TBM Full Face Driving - Recent Innovations

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Abstract

Full face tunnel boring machines (TBMs) have greatly advanced in technical capability and size during last years. They are being applied, increasingly, in difficult ground conditions such as poor quality of soil or rock, under high water pressure and with minimal cover.

Depending on its properties, the ground exposed during the excavation process will require no support, if the cohesion is sufficient for a stable surface, or require immediate mechanical support from compressed air or with a pressurized liquid, if the face is not stable by itself.

Of concern is the reliable stability of the face in complex ground conditions during the process of excavation and during interventions for maintenance, repair and tool replacement, when it is necessary for technicians to access the face.
The importance of ground support by means of a liquid has increased significantly: Therefore, means and methods are constantly being developed and recent innovations are reflected in this paper.

1. Size of TBMs

As early as 1984, a TBM with an outstanding diameter of 12,20 m started its drive on the Gubrist tunnel, in Switzerland. This marked the beginning of an impetuous development of TBMs regarding their size.

The request to construct a 2-lane motorway required an excavation diameter of more than 12 m. The favourable ground conditions – hard marl – on the alignment and cooperation between machine manufacturers Herrenknecht and Robbins facilitated this start.

Following that success, the size of TBMs grew steadily also for application in more or less cohesive soils. Part of the Grauholz tunnel in Switzerland had to be driven through glacial deposits with an 11,80 m Slurry-TBM, which had been converted into an open face TBM for the stretch through stable marls.
To underpass the river Elbe, in Hamburg, for a motorway through glacial deposits, a Slurry-TBM with a diameter of 14,28 m was brought into action. The machine was manufactured by Herrenknecht, and afterwards it was used in Moscow.
Only few years later, the manufacturer NFM / Wirth built a Slurry-TBM of 15,20 m in diameter to underpass the Greune Hart, a country site in the Netherlands.

Presently, “state of the art” TBMs have diameters larger than 15 m for the slurry type, and approximately 14 m for the EPB type. Delivery is in course for two Herrenknecht Slurry-TBMs, with a diameter of 15,43 m, to Shanghai, China

2. Operation Procedures

Besides the improvements of the mechanical aspects of Full Face Tunnel Boring Machines, the systematization of the operation procedures, based on physical and chemical knowledge, have developed significantly. This has led to the result that, nowadays, a controlled tunnel drive can be accomplished even in very unfavourable ground conditions.

2.1 FACE SUPPORT

A reliable and controlled tunnel drive with a TBM requires immediate and permanent support of the ground surface exposed by the excavation process. The support can be provided either by:

a mechanical support,

a support by compressed air, or by

a liquid such as a slurry, or by the conditioned excavated material.

An effective and reliable mechanical support presupposes a certain degree of cohesion of the ground and the absence of ground water. Otherwise, deformation of the exposed surfaces is unavoidable. The devices for support are mechanical construction elements.

An effective support by compressed air requires specific ground properties. Due to the variability of the ground, this is not always achievable. The low viscosity of air, which is 50 to 70 times lower than water, allows for an easy flow through the pores in the ground and adds to the sensitivity of a permanent compressed air support.

The development of TBM systems with a liquid support has resulted in TBM types with higher performance than of those which rely on compressed air or mechanical support.

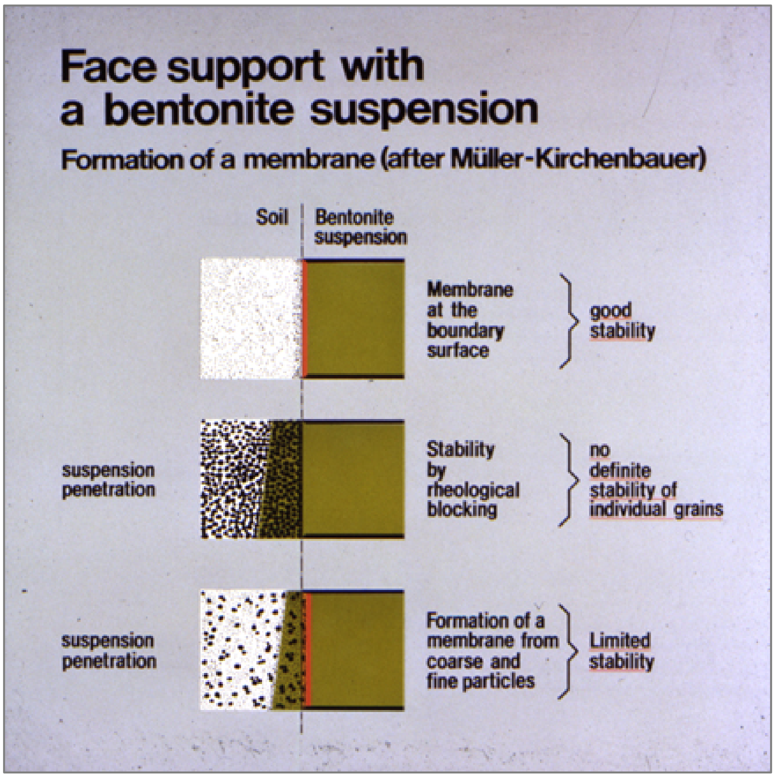
2.1.1 SUPPORT MEDIUM

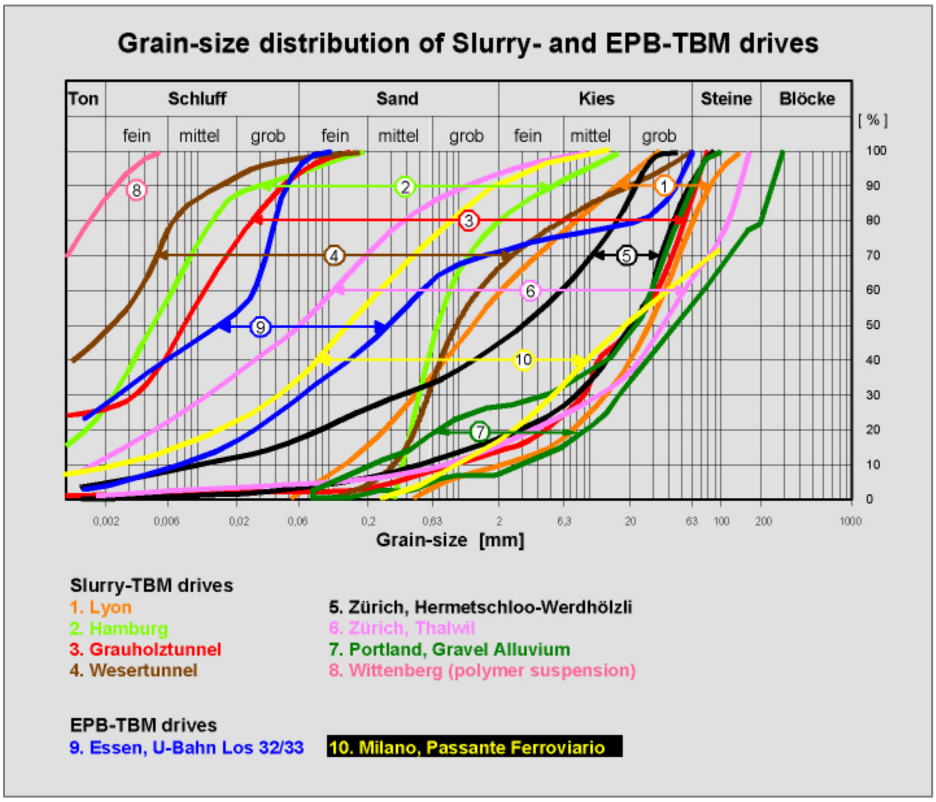
2.1.1.1 SLURRY

In Slurry-TBMs the support medium is a pressurized frictionless suspension. It consists of water and bentonite, a processed clay, which can filter out and settle on the surface of the exposed ground face to form a membrane, a more or less impervious layer, the so called filter cake.

Via this membrane, the support forces generated from the pressurized slurry are transferred onto the unstable face. The properties and the quality of this membrane influence the pore water pressure in the ground behind the face, affecting, consequently, the pressure gradient between the support pressure and the pressure in the ground (induced by earth pressure and ground water loads).

Additives, special polymers, can be added to the slurry, if the ground at the face is so pervious that the slurry penetrates into it without generating a membrane at the surface. With the application of specially designed mixtures, tunnels have been driven recently through grounds displaying extreme permeability. Figure 1 shows the application of Slurry- and EPB-drives through various ground conditions, specified by its grain size distribution.



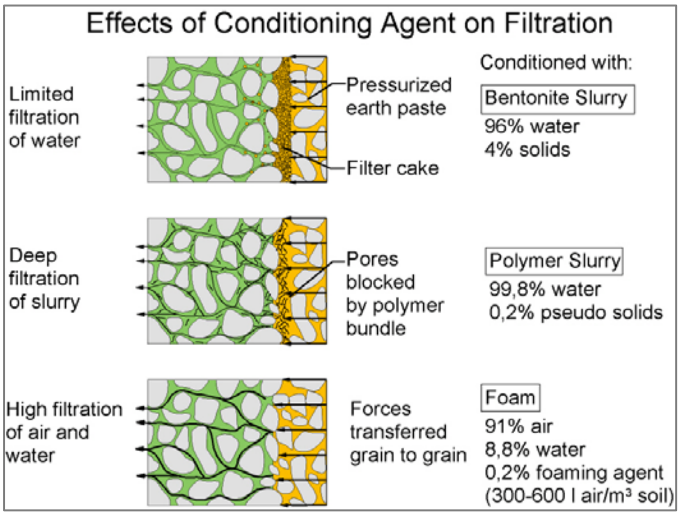


2.1.1.2 CONDITIONED EXCAVATED EARTH MATERIAL

Because the support medium on EPB-TBMs is the excavated material itself, it does not lend itself to a precise definition due to the variety of ground properties. Even when ground water is present, the properties of the support medium are, at best, those of a non-frictionless, high viscosity fluid. If the soil does not contain enough fine particles and the water inflow from the ground water is insufficient, additives have to be added to achieve fluid properties suitable for pressure transfer to the unstable face.

Mechanical elements such as mixing bars, mounted on the revolving wheel and at the stationary pressure bulkhead, mix the excavated material with the added suspension and additives to a homogeneous mass, the earth paste.

Different agents are added for conditioning, Bentonite slurry, Polymer slurry or Foam. Bentonite slurry or Polymer slurry have the same suspension content as for Slurry-TBMs. Foam however is an economic agent often used for conditioning excavated ground in EPB-TBMs. It consists generally of 91% air, 8,8 % water and 0,2 % foaming agent. The type and volume of the foaming agent have to be designed. They are variable, resulting in different properties. This has also a decisive influence on the time span until the foam-soil mixture in the working chamber of the TBM becomes unstable. Then, the air bubbles diffuse and accumulate in the top area of the working chamber. This effect starts after 10 to 50 minutes.

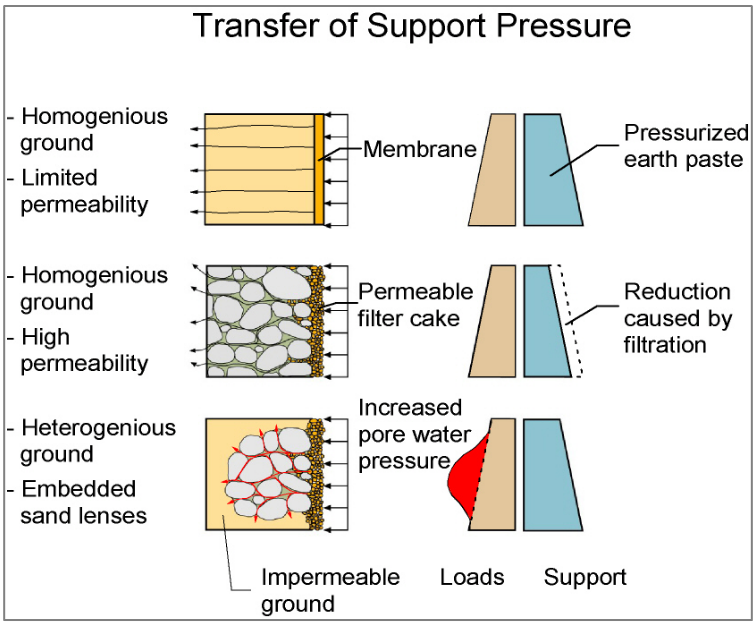


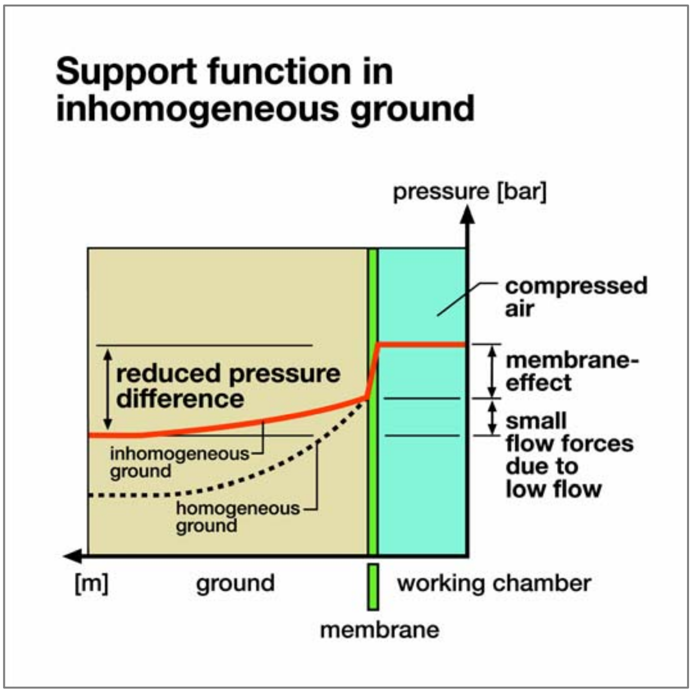
This concentration of air in the crown area reduces the support pressure in that sensible area and consequently causes over-excavation. The air diffusion, on the other hand, stiffens the muck and facilitates its transportation and deposition.

2.1.2 Transfer of Support Pressure to the Face

2.1.2.1 Transfer in Slurry-TBMs

In Slurry-TBMs, the support forces are produced by pressurizing the supplied slurry with regulated air compressors. This pressurized fluid will be pumped into the working chamber, (a closed room). Because of the friction-less pressurized liquid, the support forces are transferred directly onto the unstable face, via the out-filtered membrane at the face, the filter cake.
To maintain the predetermined pressure in the closed room, and also to compensate for volume differences of the pressurized slurry between inflow and outflow, an adjusted gas reservoir is integrated in the working chamber.
This system, a Slurry-TBM with the integrated gas-reservoir, has proved reliable in many projects. Tolerances of less than 0,1 bars for the support pressure are real. Actual developments of the slurry design have therefore widened the successful application in very pervious ground, such as the Portland CSO project, in the USA.





2.1.2.2 TRANSFER IN EPB-TBMS

In EPB-TBMs, the support forces are produced by the advance forces, which press the conditioned earth paste via the bulk head against the unstable face. The compressible, high viscosity material in the working chamber, make it difficult to determine the support pressure applied at the face. The imposed pressure is measured at the bulkhead by pressure cells. The distance between bulkhead and face is 1 to 2 m. The compressible earth paste transfers only a reduced support force to the face. A pressure reduction of approximately 1 bar is a reality. Together with the influence of the accumulated diffused air from the conditioning agent foam, the support pressure becomes uncertain, even unpredictable, and can not be derived from the values of the pressure cells at the bulkhead.

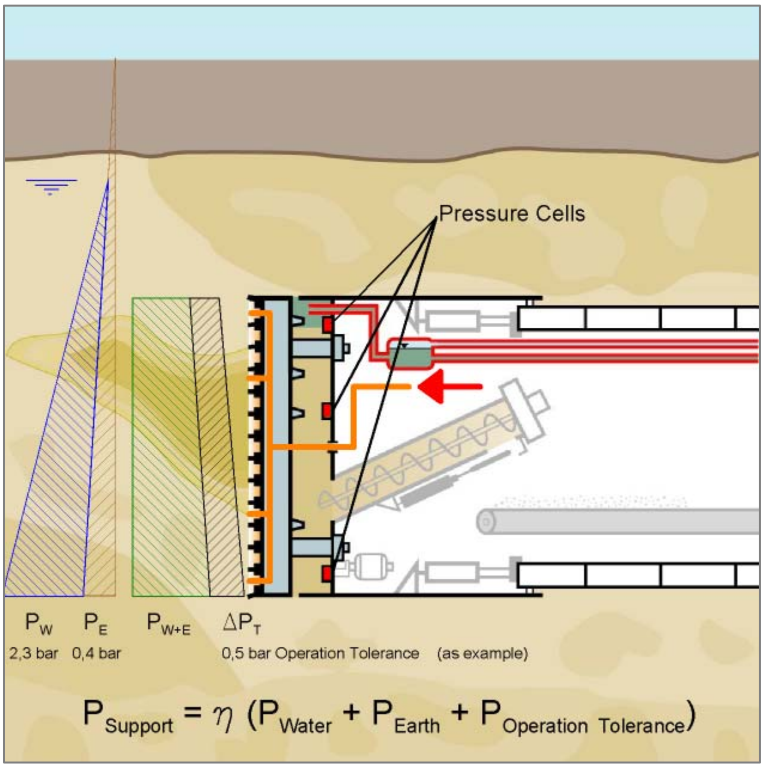
Reduced and uncertain support pressure in the crown area is the result of these affects. This causes over-excavation, which can not be detected, and consequently not compensated by the TBM operator.

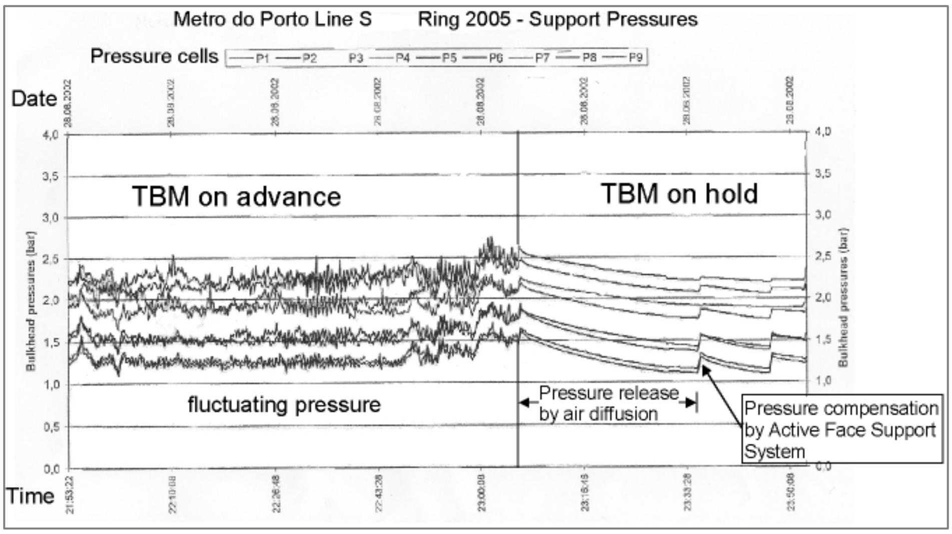
Aggravating this is the fact that, currently, all known means and methods to assess the exact volume of the excavated ground are not reliable, and therefore not suitable for the adjustment of the operation process by the TBM operator.

On the EPB-TBM operated in Porto, Portugal, in extremely heterogeneous ground, a special device was installed: the **Additional**

Face Support System, compensates automatically for a support pressure drop in the crown area of the working chamber, by injection of a predetermined pressurized bentonite slurry from a tank positioned on the back-up train. The tank is connected via pipes with the crown area of the working chamber.

This system operates automatically in the same way as a Slurry-TBM with the integrated gas-reservoir and is, consequently, as reliable. It has proven successful, and is installed also on the EPB-TBM in construction for an extension of the Metro lines, in Athens, Greece.





2.2 MAINTENANCE AND REPAIR

Lack of maintenance, in particular of excavation tools, often causes problems on TBM drives with liquid face support.

During interventions, access into the working chamber for inspection or repair must be provided under compressed air. This action requires special knowledge and experience with compressed air techniques, which is not available everywhere.

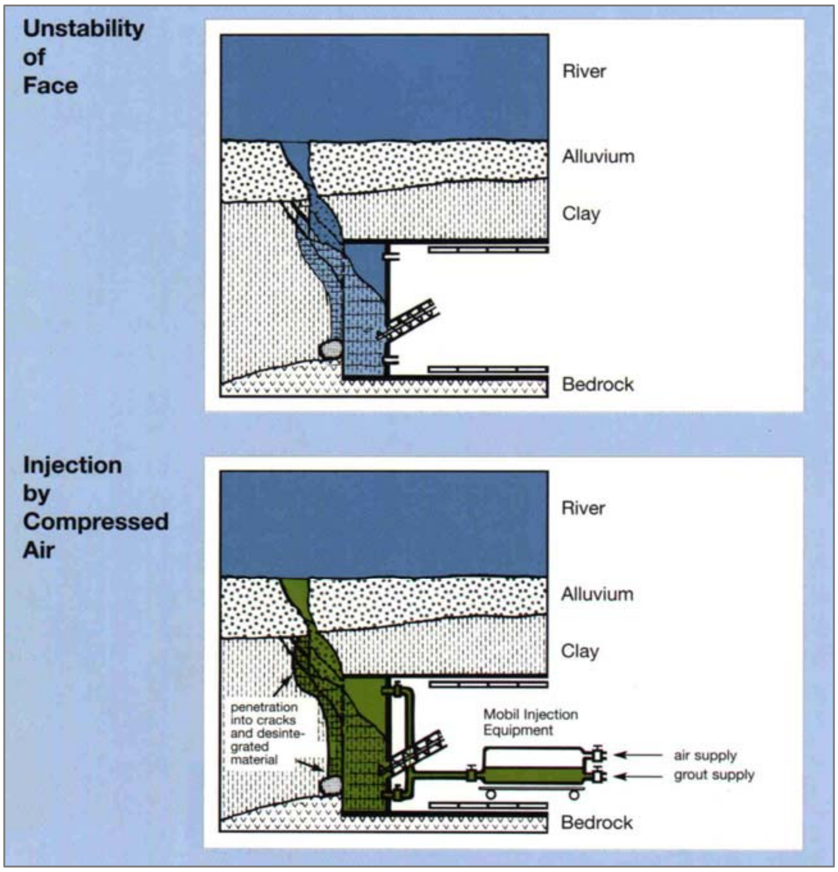
Therefore, some TBM management teams often shy away from systematic inspection and maintenance of excavation tools.

The consequences are fatal if the ground is abrasive. On several TBMs, the tools were completely worn down to the structure of the cutter head. Long lasting repair works were necessary to continue the drive.

On the Metro project in Porto, the consumption of the excavation tools of the 9 m diameter TBM summed up to one disc per running meter of tunnel, because of the high abrasiveness of the granite. Daily routine interventions managed the problem for an unimpeded tunnel drive.

At another project, the tunnel drive was stopped because of loss of excavation tools, as a result of ignored maintenance. With the disabled TBM, the ground was loosened and significant over-excavation was discovered. Long lasting underground repair work under compressed air conditions had to be envisaged. However, in that disturbed ground compressed air intervention failed because of air loss through the loosened ground.

The problem was solved by pumping pressurized artificial soil into the working chamber which penetrated, under pressure, into the disturbed ground. After 2 days of setting, the ground around the TBM was ready for repair works. Manual excavation of the artificial soil from the working chamber prepared the area for repair works.



Special care has to be taken regarding the membrane at the face. Out-filtered bentonite can provide a suitable filter cake only for a short time. It has to be replaced by shotcrete or quick-cement if long lasting compressed air support is necessary. The face has to be sealed as dense as possible to prevent penetration of air into the ground, which deteriorates the stability of the face. On some occasions large lumps of ground slid off the face after weeks of compressed air support, endangering the life of the workers in the working chamber.

2.3 Strict Management Program for Operation Procedures

The above mentioned examples demonstrate the essential requirements for a strict management program of operation procedures for any individual tunnel project.

It has to be based on the specific ground conditions and the proposed TBM technique. All relevant data for:

- the operation of the TBM,
- the face stability during drive and down time,
- the maintenance,
- the installation of lining and bedding in the ground must be elaborated for the total length of the drive.

3. TBM Drive under High Ground Water Heads

The impetuous developments of Tunnel Boring Machines have extended the span of successful application to projects under high ground water heads.

It is not only the high burden of the water head on the TBM construction which has to be sustained, but more so the difficulties to dominate safe techniques to enter in a working chamber for maintenance and repair work, under high pressure, balancing the high ground water head.

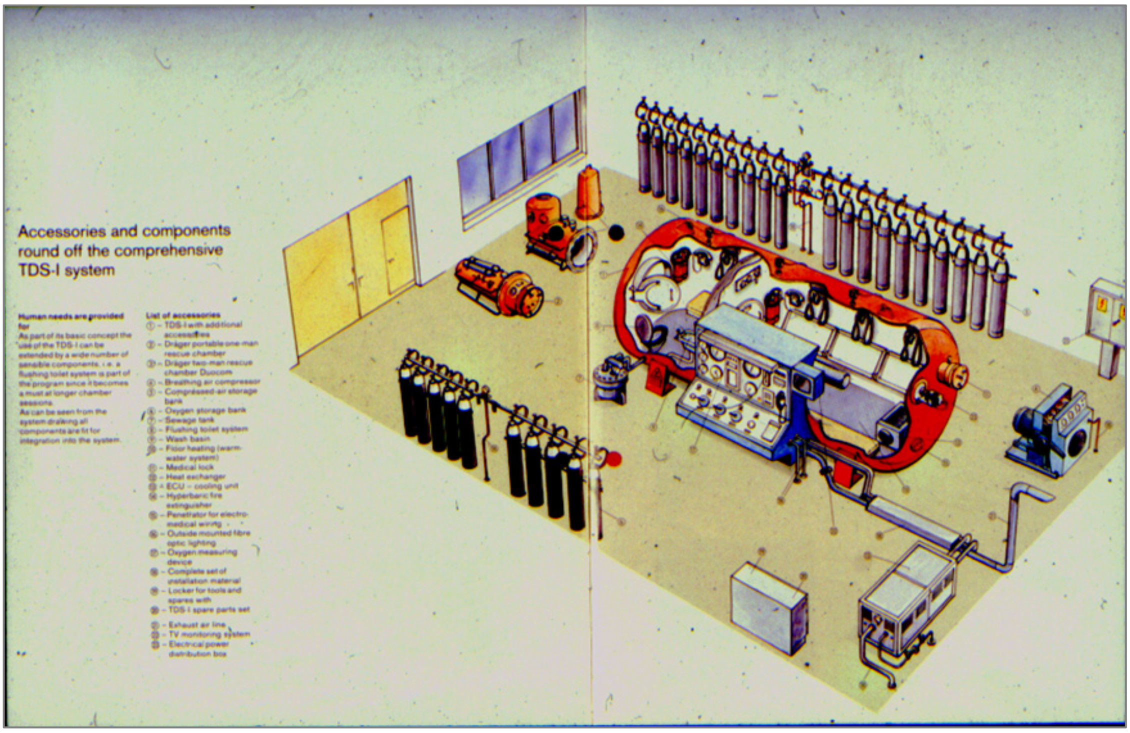
TBMs have been used, in general, for tunnel drives with ground water heads up to 4 bars, which allow workers to enter into the empty working chamber under compressed air. For special projects, such as the Elbe crossing and the Wesertunnel, in Germany, exceptions to these limits were granted to 4,2 and 4,3 bars, respectively, with imposed conditions.

Interventions under such water head could be performed while the workers breathed compressed air. Working time in the chamber was restricted to 80 minutes. Decompression required 2 hours, with additional oxygen supply.

For higher water heads, on other tunnel projects, the technique to work in a pressurized atmosphere received and adapted elements of diving routines. Actual tunnel projects have required or will require support pressure exceeding the tolerable regular compressed air limits. For instance, in St. Petersburg with 5,5 bars, or in the Westerschelde tunnel, in the Netherlands, with 6,4 bars, and more recently in Shanghai, with 6,5 bars. Several projects in the USA with 7 bars as in the Bright Water project, in the Seattle area,

or 10 bars in the Arrowhead tunnels in California, are in the design phase and challenging the tunnel boring technique.
All these projects apply elements and equipment with ocean diving technology. For short term interventions, and for inspection purposes, the working chamber is under ordinary compressed air pressure up to 8 bars, while the workers wear a special helmet through which a gas mixture consisting helium, oxygen and nitrogen is provided.

For longer interventions, and higher water heads, the application of saturation diving technique is an essential requirement, as used in the Westerschelde project.



4. CONCLUSIONS

The steady development of the mechanical aspects of TBM technique has achieved full face boring machines with diameters of more than 15 m.
Also, the intensive and detailed preoccupation with the operation procedure resulted in significant progress, expanding the feasibility of full face tunnel drive to extreme unfavourable ground conditions, as well as with very high ground water heads.

The operation of modern TBMs requires more and more a high standard of theoretical knowledge in the field of soil mechanics, applied physics and chemistry. For some fields, such as intervention under high water head, a specialist must be employed.

For the benefit of an optimal and safe use of the actual available TBM technology a strict management program of operation procedures will be a future essential task, which includes certainly substantial training programs for the management and the working force.