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Tunnels and Underground Spaces:
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Newest technology and trends in mechanized tunnelling

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ABSTRACT

Two trends have become discernible in the development of mechanized tunnelling technology in recent years: firstly demands on the engineering technology have risen significantly and secondly ever more complex challenges have to be mastered regarding the technical and logistical aspects of projects. Essentially the feasibility of mechanized tunnelling is not just affected by the subsoil conditions but also by the lengths of tunnelling, the demand for larger profiles and the prevailing hydrostatic pressures. Surface requirements (densely built-up inner-city areas, restricted working space at the access and target shafts) determine the design of tunnelling installations for an increasing number of projects and pose challenges for the construction site logistics. The future-oriented infrastructure projects call for mature engineering technology that is adapted to growing demands.

Thus Mixshields both in their classical operating mode as a shield with liquid-supported tunnel face as well as a shield with dual mode operation are being used more frequently for complex subsurface conditions. This type of machine has turned out to be a multi-purpose solution for projects posing high demands by dint of its engineering concept. At the same time the range of application of EBP-Shields has been extended by the introduction of foam conditioning which has gained in popularity following successful projects in Europe, Asia and Far East. At present EPB Shields are also being used for heterogeneous subsoil conditions. In hard rock the developments in mechanized tunnelling has been aimed at handling more and more demanding rock massifs of high abrasiveness, high rock strength and the mastering of blocky and squeezing rock conditions.

RÉSUMÉ

Ces dernières années, deux tendances se sont dégagées dans le développement des techniques pour l’excavation mécanisée des tunnels. D’une part, la demande en technologies industrielles a considérablement augmenté et d’autre part, les projets impliquent des enjeux bien plus complexes en termes de technique et de logistique. Sur le fond, la faisabilité de l’excavation mécanisée des tunnels n’est pas simplement affectée par les conditions du sous-sol, mais aussi par la longueur du tunnel, la demande de profils plus grands et les pressions hydrostatiques. Les exigences en surface (zones intra-urbaines densément construites, espace de travail restreint aux puits de départ et d’arrivée) déterminent la conception des installations de creusement de tunnel pour un nombre croissant de projets et posent des défis en termes de logistique sur le site de construction. Les projets d’infrastructure tournés vers l’avenir nécessitent une technologie industrielle efficace et adaptée à la croissance de la demande.

Par conséquent, les boucliers à pression de boue utilisés soit dans leur mode classique avec face à support liquide, soit comme bouclier convertible sont utilisés de plus en plus fréquemment dans des conditions souterraines complexes. Ce type de machine s’est révélé être une solution à des fins multiples pour des projets présentant une forte demande en raison de son concept industriel. Dans le même temps, la série d’applications de boucliers EPB a été étendue par l’introduction du conditionnement en mousse, qui a gagné en popularité à la suite de projets réussis en Europe, en Asie et en Extrême-Orient. Actuellement, les boucliers EPB sont également utilisés dans des conditions souterraines hétérogènes. Dans la roche dure, les développements de l’excavation mécanisée des tunnels ont pour but de traiter de plus en plus de demandes de massifs rocheux présentant une abrasivité importante, une forte résistance rocheuse et nécessitant de s’adapter à des conditions de forte pression, de rocher convergent et de blocs instables.

1 INTRODUCTION

Availability and use of transport and communication systems are important for social and economic development. A well-developed infrastructure system has today, and even more in the future, a significant weight in terms of social contacts, services and communication resources. The existing infrastructure will quickly come to its limit due to the rapid economic growth and continued development. Therefore it is the aim of a fast implementation of demanded infrastructure issues which can be realized by means of mechanized technology. In most cases the needs are focused on the urban transportation systems which demand tunnel solutions. By means of mechanized tunnelling technology the construction of road, railway or metro and also the construction of utility tunnels can be realized in a faster and safer way with less disturbance to the environment compared to existing conventional tunnelling solutions. In congested areas and metropolises underground transportation systems are typically used.

The paper addresses newest technologies and tendency in mechanized tunnelling with main focus on tunnelling in urban area. Case studies with specific construction aspects such as complex and mixed geology, long headings, prevailing high hydrostatic pressures, low overburden and demanding rock conditions and accordingly adapted machine technology are highlighted.

2 TENDENCY IN MECHANIZED TUNNELLING TECHNOLOGY

The underground infrastructure is the lifeline for the supply and disposal of the cities and decides on the quality of life and sustainability. The current trend in mechanized tunnelling technology is for the fast implementation of systems for utility infrastructure, passenger transport or multiple purpose systems such as flood control. Based on the usage of the tunnel profile different diameters are taken into consideration. Road tunnels of today demand larger tunnel profiles due to the tendency of integrating three instead of two lanes of traffic. In respect of multiple purpose usage of the tunnel profile such as realized for the Storm Water Management and Road Tunnel project in Kuala Lumpur a larger cross section and thus larger shield diameters of up to 13.21 meters were required. The development of larger tunnel profiles started with the 4th Elbe road tunnel project in Germany integrating two lanes of traffic in the profile and a shoulder. This 14.2m-diameter machine was reused for several follow on large diameter traffic tunnels in Moscow. One of the tunnels in Moscow also integrated a metro line in parallel to road traffic.

2.1 Dual Mode Tunnel Boring Machines

Another tendency which has developed more and more over the past 10 years is the application of tunnelling technology to complex heterogeneous subsurface conditions requiring a quite flexible machine to cope with high hydrostatic pressures in addition to the geological conditions. Machines adapted to specific project demands and being able to handle heterogeneous conditions comprising rocks, soft soil and mixed face conditions can be designed as dual mode machines that can operate in an open non-pressurized mode for the hard rock or stable soft ground sections or operating in a complete closed mode as a Mixshield with hydraulic conveying of the material for the unstable loose soils below the groundwater table or as an EPB Shield with mucking out via a screw conveyor. These days such dual mode machines are more frequently used due to their flexibility in varying subsurface conditions and because the conversion of operating modes can be realized underground without the need of a shaft for the change of mode.

2.1.1 Weinbergtunnel, Switzerland

For the Weinberg rail tunnel in Zurich the 11.24m diameter tunnel boring machine started excavation in open hard rock mode in the molasse rock for a section of about 4km. The machine achieved performances of 20m per day in the molasse. The limiting factor along this drive was not the TBM itself but the logistics of transporting the excavated material.

For the remaining 250 meters, the machine was then changed to closed slurry mode when the tunnel alignment passed with minimal overburden below the River Limmat. This section was characterized by loose soil conditions of high permeability where the tunnel also passed under numerous important traffic carriers and supply lines. For this section a safe and reliable and settlement controlled tunnelling technology was required which guaranteed a safe river crossing and to minimize all possible risks. The Mixshield with the possibility of liquid or slurry supported operation mode was chosen. Here the support pressure can be precisely controlled by using a compressed air reservoir which is especially relevant for sections with low overburden like those encountered along the soft ground section. The TBM conversion process required the change of material conveying from belt conveyor to slurry transport. Furthermore the excavation area was completely sealed off from the atmospheric part of the tunnel so that pressure could be supplied to support the face during tunnelling. The conversion also required an adaptation of the back-up to connect to the slurry transport system. The remaining section in loose soil conditions along the 250 meters including the river crossing demanded additional auxiliary construction measures that were realized from the pit in front of the south tract of the Central Rail Station in Zurich. These additional measures comprised the use of six pipe jacking systems with a diameter of DN1800 and one drive with a diameter of DN2600. With these pipe jacking drives a pipe-umbrella was realized above the crown of the main tunnel. They were installed with lengths of 100m to 120m in the gravel layers and the marine deposits. This stable arch above the tunnel prevents settlement of the roof especially in the soft ground.

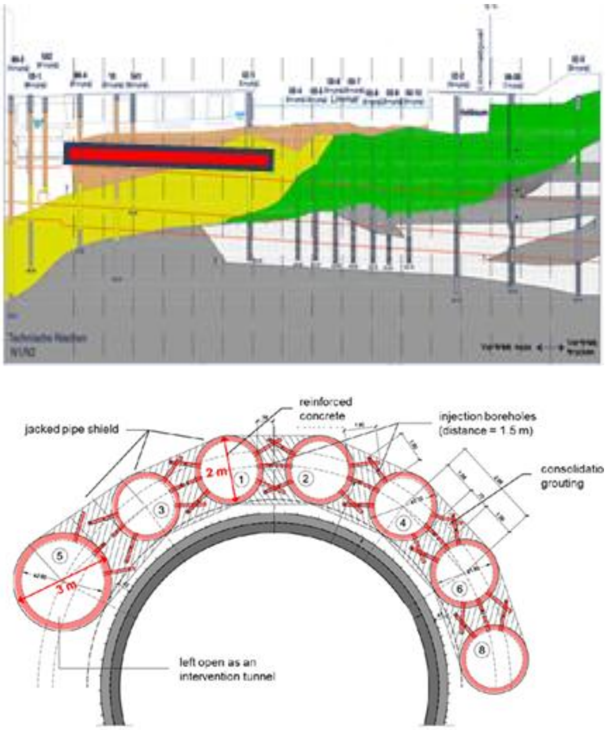


Figure 1. Longitudinal section of the pipe umbrella [1]

The cutting wheel was adapted to the anticipated geological conditions comprising molasse rock and loose soil conditions. The cutting wheel had a weight of 220 tons and was equipped with 46 disc cutters and 164 soft ground tools. The shield itself had a diameter of 11.24m and a length of 10.6m and a weight including erector and main drive of 1,060 tons.

The construction of the Weinbergtunnel was demanding in respect of the logistics which was one of the limiting factors during the hard rock drive. The total excavated volume of the Weinbergtunnel and the underground through station reached about 2 million cubic meters. The site logistics for the entire project was due as specified by the client on rail transportation. For this, three rail loading facilities were in use. The removal of the excavated material from the Weinbergtunnel was realized via the Oerlikon station.

This mechanized tunnelling technology of a dual mode Mixshield was used for the first time for the Grauholz rail tunnel in Switzerland in 1990 and later for the northern section of the Zimmerberg base tunnel in Zurich Thalwil in similar loose soil conditions than faced during the construction of the Weinbergtunnel.

2.1.2 Tunnel Saverne, France

Within the framework of the extension of the high speed rail line (320km/h) between Paris and Strasbourg mechanized tunnelling technology is being applied for one section of this rail connection. The Saverne tunnel is part of this eastern European high speed rail line (LGV Est) providing high speed rail connections from Paris all the way to Bratislava and Budapest.

Advantage of the construction of the Saverne tunnel will be a reduction in travel times between Paris and Strasbourg from the current time of two hours twenty minutes to just one hour and 50 minutes. Construction for the Saverne tunnel comprises of two 4km long bored single track tunnels through the northern part of the Vosges Massif. Tunnelling operations for the first tunnel started in November 2011. The machine is designed as dual mode EPB-Hard Rock TBM with a diameter of 10.02m and an installed cutterhead power of 3,600kW. The machine can operate as a closed EPB Shield with muck removal via screw conveyor from a pressurized excavation chamber and as an open hard rock TBM with mucking out via belt conveyor.

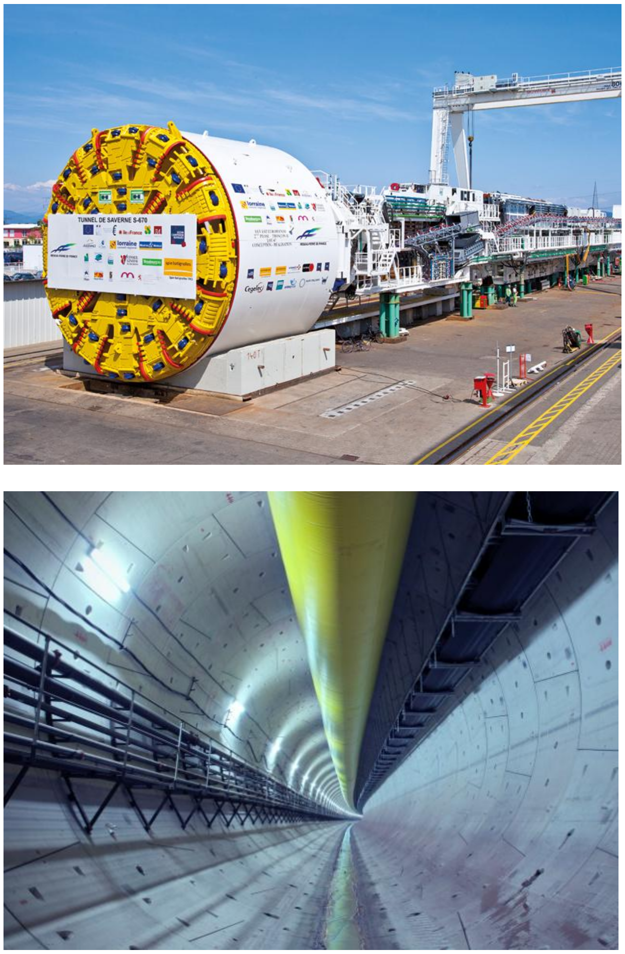


Figure 2. Rail tunnels Saverne: Application of dual mode EPB-Hard Rock TBM

The prevailing geology comprises mainly Buntsandstein, a heterogeneous sandy-sandstone formation, ranging from fine sands to sandstone as the main conglomerate of abrasive nature. The eastern part of the tunnel is located within a set of faults (Saverne dislocation) characterized by marly ground. Through the sandstone formation also some sand pockets filled with water are likely to be encountered. Safe excavation in these sections is achieved by applying an active face support. The remaining sections are to be excavated in hard rock so for this reason the machine was designed as dual mode TBM that is able to switch between closed pressurized mode and open hard rock mode. The cutterhead is equipped with 19inch disc cutters and buckets. In closed EPB mode (soft ground) the cutterhead is designed to rotate in both directions, but when converted to open hard rock mode the design is for only one direction of rotation. The machine was equipped with three horizontal drill rigs in the shield for exploratory and injection drilling in the predicted fault zones along the alignment.

The lining of the dual mode EPB shield is constructed in the same way as with normal shielded TBMs with the installation of precast concrete elements within the protection of the shield. The segment ring of 8.90m internal diameter has a length of 2m and a 7+1 ring division. Along the first tunnel drive the machine has been advancing with performances of up to 20 meters per day.

After completion of the first tunnel the machine will be prepared for the construction of the second parallel rail tunnel.

2.2 Large Diameter Tunnel Boring Machines

The development of larger diameter tunnelling machines has been driven by the demand of the proposed utilization of the tunnel. In the past, two and three lane road tunnels were built with diameters of 11.2m for a double deck road tunnel in Paris carrying two lanes of traffic each and tunnels with diameters larger 14m for two lane road tunnels with shoulder, twin-track or double-stack rail tunnels. The first large diameter TBM applications had been for twin track rail tunnels and two lane road tunnels in Switzerland towards the end of the eighties with shield diameters between 11.4m to 12.6m. With the demand of operational safety measures for emergency rescue and escape routes there is further need for larger tunnel clearances and thus larger TBM diameters. Future road tunnel concepts will integrate two decks with each four lanes of traffic and appropriate shoulders in the cross section. Figure 3 gives an overview of machine diameter developments over the past 27 years.

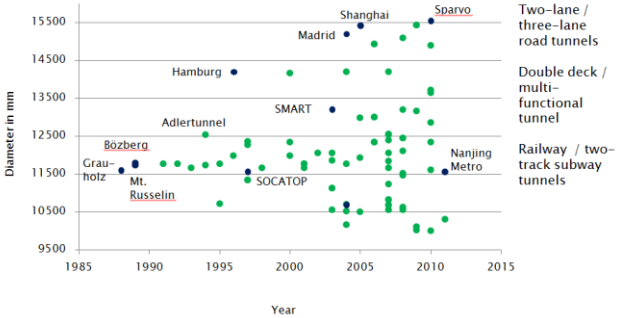


Figure 3. Development of large diameter TBMs over the past 25 years

The projects being built today with larger tunnelling diameters can be in soft ground, hard rock and mixed face conditions often with high hydrostatic pressures. The very large diameter application is thus not restricted to special subsurface conditions. The first machine which exceeded the diameter range of 14 meters was for the Fourth Elbe road tunnel in Hamburg (Germany). The machine started tunnelling in October 1997 and was at that time the largest machine built. The successful completion of that job has triggered a trend in terms of large diameter tunnelling. Follow-up large diameter projects were realized with Mixshields in Moscow for the Lefortovo and Silberwald tunnel, the dual usage tunnel in Malaysia for the Storm Water Road and Management Tunnel in Kuala Lumpur. Start of operation for the largest EPB shield was in 2003. With a diameter of 12.06m the EPB shield for the Metro Line 4 in Barcelona was in 2003 the largest EPB machine built. With the experiences gained during that Metro tunnel job with a large diameter EPB Shield in conglomerate, granodiorite, sandy and clayey formation an EPB machine with a diameter of 15.2m was designed for the excavation of a 3.65km long highway tunnel through the inner city area of Madrid. The M30 highway North tunnel in Madrid is a three-lane tunnel that was realized with an extremely tight time schedule. The target construction time of 12 months could clearly be reduced, and the 8months tunnel construction time was an excellent TBM performance of more than 405m per month. The unique TBM with a cutting wheel design characterized by two concentrically arranged cutting wheels and three screw conveyors for material discharge out of the working chamber achieved daily performances of up to 36m of excavated and lined tunnel. For that 15.2m-diameter excavation the size of the tunnel profile was not a challenge but rather the logistics. During the excavation of the 3.65km long motorway tunnel an average of 60 trucks per day passed through the inner-city for the delivery of the segments used to line the tunnel to the construction site. At peak times, 720 trucks passed through the construction site on one day to remove the excavated material.

2.2.1 Largest EPB Shield to Date in Operation for the Galleria Sparvo Tunnel in Italy

Today the largest machine in operation has a diameter of 15.62m. In 2011 this EPB shield started tunnelling for two parallel 2.5km long 3-lane road tunnels which are part of the A1 highway extension between Bologna and Florence. The machine for the Galleria Sparvo tunnel is designed to cope with the predicted geology consisting of mainly clay, argillite, sandstone and limestone which is partly highly fractured. Rock clasts in a fine grained matrix or soil intercalations in hard rock as well as mixed face conditions are likely to be faced during tunnelling. Apart from the large diameter, the specific project conditions are complicated by the presence of methane gas along the alignment. The machine was specially equipped to deal with this condition. The conveyor belt is enclosed from the screw conveyor discharge gate to the cross belt conveyor on the gantry. Additionally a continuous feed of large volumes of fresh air greatly dilutes the gas content inside the enclosure and further mixing is carried out at the open outlet. The gas concentrations and gas-tightness of the system are continuously monitored allowing a controlled excavation process even in sections where there is a possibility of gas presence.

Large to very large diameter EPB shields require a higher cutting wheel torque than Slurry and Mixshields. Machine and process technical factors such as drive unit and bearing unit, cutting wheel design and rotational speed have an effect on the torque of the cutting wheel. The Galleria Sparvo EPB Shield has a special designed “high torque” cutting wheel drive employing a dual main gear system. The nominal installed torque comprises 125,000kNm, powered by fifty hydraulic motors. The high pressure and torque enable the high-strength steel disc cutters and cutting knives to excavate the tunnel face. In sections where the tunnel face may be unstable, an active face support pressure is generated to counteract any loss of stability at the tunnel face. The excavated soil is then used to support the tunnel face. During advance, the excavation chamber is always completely filled, preventing settlement on the surface. To achieve a state of balance, the face support pressure is transmitted from the hydraulic thrust cylinders to the conditioned, loose soil through the bulkhead. The internal stators and rotors cut through the spoil mixture, while foam can be injected via a total of 48 nozzles to ensure that the required consistency is maintained.

2.2.2 World Largest Mixshields applied for Long River Crossing Tunnels in Shanghai

The development in large diameter tunnelling was mainly focused on Mixshield machines. This had been because of the lower torque demand for large Slurry and Mixshields compared to EPB shields and also an easier access to the tunnel face in pressurized conditions. In 2006 the largest Mixshields with diameters of 15.43m started their operation for the Changjiang Under River Tunnel project in Shanghai comprising two parallel 7.47km long tunnels. The three lane highway tunnels were excavated at a depth of up to 65 meters connecting the Changxing River Island with the mainland of Pudong/Shanghai. An innovative feature of these shields had been the accessible cutting wheels that allowed the process of cutting tool replacement to be undertaken in free air, thus avoiding the need to work in compressed air to balance the prevailing hydrostatic pressures of up to 6.5bars. The cutting wheel was designed with six accessible main spokes which were sealed against the water pressure. See figure 4. To avoid adhesion of sticky clay due in the clayey formations with shell debris, the center area of the wheel was equipped with its own slurry circuit. Large openings in the cutting wheel optimized the flow of material and reduced the risk of blockages of material in the center. Another installation which was state of the art was the wear detection system. Reliable information about the condition of soft ground tools and buckets, especially in the loaded outer area of the cutting wheel can be gained. Therefore ten cutting tools (2 buckets and eight soft ground tools) were equipped with an electronic wear detection system. Online data on the state of the selected cutting tools enabled an early warning of possible wear to the TBM staff. Thus maintenance work can be planned and the service life of the tools can be optimized thereby minimizing costly chamber interventions under compressed air.

The machines achieved performances of up to 142 meters per week and finished 10 and 12 months earlier than scheduled.

Outstanding pioneering references such as Shanghai (Mixshield Ø15.43m) and M30 Madrid (EPB-Shield Ø15.20 m) support the feasibility of the construction of very large tunnels. The performances that have been achieved by the current largest tunnel boring machines include also an excellent logistical concept which presents a good basis for administrative authorities, project owners and contractors regarding the feasibility, reliability, safety and speed of upcoming large diameter projects.

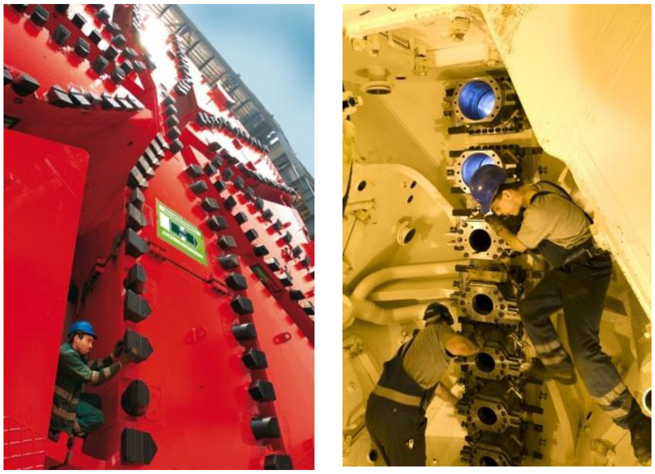


Figure 4. Large diameter Mixshield: accessible cutting wheel in free air for safe tool change

2.3 High Hydrostatic Pressures with the Example of Lake Mead Intake N°3

In the US there is a project under construction challenged by the depth of the tunnel with corresponding hydrostatic pressures which are expected to amount to a maximum of 16 bars. The project is located in Nevada. There are two water intakes and two pumping stations in operation by the Southern Nevada Water Authority (SNWA) on the west side of Saddle Island and the shore of Lake Mead. The area has been affected by severe drought in recent years resulting in falling water levels along the Colorado River Basin. Therefore the SNWA decided to construct the Lake Mead Intake No. 3, a scheme with a deep-water intake and pumping station which will also provide for a future extension to deeper waters to the northeast. This new water supply tunnel will have a length of 4.8km and is located about 24kms east of Las Vegas. The tunnel is currently under construction by means of a tunnel boring machine. The 7.22m-diameter machine is a convertible Hard Rock Mixshield. Assembly of the equipment was done in a 170m deep concrete lined access shaft of 9.1m in diameter.

Requirements for the machine design resulted from the challenges of the project. The main demand is to handle the high hydrostatic pressure of 16bars. This pressure is in the range of the groundwater pressure that was predicted for the TBM excavation for the Hallandsas rail tunnel in Sweden of which the first tunnel of 5.5km was excavated and lined in August 2010.

Due to the predicted geological and hydrogeological conditions in the project area of Lake Mead the machine design foresees the feasibility of operating the machine in open mode and closed slurry mode. The geology along the alignment includes sedimentary and volcanic geology. The machine is capable of handling difficult hard rock conditions with a potential for high groundwater inflows and high hydrostatic pressures. Ground treatment for consolidation in front and all around the TBM, pre-excavation grouting, drainage drillings and probing can be achieved from within the TBM and in open or closed mode. Therefore the TBM is equipped with drilling and grouting equipment. Pre-excavation grouting will be considered to improve the quality of the rock mass and to seal the ground with the aim of reducing the water pressure. Figure 5 illustrates the possibility of drilling through the face and perimeter drill holes which are permanently available or available with minor disassembly.

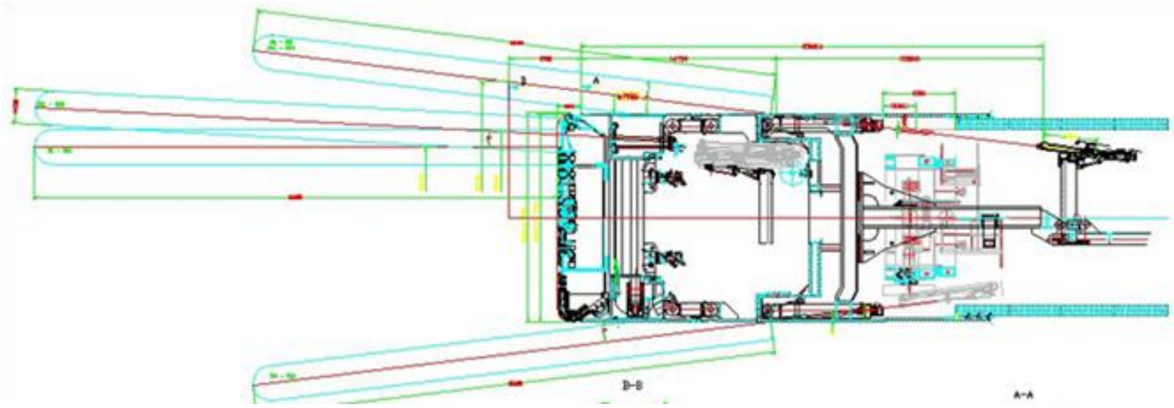


Figure 5. Available drill pattern on the TBM

Further requirements for the machine design when operating in an open mode was the ability for rapid closure of the face within 120 seconds and the layout for operation and access at pressures of up to 17bar.

The cutterhead has a diameter of 7.22m and is fitted with 17-inch back-loading cutters. In open hard rock mode the muck is transported via buckets and muck channels to the muck hopper arranged in the centre of the cutterhead. From there the material is extracted by a horizontally arranged screw conveyor and transported to the end of the back up where the muck is handed over to a continuous tunnel belt conveyor.

To allow a rapid closure within seconds, the screw conveyor used in open mode operation ensures the best and reliable option to close the excavation chamber in case of a sudden water inflow by closing the rear screw discharge gate.

In semi closed or full pressurized (closed) mode operation the excavated material passes a stone crusher and is transported out of the tunnel via slurry circuit through pipes installed along the tunnel. The muck is then separated in a slurry treatment plant installed at the tunnel portal.

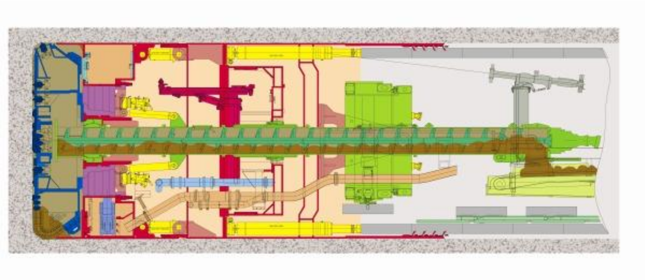


Figure 6. TBM Operation open mode

Figure 7. TBM Operation closed mode

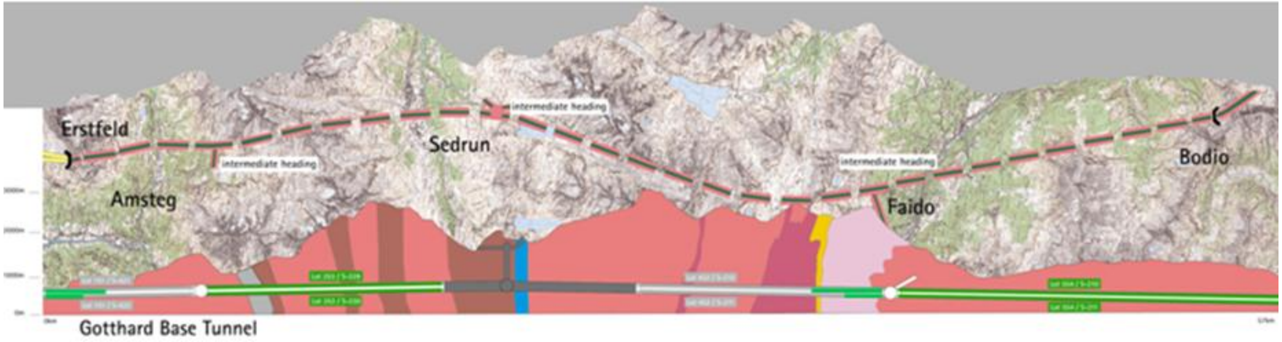
The tunnelling system must be prepared for hyperbaric face access for inspections, maintenance and tool changing under hydrostatic pressures of up to 16bar. A new concept for intervention was developed where planned interventions can be carried out without the use of a shuttle. This is depending on the anticipated pressure for the intervention or in other words if decompression is still feasible within the TBM then no saturation process is required. This concept comprises a standby compression chamber which is permanently located behind the ring erection area. This chamber is equipped with an oxygen decompression system and can be connected by an access tube to the rear shield bulkhead. Access to the drill chamber behind the front shield bulkhead is thus possible. The compression chamber is big enough to allow for extended decompression times and to perform the complete decompression process. For higher chamber pressures the system is prepared for the use of mixed gas breathing systems. For extended chamber time under high pressure, the tunnelling system is also prepared for a shuttle transfer under pressure of the personnel between the airlock and a hyperbaric habitat at the bottom of the access shaft. The technology even for safe interventions, even at high pressures, exists and the tunnelling industry is benefiting from use of technologies and procedures from other applications such as offshore diving. Professional diving companies have found and established a new field of activities in supporting specialist activities in tunnelling operations. Difficult projects are possible today but as in all fields there is a relation between increased difficulties and required effort. High pressure project designs should address this in budget and schedule to assure a safe completion. [3]

The 4.8km long intake tunnel is supported and lined with a precast concrete segmental lining fitted with sealing gaskets. The lining is a universal type ring, consisting of 5 segments plus a key segment with ring length of 1.8m. The tunnel has an inner diameter of 6m and is designed for a pressure of 17bar.

2.4 Demanding Rock Massifs of High Abrasiveness, High Rock Strength and the Mastering of Blocky and Squeezing Rock Conditions

Tunnelling is not just undertaken in urban area and soft ground conditions. When talking about big infrastructure projects often mountain ridges need to be passed through such as for the Hallandsas rail tunnel project in Sweden that crosses through a mountain ridge under toughest conditions with high water pressures. Another challenging project that was characterized by long bored tunnel sections and difficult rock formations was the Gotthard Base tunnel project that finished excavation in March 2011and is today the largest rail tunnel in the world. It includes two parallel single track high-speed rail lines of 57km each through the Gotthard Massif which is part of the Alps. The Alps are, like the Himalayas and the Andes, one of the most difficult tunnelling locations in the world. Four tunnel sections were excavated by a total of four Gripper TBMs:

- Erstfeld (2 x 7,178m)
- Amsteg (2 x 11,350m)
- Faido (1 x 12.4km, 1 x 11.9km)
- Bodio (2 x 14km)



Lot 151 Erstfeld – Amsteg

	TBM	Contractor	Tunnel Length	Shield Diameter
East Tube:	S-421, Gripper	ARGE AGN	7,400m	9,580mm
West Tube:	S-422, Gripper	ARGE AGN	7,400m	9,580mm

Lot 253 Amsteg – Sedrun

	TBM	Contractor	Tunnel Length	Shield Diameter
East Tube:	S-229, Gripper	ARGE AGN	10,722m	9,580mm
West Tube:	S-230, Gripper	ARGE AGN	10,702m	9,580mm

Lot 554 Bodio – Faido

	TBM	Contractor	Tunnel Length	Shield Diameter
East Tube:	S-210, Gripper	ARGE TAT	13,425m	8,830mm
West Tube:	S-211, Gripper	ARGE TAT	14,099m	8,830mm

Lot 452 Faido – Sedrun

	TBM	Contractor	Tunnel Length	Shield Diameter
East Tube:	S-210, Gripper	ARGE TAT	11,897m	9,430mm
West Tube:	S-211, Gripper	ARGE TAT	12,370m	9,430mm

Figure 8. Gotthard Base Tunnel subsections driven using mechanized tunnelling technology

Challenges in connection with the TBM drives for this giant tunnel project have included long tunnel drives with large overburdens (> 2,500m) and the tectonically active rock mass (folding of the Alps). Based on these demands and the experiences gained along the sections that are now completed, one can draw the conclusion that despite extensive investigations before the start of the project, there can be a great difference between geological predictions and geological findings (e.g. rock class distribution). The rock behaviour and the hazard scenarios can prove to be less favourable than expected, which on the one hand can show the benefits of a flexible operational sequence with separate of drive and support operations, but on the other hand it can make it impossible to make optimum use of the drive that have been designed to suit the anticipated conditions.

Experience showed that the construction conditions can change very quickly on site, and the mountain only forgives mistakes in exceptional cases and this sometimes requires quick decisions from all persons involved in the project and the prompt implementation of immediate measures.

The tunnel boring machines proved, however, that they are in a position to technically overcome situations that were much more difficult than those envisaged in the contract. In total 4 Gripper TBMs were applied to the Gotthard projects. All four Gripper machines excavated and secured demanding rock massif. The machines faced also local fault zones which extended over long stretches, especially in the southern lot starting in Bodio. Nevertheless the TBM drives comprising in total 50km were completed on time. All four machines have been refurbished and modified after the excavation of their first tunnelling sections and were put into operation for the follow on lots from Erstfeld to Amsteg in the north and Faido to Sedun in the south. The adaptations on the machines were done based on the experiences along the first drives but mainly to suit the predicted geological conditions along the remaining stretches. Along the subsection from Faido to Sedrun two tectonic units were identified, the Penninic Gneiss zone (approx. 5km) and the Gotthard Massif (approx. 10km). The predicted Piora Zone interpreted to be one of the most difficult sections was faced by the presence of solid, compact and partially metamorphic dolomite anhydrite rocks at tunnel level. The adaptations on the TBMs for the subsection Faido comprised following:

- Increased excavation diameter of 9.40m in order to be prepared for the greater overburden from 1,200m up to 2,470m and thus greater rock pressures along this section.
- Application of 12 instead of 8 buckets for better material removal
- Replacement of 17-inch disc cutters by 18-inch cutters
- Adaptation of the gripper and the walking legs to support the larger diameter of 9.40m.

Modifications were also done on the cutterhead dust control system, to increase the extraction from 600m3 per minute to 1,100m3 per minute.

The final breakthrough of all mechanized tunnelling by means of Gripper TBMs was achieved in March 2011 with performances in good conditions of up to 56 meters per day. This complex and demanding hard rock project showed that with flexible machine designs it is possible to master significantly more difficult situations than originally were thought about.

3 INNOVATIVE SHAFT CONSTRUCTION IN DOWNTONW AREA OF NAPLES FOR METRO LINE 1

Naples, the third largest city in Italy, with a population of about one million people has almost no open spaces or parks. It is one of Europe's most densely populated cities with an extremely sophisticated public urban transportation system. Besides an existing metro system with several lines and operators which will at present be expanded, Naples has also a cable car and bus network which extends along the coastline. Between 2004 and 2008 two EPB shields were used for the construction of two 4km long sections for the extension of the metro line 1 in Naples. The machines had a diameter of 6.74m. The extension of Line 1 provides a connection between the city center and the airport. The tunnels cross sections beneath the oldest part of the historic center of Naples. Due to the building density and a groundwater level near the surface, the alignment of the extension line was designed in greater depth of 20 and 30 meters in the tuff layers to prevent damage to the foundations of the old buildings. In connection with the construction for the metro line there was a need to build ten vertical circular shafts between the Dante and Garibaldi stations in the old center to give access to the tunnel. These shafts have an internal diameter of 4.5 meters and range in depths of up to 45 meters. They provide natural ventilation for the tunnels and also ensure safety for passengers by acting as emergency exits. The ten shafts were built in the historic center and the shopping mile of Naples in very restricted areas by using a Vertical Shaft Sinking Machine (VSM). The shafts were sunk with the VSM to a depth of 45 meters. This construction method was chosen because it is precise and safe and permitted a clearance of five meters from the tunnels. For urban applications such as in Naples, the VSM technology offers compared to conventional methods using piles or ground freezing techniques advantages such as:

- Quiet machine operation in inner city areas as excavation takes place below the groundwater table in the flooded shaft
- Modular structure of the VSM: all machine components can be transported quickly and safely to the construction sites in narrow alleys of city centers
- Space saving: site dimensions for both machinery and equipment are low
- Time saving: automatic working process with parallel excavation and shaft lining

The parallel procedure of shaft sinking and simultaneous shaft lining enables a much faster progress with the advantage that residents and the environment are less affected by the construction. The VSM consists of a sinking unit and a shaft boring machine and can be applied to stable and unstable soils below the groundwater table. In Naples the subsurface conditions comprise sand, gravel, volcanic tuff and a groundwater level near the surface. The VSM uses a sinking unit to lower the shaft. The cutting process is comparable with that of a partial face excavator. The rotary cutting drum is fitted with special tools and is fixed on the telescoping road header boom. The cutting unit loosens the ground at the bottom of the shaft. The cutter boom works with pre-determined movements and can rotate 360° to cover the whole circular profile. The liquid level in the shaft balances the groundwater pressure and reduces settlements. The excavated material is transported hydraulically by pipeline to the separation plant located on surface. During the whole shaft sinking operation, the VSM is attached via steel ropes to the surface. The control and supply units are located on surface.

The shafts have an outer diameter of 5.2 meters and are lined with precast concrete elements. The shaft segments can be removed at the planned openings for the cross passages. The load-bearing capacity of the segments across the openings was provided by additional reinforcement.

To save time, the concrete elements are assembled to a complete ring on surface by using a mobile crane. The elements are bolted both in horizontal and vertical direction. The ring assembly can proceed in parallel to the excavation of the remote controlled shaft sinking. The segment stock is placed near the jobsite (Fig. 9).

Figure 9. The launch of the Vertical Shaft Sinking Machine VSM9000 using lining segments in downtown Naples

An advantage development related to the VSM equipment was the design of the reusable ring beam (Fig. 10). The foundation segments are bolted together to form the ring beam. The fast installation of the units on surface and the elimination of time intensive preparation of a cast in-situ concrete ring beam thus reduce the costs for each shaft.

Figure 10. Reusable Ring Beam

The shafts could be excavated and lined with performances of up to 4.7m per day.

4 CONCLUSION

Newest technology in mechanized tunnelling is focused on the demand from the market and especially on the prevailing geological conditions along the planned tunnel alignments. The highlighted projects show that the demand of today’s tunnelling jobs is more and more directed toward overcoming adverse geological conditions with specific project conditions such as urban tunnelling, low overburden or projects with high hydrostatic pressures thus that dual mode machines are taken into consideration for the accomplishment of the construction work. These dual mode machines can be adapted - compared to a single mode machine - more flexible in respect of varying subsurface conditions and are of interest also in respect of budget and reliable time schedules.

Another trend which demands for developments is focused on large tunnel profiles exceeding the diameter range of 10 to 12 meters. The highlighted projects show that tunnels with diameters larger 15 meters can be safely excavated and lined and this also with high tunnelling performances even under demanding geological conditions such as high hydrostatic pressures or even in coarse soils as demonstrated by the projects that were realized in China.

In general large tunnelling projects benefit from an effective reduction of interface complexity. Interface management needs to deal with highest standard of performance, budget and schedule. That’s why a strong efficiency in planning, engineering design and operation is required. This together with pooling of know-how and technology offers the advantage that the risks for the owners and the joint ventures can be reduced significantly due to adapted machine technology.

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