B. Maidl, L. Schmid, W. Ritz, M. Herrenknecht

Hardrock Tunnel Boring Machines

Ernst & Sohn
A Wiley Company

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o. Prof. Dr.-Ing. Dr. h. c. mult. Bernhard Maidl
Ruhr-Universität Bochum
Fakultät Bauingenieurwesen
Lehrstuhl für Bauverfahrenstechnik, Tunnelbau
und Baubetrieb
44780 Bochum

Cover picture: Gripper TBM for the Gotthard Base Tunnel, Switzerland

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Preface

"... I have discovered methods for tunnels and engulfed secret ways, which are excavated without any noise, in order to reach predetermined locations, even if they have to be dug under ditches or under a river."

"... I have noiseless methods to dig tunnels and winding secrete catacombs in order to reach a pre-planned place, even if they have to be built underneath ditches and rivers."

(Leonardo da Vinci, 1452–1519)

Leonardo da Vinci is considered to be one of the greatest inventors of all times. His revolutionary and futuristic construction plans e. g. in aviation and in the construction of canals and bridges were ridiculed during his time. Many of his discoveries were later 're-invented' at times when they were actually necessary.

A horizontal drilling machine cannot be found among Leonardo's known and published sketches, but he elaborated extensively about their usage and advantages in the construction of shafts. In his writings one can find descriptions of the method of drilling horizontal or vertical shafts, which means that he had already plans for useful applications in this field before Agricula, Brunel and all the following patent holders.

The drilling of tunnels has a long history. First patents were already distributed in the beginning of the 19th Century, but it took almost another century until a similar machine had drilled a longer distance through mountains. There were several reasons for this delay. Among them were ineffective mining tools, which were too soft, but above all it was the lack of sufficient energy sources at the workplace. In those days movable steam engines, even hydraulic devices for blasting rock formations were in use, but those techniques were not effective enough to dig a tunnel through an entire mountain.

Nowadays TBM tunnelling gains more and more significance in hard rock formations even with larger diameters. The number of substantially longer tunnels as well in road and rail traffic, as in the areas of supply and waste are constantly on the rise; not only are those projects worth mentioning like the Alpine tunnels that are in process or in developmental stages, but also those subterranean tunnels underneath straits, which will be realized in the future. Those procedures are still considered as spectacular. Bernard Kellermann wrote about a similar project in his utopian best seller 'The Tunnel' (published in 1921), describing the construction of a railway tunnel connecting Europe with the North American continent by means of four drills.

The varying usage of open tunnel drills with grippers will be extended from that for smaller or medium diameters to larger, which will be effective also under mixed geological circumstances. Those mixed geological circumstances have already led to an enormous push in the development of the shield machines and prefabricated tunnel linings. Open hard rock machinery has no or only a short protective shield and as a result, its usage is rather limited under difficult geological circumstances. Currently there is a development of open hard rock machinery on the way, with the main focus on securing the area behind the drill head and advanced safety. The safety systems, with shotcrete, anchors and plates, which where developed for the traditional construction of tunnels are not of much use for continuous boring with Gripper-TBMs. Still, one cannot foresee if there are modifications of existing procedures possible or if one has to find completely new ways of dealing with these problems. In addition there is further demand for refining the use of tunnel bore machines in high altitude with high pressure.

The goal of the authors, Maidl, Schmid, Ritz and Herrenknecht was to accumulate existing knowledge and experience, to define requirements of use and to present as well as to encourage potential developments. This endeavour requires an interaction of Science and Practice at the highest level.

I am grateful to the entire team of collaborators, primarily, Leonhard Schmid, without whose contribution this book would have never been written, as well as, Martin Herrenknecht and Willy Ritz for their work on specific chapters of this book. Hereby I also acknowledge the support of the associates of my co-authors and the companies for providing the most current information. Furthermore I like to express my gratitude to Gerhard Wehrmeyer and Marcus Derbort for their coordination and detailed analyses, as well as the collaborators from the chair, who were involved in the writing of additional articles, Ahmed Karroum and Volker Stein. Also many thanks to the staff members from the engineering office of Maidl/Maidl, Ulrich Maidl and Matteo Ortu and my technical assistant, Helmut Schmid for his expert draftsman ship, Christian Drescher for his typing and my secretaries, Brigitte Wagner and Ruth Wucherpfennig, for their varied assistance and also to Gerhard Wehrmeyer.

February 2008 *Bernhard Maidl*

Contents

1 Historical Development and Future Challenges

Tunnelling developed rapidly during the industrialisation at the start of the 19th century with the building of the railway network. In hard rock, this was by drilling and blasting. The first stage of the developing mechanisation of tunnelling therefore was the development of efficient drills for drilling holes for the explosive [96]. There were also attempts to excavate the rock completely by machine.

The story of the development of the first tunnel boring machines contains, besides the technically successful driving of the Channel Tunnel exploratory tunnels by Beaumont machines, many attempts, which failed due to various problems. Either the technological limits of the available materials were not observed or the rock to be tunnelled was not suitable for a TBM. The early applications were successful where the rock offered the ideal conditions for a TBM.

The first tunnelling machines were not actually TBMs in the true sense. They did not work the entire face with their excavation tools. Rather the intention was to break out a groove around the wall of the tunnel. After this had been cut, the machine was withdrawn and the remaining core loosened with explosives or wedges. This was the basic principle of the machine designed and built in 1846 by the Belgian engineer Henri-Joseph Maus for the Mount Cenis tunnel (Fig. 1-1). The machine worked with hammer drills chiselling deep annular grooves in the stone, dividing the face into four 2.0×0.5 m high stone blocks. Although this machine demonstrated its performance capability for two years in a test tunnel, it was not used for the construction of the Mount Cenis tunnel because of doubts about the drive equipment. The compressed air to power the drills was to be provided by water powered compressors at the portal and fed to the machine through pipes. Considering the 12,290 m length of the tunnel, Maus expected that only about 22 kW of the 75 kW generated would arrive at the machine. It also turned out that the material used at that time could not resist the wear during tunnelling. The result would have been increased wear of the bits. Despite these problems, Maus assumed an average advance rate of 7 m, or considering downtime for cutter change, 5 m per day.

The American Charles Wilson developed and built a tunnel boring machine as early as 1851, which he first patented in 1856 (Fig. 1-2). The machine had all the characteristics of a modern TBM and can thus be classified as the first machine, which worked by boring the tunnel. The entire face was excavated using disc cutters, which Wilson had already developed in 1847 and applied for a patent for. The tools were arranged on a rotating cutter head and the thrust required for cutting was resisted by pressure sideways against the rock. In comparison with modern TBMs, the integration of a rotating mounting for the disc cutters stands out. The mounting plate was arranged with its rotational axis perpendicular to the tunnel centreline in the cutter head holder, which combined with the rotation of the outer cutting head to cut a hemispherical face. Wilson's machine underwent various tests in 1853. After advancing about 3 m in the Hoosac tun-

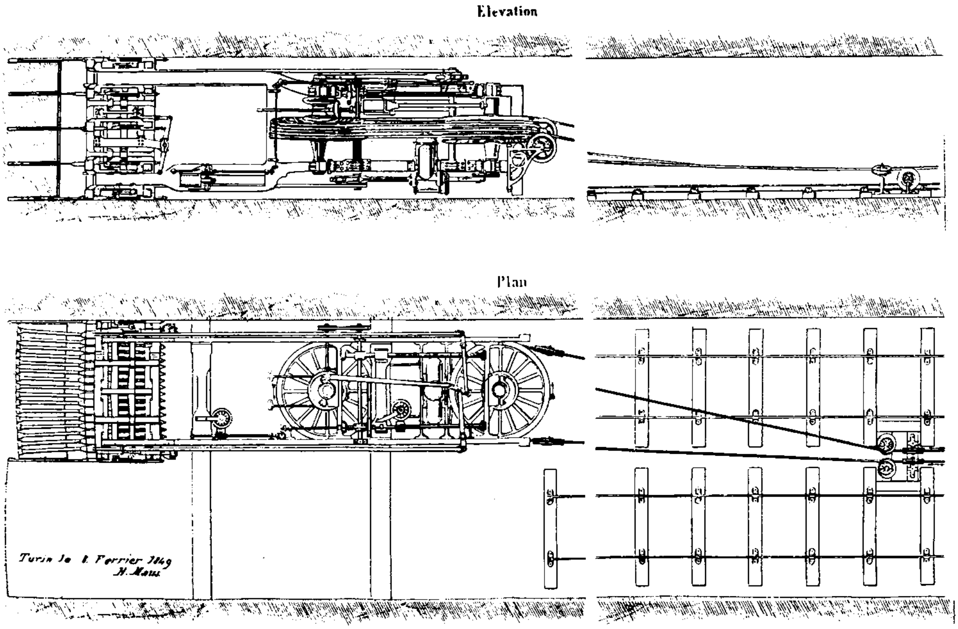


Figure 1-1
Tunnelling machine by H.-J. Maus, Mount Cenis tunnel, 1846 [159]

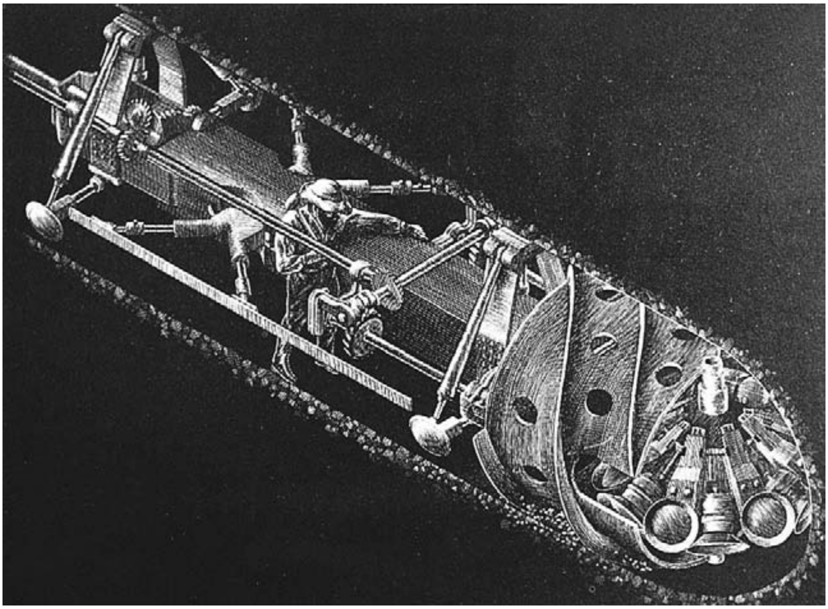
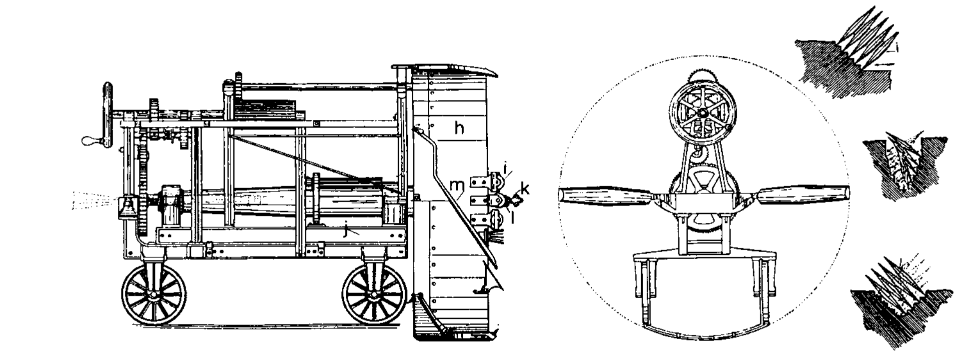


Figure 1-2
First tunnel boring machine by C. Wilson, Hoosac tunnel, 1853 [127]



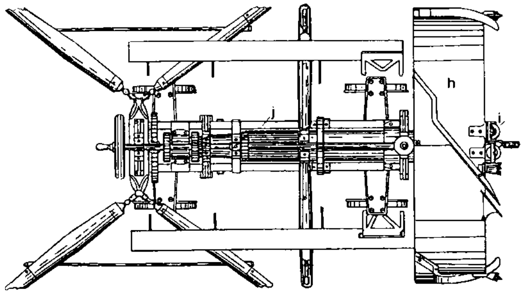


Figure 1-3
Further developed TBM by C. Wilson, U.S. patent No. 17650, 1875 [159]

nel (Boston, USA), the machine proved, because of problems with the disc cutters, unable to compete with the established drill and blast method.

After his experiences with the TBM at the Hoosac tunnel, Wilson applied for a patent in 1875 for an improved version of the machine (Fig 1-3). This was based on a completely new design of cutting head; no longer was the entire face to be excavated with cutting tools, but only an external ring and a central hole. This was to be achieved by mounting disc cutters at the outer rim and the rotational axis of the cutting wheel. After reaching the maximum cut depth, the machine had to be withdrawn to enable the remaining core to be loosened using explosives. The advantage was the precise profile of the excavation. This type of excavation with outer groove and central drilled hole proved to work well and was also used for other early tunnel driving machines like that of Maus, and this type of excavation has also been used from time to time since.

Also in 1853, the same year as Wilson was testing his first machine in the Hoosac tunnel, the American Ebenezer Talbot developed a tunnelling machine, which worked using disc cutters and a rotating cutting wheel. But this construction had the disc cutters arranged in pairs on swinging arms on the cutting wheel (Fig. 1-4). The combination of the rotation of the cutting head and the movement of the cutting arms enabled the excavation of the entire face. Talbot's machine failed in the first tests boring a section of diameter 5.18 m. Looked at with modern eyes, it is possible to recognise in the arrangement of the disc cutters on cutting arms parallels to the System Bouygues (see Fig. 3-36) tunnelling machines used in the 1970s.