated in the soft chalk marl on each side of the Straits of Dover and later in the relatively soft sandstones of the Mersey River in northern England. These soft rocks were not too demanding on the metallurgists of the day and permitted the developers the opportunity to concentrate on the other aspects of the equipment. The chalk excavation was the first start of construction of an English Channel tunnel in 1882. The machines were the Beaumont/English machines, designed by two officers of the Royal Engineers and put to work on each side of the Channel. Until political pressure stopped the work, the machines excavated 7-ft diameter tunnels at the very respectable rate of 50 ft per day for the final 53 days, with peak rates of over 80 ft per day. The unlined tunnels were still standing almost a century later, when they were crossed by the service tunnel bore of the new Channel Tunnel.

On this and the Mersey Tunnel projects, the soft rock meant that the demands on the cutting steels were not too heavy, and the tunnel diameters were small enough to permit the use of compressed air motors, the exhaust from which supplied relatively fresh, cold air to the working face.

In the United States, several machines had been built earlier. One was patented by John Wilson as early as 1851. This machine cut an annular slot a foot wide and of unspecified depth around the perimeter of the Hoosac Tunnel East Portal in Massachusetts before being withdrawn. A second machine, by Haupt, was tried at the West Portal in 1857, this time attempting to drive an 8-ft diameter pilot heading. Both these attempts in the hard igneous rocks of New York and New England were technical and commercial failures. They were in honorable company, however; several contractors using the conventional methods of the day were bankrupted before the tunnel was completed. These early endeavors remain as testimonies to men of vision and to the entrepreneurial spirit, which in later generations produced the successful machines of today.

Features now found in the modern rock TBM were being developed in soft ground TBMs. The demand for more and more underground rail lines in London, and the presence of the London Clays under the city, led to rapid development of mechanized shields. In 1893, J.J. Robins patented a shield with a full rotating head equipped with drag picks, hydraulic jacks thrusting against cast iron rings, and a mucking system employing an endless chain belt to remove the spoil. The patent drawing even appears to provide for circumferential seals between tailskin and segments, such as are necessary to operate under external groundwater head. There is no record that the machine was built. It had a weakness in that the cutterhead drive was located close to the axis of the cutter wheel, where it would have been subject to heavy torque loading. This weakness was shared by a successor, the Price Shield patented by J. Price in 1896. After modification of the drive to turn the head closer to the periphery, the machine was a success. The machine was modified and developed further, and Markham and Co. Ltd. began commercial production of the unit in 1901. The soft ground TBM had arrived.

A new era in rock tunneling began in the 1950s, when James S. Robbins, then of Chicago, designed and built a machine that operated successfully on the Oahe Dam project in South Dakota in 1952. It drove a 26-ft-diameter tunnel through faulted and jointed weak shale of 200 to 400 psi compressive strength. Cutterhead horsepower was 400, and thrust 50 tons. This and a similar machine supplied in 1955 drove 22,500 ft of tunnel, reaching maximum rates of 140 ft per day and 635 ft in one week. The machine drew considerable attention, but it had performed only in soft rock. Robbins then achieved notable success when one of his machines drove a 10-ft, 9-in. diameter tunnel in Toronto through limestone, sandstone, and shale with strengths of 8,000 to 27,000 psi. This machine was the first to be equipped with rotary disk cutters. It had 24 cutters, a cutterhead horsepower of 340, and a thrust of 157 tons. The performance of this machine drew worldwide attention and initiated a period of in-