

Designing TBMs for subsea tunnels

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ABSTRACT: Recent years have shown great advances in the feasibility of long subsea tunnels. Projects such as the Channel Tunnel, the Stoerebelt Tunnel or the Bosphorus Crossing have pushed the boundaries of TBM tunneling technology and fueled the work on feasibility studies for even more challenging projects such as crossing the Qiongzhou or Gibraltar Straits. There are numerous geotechnical challenges such as wide variations of ground conditions, high operation pressures or long tunnel distances and finally geological uncertainties which must be solved in order to attempt such projects. Several operational challenges such as large muck quantities interventions under difficult conditions and long transport distances also have to be tackled. TBM manufacturer and construction industry have developed a number of approaches to these challenges which point into the right technical direction and have been proven successfully in recent experiences. Their further development will allow attempting several megaprojects which are currently under discussion.

Keywords: TBM, High pressures, Long distance, Subsea, Large diameter

1. Introduction

TBM technology has advanced greatly within the past decade. This has enabled the successful completion of projects which had been deemed impossible a decade earlier. Examples are the Bosphorus Strait Crossing in Istanbul, the Lake Mead Intake Tunnel in the United States or Hong Kong's Tuen Mun Chek Lap Kok tunnel.

Innovations among TBM suppliers have created the technology which was necessary to attempt these projects. Their active participation in planning from feasibility studies to operational aspects has led to a situation where the advantages of TBM technology can be maximized by designing many aspects of the projects around the TBM. Many processes and design

aspects have been transformed to suit the needs of successful TBM operation. As a benefit of this paradigm shift, it was possible to fully utilize the capabilities of innovations in TBM design. These specific developments such as accessible cutterheads, tool monitoring or seismic exploration systems have added immense capabilities and safety to traditional TBM systems and created the confidence required for planning the megaprojects of the future. Therefore, projects like the Qiongzhou Strait and the Gibraltar Strait have reached a point where technical discussions can take place near feasibility and the developments which are necessary before these projects can be attempted will be available in the foreseeable future. In fact many of the necessary systems are already under development and need to reach maturity or require further improvement. The key point is that the solutions lie within the range of today's knowledge.

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2. Technical Challenges

There are several challenges which have to be overcome by the industry to safely complete challenging subsea tunnel projects. With regards to TBM tunneling, these can be classified in two separate areas. Firstly geotechnical challenges which are specific to subsea projects and secondly operational challenges.

2.1 Geotechnical Challenges

The number of geotechnical challenges for subsea projects can be immense. Although individually they might not generally differ in magnitude from large projects on land, subsea tunneling poses a unique combination of challenges. While building tunnels in stable rock is feasible with traditional methods (NFF, 2009), heterogeneous ground conditions cannot necessarily be excavated economically. Mastering heterogeneous ground conditions over long distances, operating and maintaining machinery in high pressure environments and dealing with obstacles in the ground are some of the areas where innovations in TBM technology help overcoming geotechnical challenges.

2.1.1 Heterogeneous Ground Conditions

Tunnels crossing ocean straits, lakes and river deltas inevitably cross various geological formations. Typically there are sections governed by fluvial and marine deposits which bear a risk of clogging and require TBMs with active face support and soft ground excavation methods. Deeper tunnel alignments are often located through bedrock formations which require designing TBMs for hardrock excavation. Additionally these must deal with potentially high water pressures. The design requirements regarding excavation tool,

cutterhead design and material transport in such sections differ fundamentally from softground excavation. A TBM for subsea tunnels has to be balance those contrary requirements. Beyond the mere difficulty to master different ground conditions also dealing with geological uncertainty becomes important as the geological investigation and mapping is usually more complex and less complete than on land.

2.1.2 High Pressure Environments

As longer subsea tunnels lay in much deeper alignments than for example metro tunnels, the excavation technology has to be adapted to high face pressures. There are several fields in TBM tunneling which are strongly affected by pressure. Firstly the excavation technology itself: High water pressures rule out the use of EPB shields. Higher pressures change the behavior of the muck and foam conditioning. Therefore screw conveyors cannot safely dissipate pressures above about 8 bars. Maintenance and repairs is another field which is strongly affected by high pressures. Large TBM projects generally need maintenance work on the cutterhead and other components within the excavation chamber. The need for repairs can be minimized but it would be negligent to assume a project can be completed without any incidents which require manual work under pressure.

2.1.3 High Water Volumes Present

Oceans or large rivers are sheer unlimited reservoirs of water which can flood tunnels in a short time. In the past this has led to tunnels being flooded and lost. Therefore the dangers for men and machines are much higher than on land and must be dealt with caution. Fig. 1 shows the longitudinal cross section of the Lake Mead Intake Tunnel project. Varying

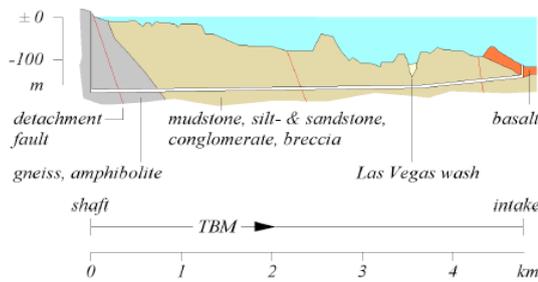


Fig. 1. Longitudinal Profile of Lake Mead Tunnel (Anagnostou, 2010)

ground conditions and high water pressures can be seen on the sketch and has been a mayor task during the execution of the tunneling works

2.1.4 Long Distances

Long tunnel distances mean greater requirements regarding wear and TBM design for allowing underground replacement of wear parts and repairs. While distance itself is not a geotechnical challenge directly, other geotechnical challenges grow over longer distances. Especially tunneling through long areas of extremely difficult geology poses great challenges to technology and operation.

Beyond those wear related challenges, also the logistics regarding mucking, ventilation and transports become more difficult with increasing tunnel length.

2.1.5 Man Made Obstacles

There are many known cases of TBM projects being delayed due to encountering unknown man made obstacles underground. Especially in harbor or strait areas there is an increased risk of encountering objects such as uncharted piles, drill casings or objects sunken into the sea. These objects can severely damage the cutterhead or other parts of the shield machine like the slurry circuit. Removing them inevitably means manual work in front of the cutterhead.

2.2 Operational Challenges

Planning and designing the operational procedures for long distance subsea tunnels differs in several points from tunnels under land as access is more restricted and the working conditions cannot be easily influenced and altered.

2.2.1 Maintenance and Repairs

TBM components can be grouped in several types regarding wear. Those exposed to the highest rate of wear such as the excavation tools are designed to be continuously replaced when worn out. For others as the cutterhead structure and hardfacing wear is tolerated up to a certain extent and the design takes into account that functionality is still guaranteed if wear occurs. With longer distances it becomes impossible though to build these components in a way to survive throughout a whole project without major repair work. For long hardrock tunnels there is usually a maintenance cavern every 5 to 10 kilometers which allows refurbishing the cutterhead. Another group of components is those which cannot easily be replaced or repaired within the tunnel. One such example is the maindrive. It must be designed and built to last for the whole project. Although it is generally possible to change a broken maindrive, it might not be possible under all conditions or in the specific location where the damage occurs. With longer tunnel distances, the risks associated with such technical failures magnify.

2.2.2 Work under Pressure

As outlined in the previous section, it is necessary to prepare for compressed air works. Especially for larger repair works this can be very time consuming

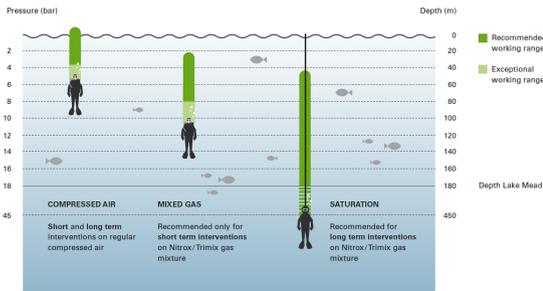


Fig. 2. Diving techniques for different pressures (Herrenknecht, 15)

as the permissible exposure time of workers are increasingly restricted with higher pressures while work productivity sinks. The latest guidance given in the ITA Report No. 10 by ITA Working Group No. 5 from February 2012 offers a better and safer framework to contractors and workers for applications of high pressure compressed air interventions.

2.2.3 Logistics

The sheer scale of large subsea tunnel projects makes them very demanding in terms of logistics. Muck transport becomes an issue as well as ventilation. Furthermore the added commuting times of the TBM team reduce shift productivity and ramp up personnel cost. Megaprojects such as the Channel Tunnel or the Gotthard Base Tunnel have shown that sophisticated logistics planning is necessary and proven that it is possible to overcome major obstacles regarding transport. Especially when local works such as building cross passages is limiting the number of parallel tracks and creates bottlenecks, careful planning of the transport operation is necessary. In recent years simulation techniques have been increasingly used to verify planning processes (Scheffer, 2014)

3. Innovative Key Technologies

There are a number of specific technologies which are crucial for the successful application of TBMs to large subsea tunnels. Past projects have proven their general feasibility and contribution to success. Their further development will push the limitations of feasibility even further. Examples for these technologies are accessible cutterheads, saturation diving, monitoring systems, multi-mode TBMs as well as seismic exploration systems.

3.1 Atmospheric Toolchange

Accessible cutterheads have first been introduced at the River Elbe Tunnel in Hamburg in the late nineties (Herrenknecht, 2007). Since then, that technology has matured considerably. The cutterhead is equipped with large, hollow arms which can be accessed from the TBM under atmospheric pressure. A complete set of excavation tools is designed in such a way that the tools can be exchanged via an interlock without pressurizing the inside of the cutterhead arm. Such systems have been built for both: softground tools and disc cutters. Safely sealing off high pressures requires extremely precise manufacturing tolerances and has proven very challenging to TBM manufacturers. Another difficulty has been the tool spacing. As the interlocks require considerable space, especially the center area is completely occupied by them. This affects the material flow negatively. In summary there are three development directions which can be observed currently and which will further advance the capabilities. Firstly the design for higher pressures, secondly increased standardization and general product maturity and thirdly the miniaturization. Smaller tool interlocks

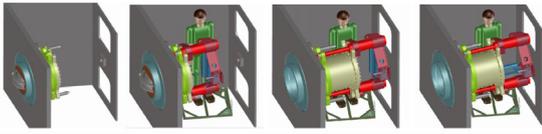


Fig. 3. Atmospheric tool change (Schaub, 2014)

are necessary to allow application in higher rock strength and smaller diameter TBMs.

3.2 Saturation Diving

While traditional compressed air or mixed gas diving is limited to performing work up to 8 bars, saturation diving has been successfully done up to pressures of more than 45 bar. As the human body can only slowly adapt to changing pressures, in saturation diving the workers are housed in a compressed air chamber over periods of several weeks. This allows them to work in shifts and rest in between while being housed in a special pressurized habitat. A pressurized shuttle transporter allows the divers to commute between habitat and TBM. Besides the development of diving technology and high pressure medicine, the smooth integration of diving into the design of TBMs and operation procedures has seen major advances in recent years.

3.3 Multi-Mode TBMs

Multi-Mode TBMs have been excavating several of the world's largest subsea tunnels. The Channel Tunnel was built by EPB / Single Shield machines. Many subsea tunnels have been designed to run through stable geological formations to allow excavation with an open shield over long stretches. In case of too much water inflow, the excavation mode can be changed to a closed mode until reaching

another stable formation. A factor that has proven crucial is the closing time within the machine can be sealed off in case of encountering water. The Lake Mead Intake Project in the US has used an innovative Mixshield / Single Shield TBM which allows closing the chamber in less than one minute as the pressures and water volumes which could be encountered here were extremely high. Recent years have seen great advances in terms of sophistication of Multi-Mode TBMs (Burger, 2013) moving from modular to integral solutions. For sure, these types of machines are offering the broadest application range which might be required by many complex subsea tunnel projects.

3.4 Seismic Exploration

A general difficulty in many tunneling projects is geologic uncertainty. A reliable detailed forecast of geologic properties ahead of the excavation face adds a great layer of safety to a project. Therefore, a number of developments are currently made to deploy seismic exploration technologies which can be used in TBMs without affecting their operation. Essentially there are two systems in the market today which fulfill this requirement. Either seismic waves are generated with a hammer in the geology or by using an electromagnetically driven membrane to create sound waves. Geophones then detect the echo of the waves as they are reflected by different geological formations. These technologies allow the reliable detection of boulders, piles, fault zones or similar geological phenomena under certain conditions. (Gehrig, 2010). Projects such as the River Elbe Tunnel in Hamburg or the the City Tunnel Leipzig have been past successful applications.

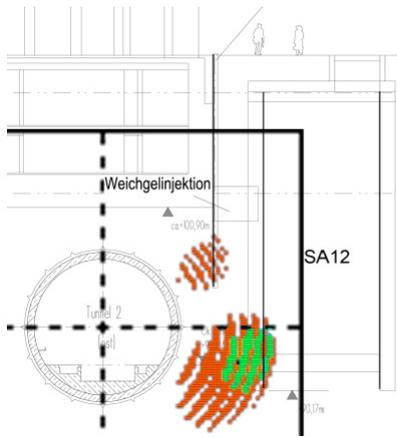


Fig. 4. Detecting a sheet pile wall on the right of axis (Gehrig, 2010)

3.5 Advance Drilling

Neither geological surveys nor seismic exploration yield information which is reliable enough to cut regular advance drilling. Many projects incorporate strict regulations for advance drilling. The contractors are required to perform regular probe drilling by demanding a minimum length ahead of the face. Further requirements usually state countermeasures to be taken in case of water ingress above a certain threshold. Such countermeasures can be mandatory boreholes and ground injection into the ground to reduce permeability. In order to speed up the drilling process, it is possible to install fixed drilling rigs on a ring carrier behind the erector.

3.6 Monitoring and Inspection Automation

There are primarily two purposes of human interventions into the excavation chamber. Firstly, inspections and measurement of tool wear and secondly the related maintenance and repair works. While it is more difficult to automatize these, the inspection works taking place beforehand can well

be automatized. The instrumentation of disc cutters (Disc Cutter Rotation Monitoring - DCRM) has proven to greatly support the prevention of severe damages on cutterheads. It allows visualizing every discs rotation speed, contact force and temperature. Further development steps allow measuring the wear on cutters in real time as well. This technology has proven very valuable on the Bosphorus Strait crossing as it could help immediately recognizing blocked cutters which then could be replaced. Another area which currently sees great advances is assisted inspection. Deploying fixed or mobile cameras into the excavation chamber and equipping them with a high pressure water jet nozzle as well as lighting allows performing visual inspections on the cutterhead without the need for human interventions. With

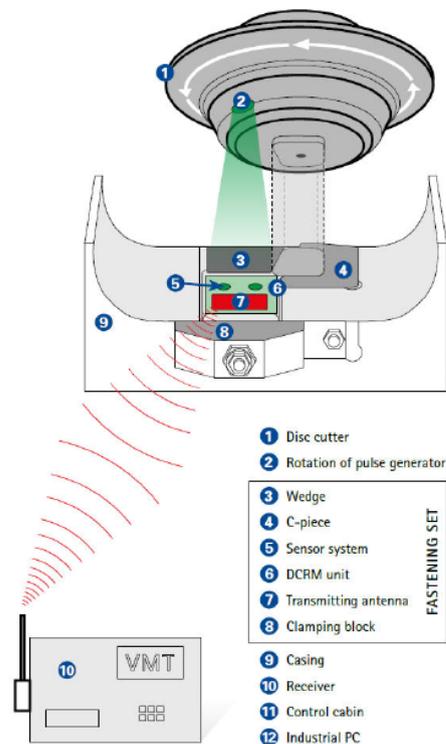


Fig. 5. Disc Cutter Rotation Monitoring (Herrenknecht)

today's technical standard it is not yet possible to perform regular maintenance work by robots. Nonetheless the developments of the industry in general lead to the expectation of further successful developments in this field over the coming decade (Duhme, 2014).

4. CASE STUDY

To illustrate the successful application of TBM technology in subaqueous tunneling, the Bosphorus Strait Crossing project is introduced here. The project has marked a milestone in several technical areas with many of the abovementioned key innovations applied. Most of them saw major improvements to previous projects.

4.1 The Bosphorus Strait Crossing

The Istanbul Strait Road Crossing is a 3,340 m long tunnel connecting the Asian and European continents in Istanbul, Turkey. The tunnel runs under the Bosphorus Strait which lies between the Mediterranean and the Black Sea. The tunnels inner diameter is 12.0 m and its outer diameter 13.2 m. Overburdens of more than 100 m below sea level lead to high pressures and within several fault zones with potentially high permeability of the rock, these can act directly on the machine. Fig. 6 shows the longitudinal cross section of the Bosphorus Strait Tunnel.

There are three main geological formations to cross.

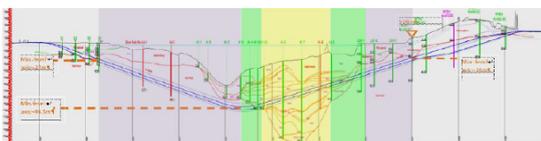


Fig. 6. Geology of Bosphorus Strait Tunnel (Herrenknecht)

The Trakya Formation is made up of sandstone and mudstone but includes dykes of higher compressive strength with up to 250 MPa. Areas with marine deposits consist of sand, clay and cobbles of different grain size and permeability. Transition zones between the different formations contain features of both within the tunnel alignment.

4.2 The Mixshield TBM Solution

The Herrenknecht Mixshield S-762 has been specially developed for the Bosphorus Strait Tunnel. It incorporates many of the key technologies which are unique to subsea tunneling in their combination. An accessible cutterhead allows pressure free tool changes and a Disc cutter monitoring on all cutters maximizes their working life and minimizes the risk of structural damages. The machine is optimized for saturation diving equipment with regards to internal logistics. Two advance drilling rigs are permanently installed in the machine behind the erector.

The Mixshield has been designed and manufactured for a maximum operation pressure of 13 bar. The challenges of building TBMs for this pressure levels

Table 1. Main Parameters of the Herrenknecht Mixshield

| | |
|----------------------------|------------|
| Max Operation Pressure | 13 bar |
| Drive | electric |
| Main Drive Power | 4,900 kW |
| Nominal Torque | 23,577 kNm |
| Cutter Head Rotation Speed | 3.2 rpm |
| Total Thrust Force | 247,300 kN |
| Total Machine Length | 175 m |
| Min. Curve Radius | 1,200 m |
| Ring Division | 8+1 |
| Segment Length | 2,000 mm |
| Segment Inner Diameter | 12,000 mm |
| Segment Outer Diameter | 13,200 mm |

lie not only in the design but also in the necessity to perform all manual production and assembly steps with the highest degree of quality and experience.

4.3 Atmospheric Cutterhead with DCRM

The S-762 Mixshield has been equipped with an accessible cutterhead which allows changing disc cutters and scrapers under atmospheric pressure from inside the cutterhead arms. The Disc cutters have been equipped with a rotation monitoring system. This combination of technologies has proved uniquely valuable as the cutter change could be not only managed more precisely but also structural damages on the cutterhead could be avoided fully once the DCRM system was operational. Due to a number of technical issues in the project beginning, the monitoring system was only fully functional several weeks after launch.

The accessible cutterhead was equipped with 6 main arms which contained the assemblies of the atmospherically changeable tools as can be seen in Fig. 7. After a learning curve, each tool change could



Fig. 7. Accessible Cutterhead (Herrenknecht)



Fig. 8. Workers Changing Discs (Herrenknecht)

be performed in two to four hours. The transport logistics have been extensively optimized inside the cutterhead and material locks to speed up maintenance. One critical factor for the maintenance performance has been extensive training in the factory as shown in Fig. 8.

During the project several issues have been encountered and improved. Problems with the tightness of the gate valves have been minimized by improved flushing procedures and damages resulting from excessive wear during the initial tunneling phase have led to increased necessary forces for moving the cutter housings. After initial difficulties regarding the signal transmission of the disc cutter

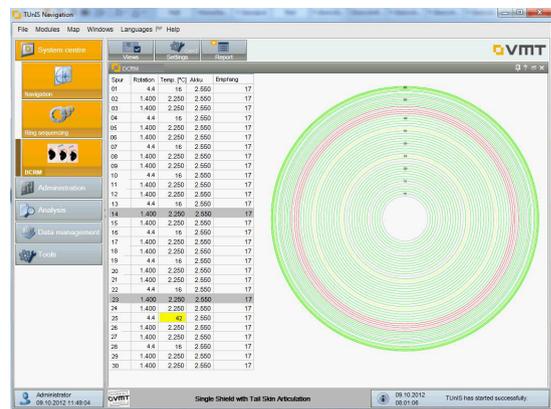


Fig. 9. Disc Cutter Rotation Monitoring

rotation monitoring system, the sensors have provided reliable readings throughout the project. As soon as a cutter was marked as not rotating, it was changed immediately after finishing the excavation of the current ring. This has proved to reliably prevent damages on the cutterhead. The visualization screen of the DCRM system is shown in Fig. 9.

4.4 Optimization for Saturation Diving

Saturation diving is the only diving technique which allows relatively efficient working shifts at high pressures. Therefore the TBM for the Bosphorus Strait Tunnel has been optimized for the related work procedures. As the divers live in a pressurized compartment on the surface, it is necessary to transport them to the TBM's manlock efficiently. This is done via a shuttle. This shuttle is first brought into the tunnel on special multi service vehicles and subsequently maneuvered through the backup gantries to the manlock via cranes and rails. While on past projects the integration of the diving shuttle transport has been made by using the cranes which exist in the backup gantries anyway, the Herrenknecht S-762 TBM has been equipped with dedicated transport systems for the shuttle lock. Scissor type lifting units provide a safe movement for the shuttle and its passengers. A dedicated rail on the gantry leads on top of the erector beam from where the shuttle is lifted to the docking position with the manlock. This process guarantees maximum safety for the divers inside the lock. Fig. 10 shows the shuttle lock during transport on the dedicated rail in the backup gantry.

Besides the technical aspects a very important factor for the successful deployment of divers was the related training. Divers which were expected to work on the TBM cutterhead have been invited for training on

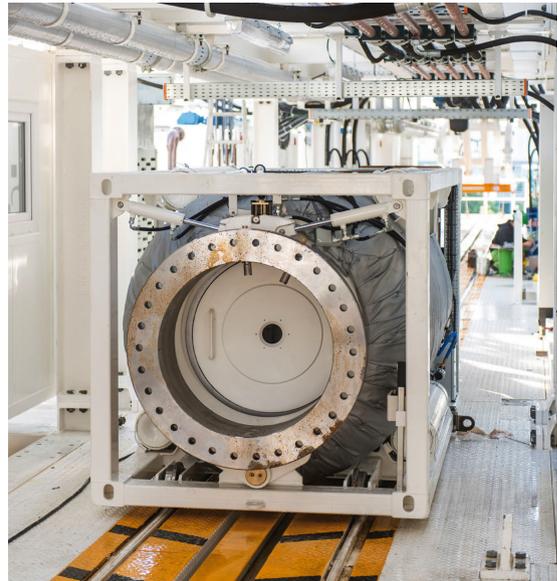


Fig. 10. Shuttle Lock for Divers during Transport (Herrenknecht, 15)

the actual cutterhead in the manufacturer's workshop during the machine assembly. As the working conditions in front of the cutterhead provide extremely low visibility, the divers are often operating blind or almost blind. As they had a chance to familiarize with every feature of the cutterhead beforehand they could always keep orientation when performing actual repair works.

5. conclusions

Recent years have shown remarkable advances in TBM technology and several related fields which today allow attempting projects which have been deemed too challenging just a few years ago. Technologies such as accessible cutterheads, saturation diving, cutter monitoring or seismic exploration have been applied in several recent projects such as the Bosphorus Strait Tunnel and can be expected to be key drivers behind the planning of future megaprojects.

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