Muir Wood Lecture 2019

Innovations in Mechanized Tunnelling since 1970

Dr.-Ing. Martin Herrenknecht

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>> ABSTRACT

Tunnelling is, without a doubt, one of the most innovative disciplines of the international construction sector. Focused on innovative and cooperative development, the collaboration amongst researchers, owners, designers, international construction contractors, highly specialized machine manufacturers and suppliers, is surely one reason for this. The second factor is the market dynamics in tunnelling, driven by a globalized world and increasing urbanization: Around the globe, emerging economies are expanding the infrastructures in their urban and regional centers, promoting the interlinking of individual economic hubs by means of new traffic, supply and disposal systems. In addition, they are investing in new water and sewage systems to enhance living comfort and provide supply services in the growing or newly built cities. Existing infrastructures have to modernize and expand their limits. More than ever we need to implement smart cities with smart links between them, optimizing not only time and resources, but use of the available space in a sustainable development.

The general worldwide trend in industry towards mechanization and automation clearly demands a similar development in tunnelling. There are challenges ahead and we need to improve our excavation methods to overcome them, learning from our past tunnel experiences, always inquiring which innovations are needed to overcome the current technical limitations. The new technological tools developed in areas other than tunnelling can be of great support when such technology could transferred to our field. In the past tunnelling history, inventors created eccentric machines in shapes and functions that were not always functional or economically viable, many times ending up having a short existence. Therefore, we need to always remember to keep our feet on the ground, because not all the inventions will fulfill the holistic set of requirements requested in such a multidisciplinary and technical demanding sector as the tunnelling one.

And, we are overall succeeding in many ways. New records were set, such as excavating long tunnels – for example the construction of the Gotthard Base Tunnel. The crossing underneath the Bosporus, the Eurasia Tunnel, at a depth of more than 100 m, mastering safely high pressures of 11 bars, is an example of a breakthrough in the tunnelling technology. Large traffic tunnels were driven in Hong Kong by the record-breaking TMCLK TBM with a diameter of 17.63 m. Added to this, inner-city megaprojects such as Crossrail and Doha Metro with huge logistical challenges and demanding time schedules have been successfully completed. They all lay the foundation for even more ambitious high-impact projects in the world of tunnelling in the future.

The next generation of international lighthouse projects is being implemented, which in turn leads to profound innovations in terms of planning, design, and realization. The 64 km long Brenner Base Tunnel will establish a new length record. In Paris, metro tunnels for the Grand Paris Express project will create more than 200 km of high-capacity, inner-city mobility, a palpable step towards a smart city set up. In the area of utilities, Singapore is building a highly effective wastewater infrastructure for the city-state with a Deep Sewer at a depth of 55 m. In Asia, the trend towards ever-larger tunnel diameters continues unabated. All around the world, the potential for innovation and optimization in the construction of high-capacity tunnel infrastructure are being seized and actively realized in ways never seen before. Presumably, we are at the beginning of a golden age for underground areas used and developed by people and societies.

1 >> INTRODUCTION

This lecture considers the past, present, future of mechanized tunneling with focus with the innovations developed since the 70s, the highlights along these years, and what lies ahead in mechanized tunnelling.

The review starts with the state of the art for mechanized tunneling at the beginning of the 70s.

The single-shell segmental lining with water-impermeable concrete is used in mechanized tunnelling in soft ground. The Hydroshield concept is developed [22] and in Japan in 1974 the first earth pressure shield is used [9]. Early precursors of the EPB could also be observed in Europe with the advances of the Swiss sewers Gümlingen-Muri and Solothurn [31].

After the efforts of the TBM manufacturers in the years before, cutting rollers are used in the hard rock which displace the button cutters used previously [7]. Machine designs for tunnel boring machines are in the most cases either single or double Gripper TBMs. Double braced Gripper TBMs were also used for the inclined tunnel drives in this period and later [7]. The double shield concept was first used in 1972 for a 4.3 m sewage tunnel [30]. The enlarging TBM is used for driving on larger tunnel diameters like the Sonnenbergtunnel in Luzern/Switzerland [7].

A new approach for the development of big diameter tunnels during this period is the use of a shield as temporary support and machine carrier and the installation of a segmental lining in solid rock. The Swiss TBMs of the Gubrist tunnel with the converted Heitersbergtunnel Robbins gripper machine in a shield TBM as well as the Seelisberg tunnel exemplify innovative machine concepts of the time [1].

Figure 1 : Excavator Shield TBM "Big John" for the Seelisberg Tunnel in Switzerland

The positive advance experience of both tunnels demonstrated the potential of mechanized tunnelling. To mechanize the construction of sewers, the advance concept of the open shield in pipe jacking is supplemented by a device carrier for an excavator with belt conveyor and skip mucking in the tunnel [12]. With the successful reference of the 1976 prototype, the «MH» principle was widely used for tunnel diameters of 1.2 - 4 m above groundwater level.

The hot spot of mechanized tunneling in the late 70s was the TARP project in Chicago with the use of Gripper TBMs.

Other technical developments were the mobile miner concept with the rotating drum equipped with cutter discs with was tested 1982. The first delivered machine was in 1985 for an Australian mine for a decline development project and had Ø 3.5-4 meters cutter head drum.

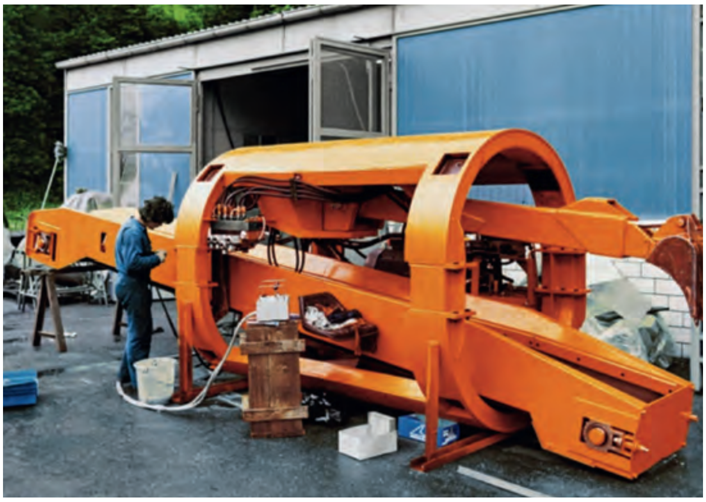


Figure 2 : The first machines, the MH1-3, for pipe jacking.

In 1984, the Japanese came with the concept of the enlargement shield method, to be applied in soft ground. The application of the method occurred in Japan, for the Minamisenju cable and utility tunnel under Route 4, enlarging the tunnel from 6.6 to 9.2 diameter, for a length of 30 meters. The enlargement of the tunnel happened by means of the shield excavating around the already existing tunnel, replacing the segments with the final desired diameter. The manual excavation followed with the ground supported by chemical pre-grouting [20].

To introduce new technologies and innovations to the market early on, the concept of micro machines for non-accessible tunnel diameters with slurry transport was developed in the mid of the 80s which were the baseline for a new machine type and project diameter. The first prototypes were tested successfully in the Hamburg mixed ground [13] [14].

3 >> The race for new concepts: 1985 - 2000

Following the requirements of the market, the newly developed Mixshield concept created the basis for a series of innovations in the soft ground sector. From the beginning the machine concept with the peripheral drive saw a greater adaptability to the specific project requirements, such as a mixed geology and more reserves in terms of drive performance. First Mixshield project was the DESY particle accelerator HERA in Hamburg 1985 [16].

Everything was being explored, even leading into a kind of eccentric machines designed by the Japanese companies [24] :

- Multiple circular face (MF) shield [35]
- Double-O-Tube (DOT) shield [19]
- Non-circular (oval) cross-section shield
- Rotating shield
- Tunnel diameter variation shield
- Ramified shield (Subterranean Stem Shield System)

Robbins and the Japanese manufacturers developed new hybrid-type machine concepts for the drives in chalk for the Channel Tunnel [21]. Three machines for the UK side of the Channel Tunnel were manufactured by Robbins/Markham and the other three by Howden. Robbins used for the first time 19" disc cutters for the Svartisen TBMs [10]. Wirth developed further the undercutting principle with the prototype Continuous Mining Machine (CMM) for the Canadian HDRK mine [36] as well Bouygues tested this undercutting technology also on their own tunnelling sites.

Figure 3 : Cutting wheel with four free-standing spokes equipped with drag picks; Mixshield S-12, HERA Hamburg 1985/1987, with Wayss & Freytag, as contractors.

The most memorable tunnel project at this time, the Channel tunnel, had started with eleven shields starting from the French or from the British side with drive towards the sea and the land side. With 39 km of tunnel excavated undersea (50 km of tunnel in total), chalk marl was the ground excavated along most of the tunnel length, with some stretches of glauconitic marl with permeable and highly fractured rock, either filled with clayey soil or even connecting directly to the seabed, where some of the machines were expected to withstand up to 10 bar of pressure. For that, specially designed sealed cutter chambers EPB machines, with multiple rows of wire brush seals in the tail were developed and used to cope with high water pressures [21], [30].

In the late 80s the Mixshield principle was further developed for diameters greater than 10 meters, also including the installation of a jaw crusher at the bottom of the excavation chamber, ensuring the crush of bigger rock pieces into easier-to-handle smaller grains. This technique was first used in Duisburg, with a 6.52 m diameter [5]. Simultaneously, the largest Mixshield in Europe, with a diameter of 11.60 meters was designed and manufactured for the Grauholz Tunnel in Switzerland (Figure 4).

Figure 4 : The Grauholz Mixshield in Switzerland.

The Grauholz geology included mixed-face, crossing heterogeneous glacial deposits, requiring a good control of the face pressure, leading into a challenge for the development of face pressure calculations and the experiences with tunnelling in non-cohesive soils [15] [32],

[33], [23]. This Mixshield started with the open star cutting wheel concept and fulfilled the breakthrough with a rim type cutting wheel.

Also in 1988, the Japanese built the first multi-head circular shield (MF shield) for the construction of the double-tube Kyobashi tunnel in Tokyo of the JR Keiyo Metropolitan line (Figure 5) [28] [35]. These machines intended to fulfill requirements of urban tunnelling, especially for metro projects, where a double tube was required, optimizing the usage of the underground space [25].

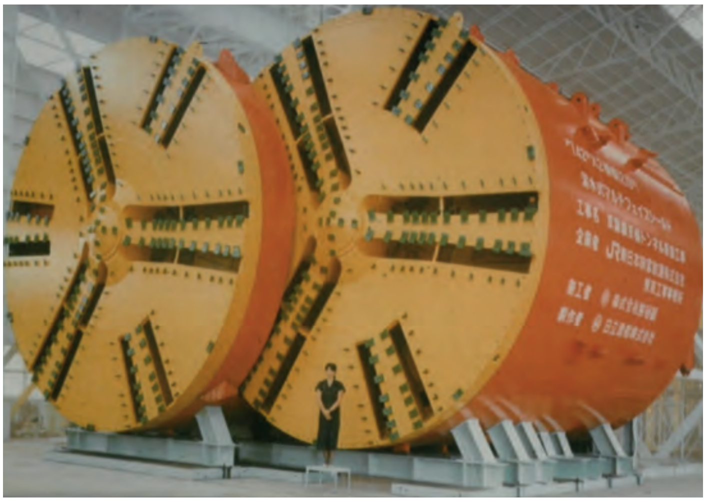


Figure 5 : Multi-face shield tunnelling machine [26]

Several multiple face shields were further developed, such as the Double-O-Tube (DOT) shield, with a prototype developed by IHI in 1988. In addition, triple or even more faces appeared years later, also developed and built in Japan. None of those had too many worldwide applications, besides some projects in Asia, when compared to the single shields, and most of them have been used for short length excavation (< 1 km). In the multi-circular face shield method the two cutterhead were set at different positions along their longitudinal direction, avoiding any interference when rotating. The DOT shield had the same purpose as the MF shield, but instead of a slurry type as the first, they had an EPB excavation system.

In 1990 the further development of TBM tunnelling in Switzerland started with the Shielded Hard Rock TBM for the Bözberg tunnel [27]. Innovations at the same time were executed for smaller diameters also in Mannheim, Germany, where the new invention for the AVN machines: a retractable micro tunnelling machine was used for the Fahrlachtunnel in Mannheim. Three AVN300 machines for 96 pipes, each 90 meters long, erected a pipe arch to be constructed around an existing tunnel and its newly built twin, serving to freeze the groundwater and protect the construction site. Since the blind holes ended in a slurry wall, no target shaft was possible: The retractable machine concept solved the challenge with involved transportation of the retracted cutter head back through the tunnel at the end of each drive.

The EPB shield known from the Japanese manufactures was further developed with integration of an airlock within the shield concept for the tunnel projects in Taipei, 1993. Very good advance rates were achieved, 16 m daily and 76 weekly maximum [6].

The year of 1994 had two major undersea projects as highlights: the Trans Tokyo Bay in Japan and the Europipe, a 630 km gas pipeline linking the North See gas fields to Continental Europe, having a significant stretch underwater.

The Europipe project with Ø 3.8 m achieved a milestone in pipe jacking (Figure 66). At a depth of seven meters in the launch shaft, a jacking station pressed the 200 to tunnel boring machine and the next reinforced concrete pipe sections into the sand with a force of 28,000 kN. Every 120 meters along the pipeline, intermediate jacking stations were installed. After 2.6 kilometers, the machine reached the target shaft. The friction caused by the grinding sand did not stand in the way of jacking operations thanks to the recently developed procedure of pressing lubricating bentonite suspension into the cavity between pipe and sand. First time this lubrication was fully automatic and computer-controlled.

The Trans Tokyo Bay, one of the longest undersea tunnels in the world, linked the cities of Kawasaki and Kisarazu, reducing the travel from 90 minutes to only 15. The tunnels with 13.9m outer diameter were excavated by eight slurry shields with diameter of around 14 meters, supplied by the Japanese manufacturers and includes some innovations like automatic ring erection [9].

Mid of the 90s the Japanese tested the rotation shield, able to turn and excavate shafts. The first machine with 5.5 diameter was used for the Tokyo sewer. The change in direction was feasible because of a smaller shield placed inside the main shield, supported by a ball joint moved by four hydraulic cylinders [34].

Figure 6 : Europipe, still a record today for Utility Tunneling.

The first time foam application in Europe was the EPB soil conditioning in 1994, for an Italian project, the "Passante Ferroviario" in Milan. The contractor decided to try foam instead of bentonite to condition a mixed and coarse-grained soil, resulting in better advance rates in the Ø 8 meter EPB machine [29]. The advantages of using foam as soil conditioner became clear also with the Metro Valencia tunnel project in Spain, as not only a more uniform face support was achieved along soft ground, but also the torque of both screw conveyor and cutting wheel were reduced by about 20% [17], [18].

In the hard rock mechanized tunnelling, the research works at the Äspö project showed the relationship between spacing arrangement, disc cutter and the generated rock chip size. This research came from the need of reusing the excavated material as a gravel for later pavement works, and, as a consequence, decreasing the disposal material [2].

The Mixshield concept was further developed for the machine for the 4tube of the Elbe River Tunnel, in 1996. Besides the record in size with a diameter of 14.20 m (Figure 7), it also provided the opportunity of incorporating several new design features. The accessible cutting wheel for safe cutter change and sonic wave technology within a Mixshield TBM for ground investigation ahead were introduced. Professional offshore diving workers were integrated in the tunnelling crew on the shield and performed interventions works during advance.

Figure 7 : TRUDE, a world record in tunnel boring machine in size and an opportunity to implement several innovations.

Looking to this era the increase of range of different products is obvious: Strong Horizontal Directional Drilling rigs (HDD rigs) as well as Vertical Shaft Machines (VSM) for the mechanized sinking of vertical shafts (Figure 8). The first application was 2003 sinking a 100m deep shaft for a water project on the island of Java.

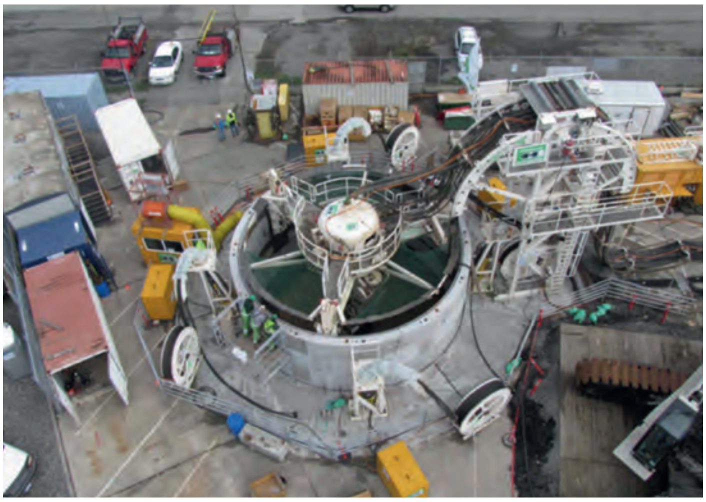


Figure 8 : Vertical Sinking Machine VSM at the Seattle´s Lake Washington Ship Canal.

The historic milestone in tunnelling in the early 2000s was set in Switzerland, starting with the tunnels of the Lötschberg Base Tunnel and followed by the construction works of the Gotthard Base Tunnel, with a length of 57 kilometer at that time the longest railway tunnel in the world.

Some unexpected events occurred along the way, such as crossing unconsolidated rocks at the beginning of the southern side excavation delayed the work in 2003. In 2005, the TBM Gabi 2 encountered loose rock and water infiltration, leading into the solution of solidifying the area with an injection of bentonite and cement mixture. In the same year, in the other side, the TBM Sissi achieved the best daily performance in the Gotthard Tunnel so far of 38 m in 24 hours in the east tube. Finally, in 2006 the breakthroughs in the Amsteg – Sedrun section with a good performance were achieved after 13.5 km and 14 km. Later in 2009, the other two gripper TBMs, Gabi 1 and 2, completed the northern Erstfeld-Amsteg section with a length of just over 7 km. In the space of only 24 hours, Gabi 2 cut through 56 m of the mountain – a world record for a TBM of this size. On Friday, October 15 of 2010, the machines achieved their final breakthrough in the eastern tube (Figure 9).

Looking to soft ground applications, two Mixshields completed in 2002 the excavation for a road tunnel beneath the Westerschelde River in the Netherlands. Challenges of this ambitious project were the record depth of 65 meters below sea level at which the tunnel had to be constructed and the demanding, varying geological conditions

Figure 9 : Final breakthrough of the TBM „Sissi" in the eastern tube of the Gothard Tunnel, Switzerland, October of 2010.

the tunnelling machines had to drive through. The Mixshields were ideally suited to cope with the geologically difficult properties of the highly plastic «Boomse clay» with high clogging potential. An open spoke-type cutting wheel with rim, an active center cutter with its own flushing circuit, agitators and a roller crusher in front of the suction intake ensured that the excavated material was removed with maximum efficiency. The Mixshields proved itself well able to withstand pressures of up to 7.5 bar and completed their tunnelling work in February 2002, after operating successfully for a good two years (Figure 10) [11]. It was the first time that diving works were executed under saturation in tunnelling where the divers remain for a longer period under higher pressure in their habitat.

Figure 10 : Breakthrough at the Netherlands project, Westerschelde, a challenge to avoid clogging issues and sustain high-pressures, under a record depth of 65 meters below sea level.

In 2005, one highlight was the Hard Rock Mixshield built for the construction of the Hallandsås railway tunnel in southern Sweden, which could withstand pressures of up to 13 bar, one of the most challenging tunnel projects worldwide. Extremely hard as well as extremely abrasive rock occurred along the tunnel route interchanging with sections of soft and mixed tunnel face conditions. The TBM named „Åsa" was designed to operate in closed slurry mode as well as in open hard rock mode. Whenever necessary, grout injections injected through a drilling and injection equipment would make sure to control the flow of water.

In 2006, the M30 Highway tunnel project was the focus of tunnellers, which required an EPB Shield with an two cutting wheel concept which can turn independent from each other in both directions. The inner cutting wheel had a diameter of seven meters and the outer, coaxial cutting wheel an excavation diameter of 15.20 meters. The center mixing dynamic due to higher center cutting wheel speed was the more important effect. As early as July 17, 2006 the breakthrough was celebrated on the jobsite in Madrid - after only 25.5 months of construction and 4.5 months earlier than expected (Figure 11).

Figure 11 : The EPB with double cutting wheel from the M-30 Madrid Road Tunnel.

After many projects going horizontal, then vertical, the Saint Petersburg escalator shaft requires in 2009, to go inclined (Figure 12). The major challenge during the mechanized tunnelling of the 105-meter-long escalator shaft in Line 5, of Saint Petersburg Metro, was the gradient of 30 degree. The solution was an EPB Shield with a diameter of 10.69 meters, which started with a special launch construction. The TBM was kept on its path during tunnelling with an innovative system of lifting cables and hydraulic cylinders. Two rail-bound wagons, drawn by winches, provided for the removal of the soil material. They also transported the segments below ground. Tunnelling went smoothly achieving performances of up to four meters a day.

Figure 12 : Saint Petersburg escalator shaft, going inclined now, an innovative tunnelling.

A mission of upward-inclined tunnelling for Herrenknecht was required in 2010 with the Kraftwerk Limmern tunnel, in Switzerland (Figure 13). The heart of this project is the tunnelling of two pressure tunnels each of a length of 1,023 meters. The steep gradient of 40 degrees (84.7 percent) in the Limmern project demanded a solution that reliably prevented under any circumstances the TBM slipping back as the grippers move in the tunnel. For that, a twin-anti-slip system was developed offering a complete redundancy of available gripper systems. In all operating conditions (advancing, standstill and regripping), at least two out of three anti-slip anchor is always securely clamped to the rock.

Figure 13 : Steep gradient that the machine had to overcome by driving upwards, with a 40° slope, at the Kraftwerk Limmern project, Switzerland.

Also completed in 2013 was the Galleria Sparvo tunnel in Italy, a widening of the A1 highway between Bologna and Florence. The tunnel construction consisted of two parallel drives, each with a diameter that set a new record in mechanized tunnelling. The two 2.5-kilometer-long tubes each house a dual lane roadway, along with a third emergency route. On the five kilometers in loose ground was expected, some containing explosive firedamp. In order to ensure a high level of occupational safety and speedy tunnelling performance, the contractor opted for a Herrenknecht EPB Shield (Figure 14).

Figure 14 : The TBM Martina, ready to excavate the Sparvo gallery, in Italy, with risks to face explosive gas along the way, well managed by the Herrenknecht team.

The shield diameter of TBM „Martina" of 15.55 meters was a world record at that time. The entire machine included a double-walled encased tunnel belt conveyor, that is additionally pressurized, and an efficient ventilation system. The first drive was completed after 12 months with the breakthrough at the first tunnel as early as July 2012. After top performances of up to 24 meters per day and up to 126 meters per month, Martina crossed the finish line after only eight months on July 29, 2013.

And finally not forget how variable underground can be, changing constantly from soil to rock, to mixed zones, not to say about all the faults and shear zones with high water flow a TBM had to drive through it. This challenging scenario kept pushing to provide adaptable machines that could easily change from one type into another, such as the one in the French TGV project, with the Saverne tunnel. The convertible EPB Shield Ø 10 meter was exactly adapted to the geological conditions of the project, enabling the machine to manage tunnelling in two different soil conditions. On the first 200 meters of the northern tunnel, the machine drove through loose rock (mixture of sandstone and shell-bearing limestone) using the closed earth pressure mode. During further tunnelling, the machine changed to the open mode to deal with mainly sandstone. To change operation modes only the cutting wheel was adapted, the belt conveyor and the screw conveyor remained installed on the machine in both modes (Figure 15).

In 2014 six innovative Variable Density TBMs are in used for the first time for the metro extension in Kuala Lumpur/Malaysia – in extremely challenging karstic limestone. The technology combined the advantages of EPB Shields and Mixshields. Without major mechanical modifications, the machine could switch between four different tunnelling modes directly in the tunnel. This made the Variable Density TBM the all-round tunnelling technology for soft ground of all kinds. The development target has been to achieve a system that can be transformed from a slurry face support into an earth pressure face support in the tunnel without any need of mechanical modification in the excavation chamber or behind in the gantry/tunnel area [3].

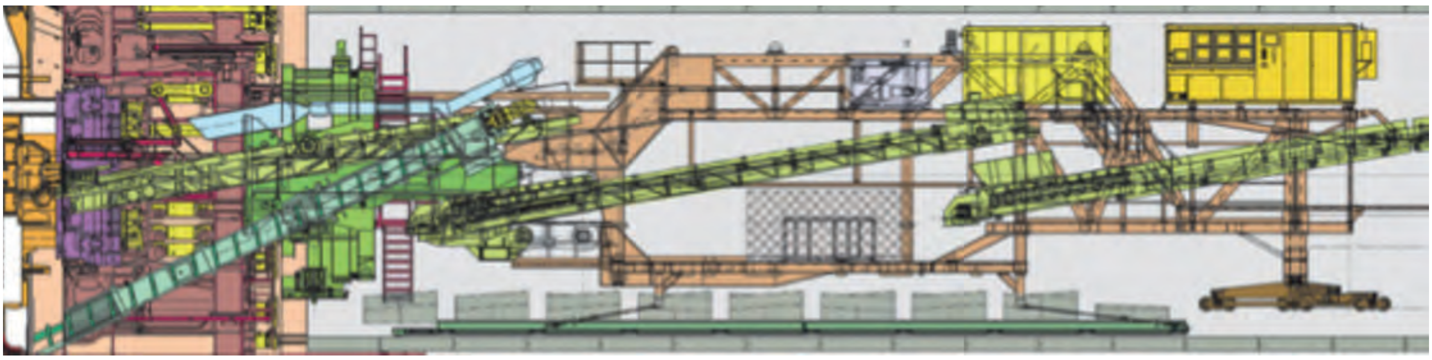


Figure 15 : Saverne dual-mode machine profile concept [3].

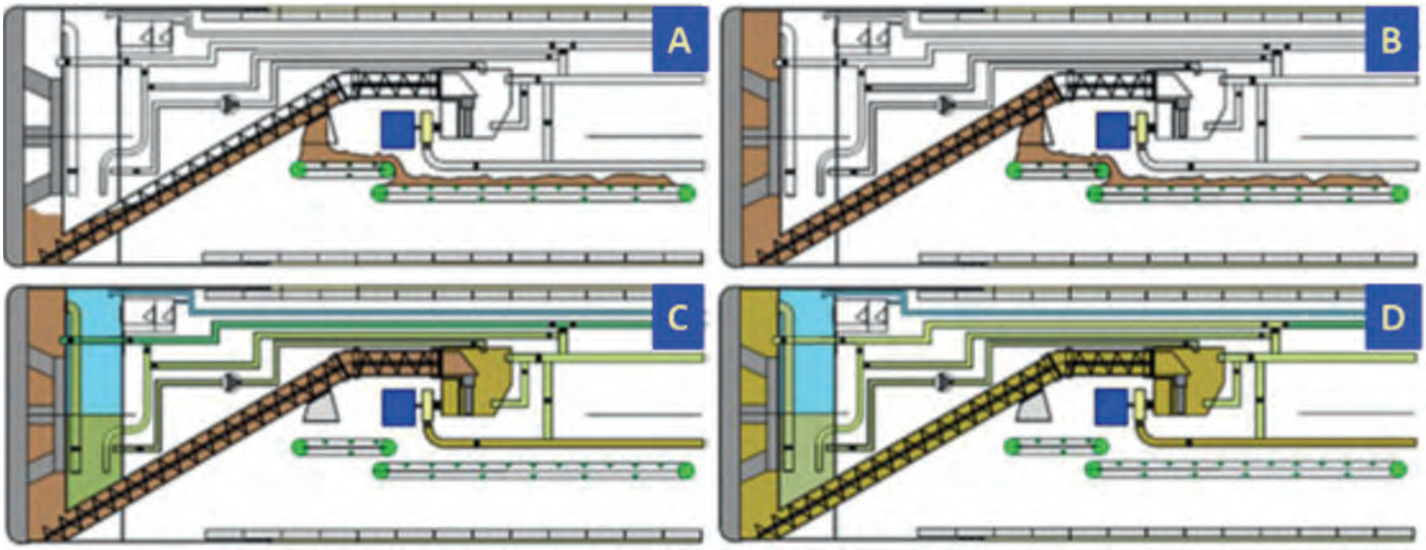


Figure 16 : Variable density machine in EPB open mode (A), EPB closed mode (B), high density slurry mode (C) and slurry mode (D).

A transition from one operating mode to the other happened quickly and without extensive adjustments. Depending on the requirements, pressurized bentonite with a connected slurry circuit or in earth pressure mode with screw discharge provided tunnel support. Combinations of the modes were possible as well as variation of the density and thus the viscosity of the bentonite in order to be able to react flexibly when changes occur in the tunnel face conditions.

Then high pressures, at the Lake Mead project were dealt, setting a new record withstanding water pressures of 15 bar under the lake for a new, deeper water intake for the Las Vegas water supply. The geological and hydrological conditions were extremely challenging. Over large parts of the tunnelling route, an enormous water pressure weighed down on the machine. The TBM designed for the project as a Multi-mode TBM (Ø 7.2 m) can be operated in open or closed mode according to the soil conditions and has considerable additional equipment.

Finally, completing the series of tunnel innovations and breakthroughs up to the year 2015, nothing better than the most challenging sea crossings ever done: the Istanbul Strait Road Tube Crossing, the first Bosporus road tunnel, completed in 2015. The route of the project runs around 100 meters below sea level at its deepest point. The interior diameter of the tunnel is 12 meters accommodating two lanes in each direction, extending one above the other on two levels. A Mixshield built a total of 3.34 kilometers of the first road tunnel between the Asian and European parts of Istanbul, with a total length of 5.4 kilometers.

According to the extensive geological and hydrogeological investigation, a water pressure of up to 12 bar has to be mastered. To be able to change the excavation tools quickly and safely even with high pressures, the accessible cutting wheel concept was further developed to the next generation level. The complete cutting wheel is accessible from the rear of the machine under atmospheric pressure. From there, all disc cutters and a large part of the scrapers can be changed safely (Figure 17). In addition, the Mixshield is equipped with a special, newly developed lock system, allowing pressurized air access over 5 bar when necessary.

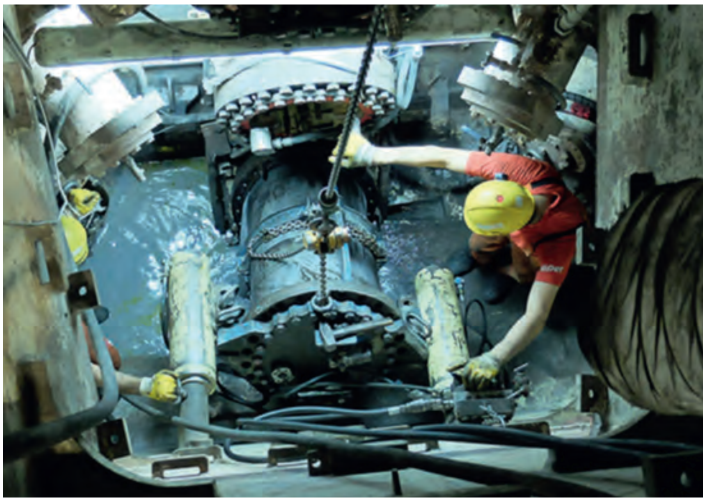


Figure 17 : Change of the disc cutter done from the rear with atmospheric air at the Bosporus road tunnel.

To detect wear early and to tackle necessary maintenance accesses in a targeted manner, wear detectors were integrated. Moreover, the disc cutters were equipped with the DCRM system (Disc Cutter

Rotation Monitoring). It provided data about the rotational movement and temperature of the disc cutters in real time to the machine operator in the control cabin. Thus, conclusions can be drawn regarding the condition of the tools and change intervals can be better planned.

The tunnelling for the project was launched on the Asian shore of the strait in April 2014. With pioneering technology and an ideal cooperation of all project partners the TBM accomplished best performances of up to 92 meters per week under the Bosporus. After only 16 months, the Mixshield pierced the reception shaft wall on the European side exactly to plan on August 22, 2015.

Even though drill & blast is still the dominating method in the Norwegian tunnelling market, four large Double Shield TBMs (Ø 9.9 meter) excavated approx. 9.5 kilometers of railway tunnel each for the Follo Line Project. On September 11, 2018, the first two Herrenknecht TBMs reached their final goal after about 2 years of tunnelling through tough Norwegian gneiss. The final breakthrough happened in the month of February 2019.

Currently, the world's largest TBM has been built by Herrenknecht for the Tuen Mun – Chek Lap Kok Link has a diameter of 17.63 meters (Figure 18), realizing a traffic feeder to enhance the transportation network of Hong Kong and linking the Northwest New Territories with Hong Kong's Airport. This project was not only a record for its size, but for the several innovations included there, a milestone in the tunnelling sector. These innovations included changing the size of a TBM from 17.63 to 14 meter, the common developed cross passage tunnelling concept using mechanized tunnelling machines and the robot application for the gauge and outer disc cutters developed by the Dragages-Bouygues JV.

Figure 18 : Hong Kong Tuen Mun - Chek Lap Kok Link, setting world records in tunnelling.

Doha was also a marking stone in the success of mechanized tunnelling, 111 kilometer of new metro tunnels are created in only 26 months under the capital of Qatar. Where before there was nothing, at peak times 2.5 kilometers of tunnel per week were added underground. What Qatar Rail and our contractors in Doha have accomplished in just 26 months of construction time with the highest standards of performance, safety and quality is an outstanding achievement in modern infrastructure development.

Figure 19 : Innovation as E-Power Pipe will enable new construction ways under existing infrastructure.

Innovations such as the E-Power Pipe follows with high precision the planned alignment and can quickly and safely cross under existing infrastructure such as pipelines, roads, railways or smaller bodies of water. E-Power Pipe has been recently nominated for receiving an innovation award at BAUMA exposition in Munich, 2019, likewise as DefAhS, a tool system for the removal of reinforced concrete structures.

The economic strategies and market growth of nowadays, and for the near future, come in hand with a global need for sustainability and process optimization. Here at Herrenknecht we are not only concerned in putting our products underground, we are interested in being part of a changing world, pushing us to optimize the use of the underground. People needs to be connected and the underground is a low impact solution.

Generated waste has to be decreased and processes have to be integrated in a fast processing platform, leading towards digitalization and automation. In line with what is called the 4th industrial revolution, the tunnelling sector has to adjust to these new challenges and take a leap towards Tunnelling 4.0. And this revolution is already been addressed in the ITA-AITES, with the ITACET Foundation course offered with this same subject in the WTC 2019 Naples.

Herrenknecht holds a major economic and strategic interest in innovating and optimizing the re-use of TBMs and its components. Improving the re-use of TBMs and components implies, not only in reducing the carbon footprint of mechanized tunnelling, but also offer customers attractive options with regard to delivery time. This brings circular economy and a sustainable manufacturing into action. The possibility of re-using machines and components offers Herrenknecht and its customers win-win synergies.

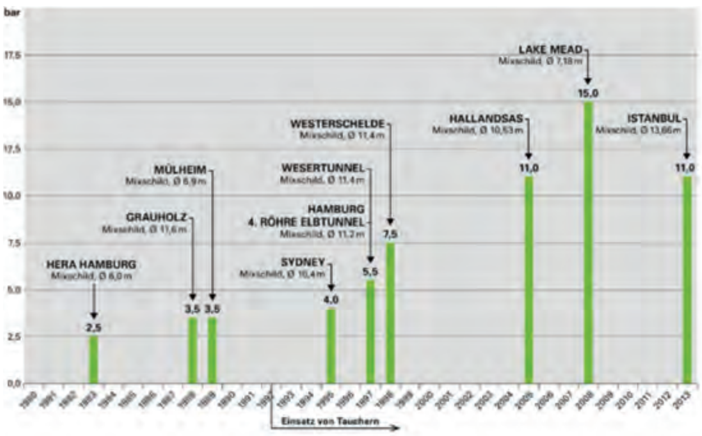
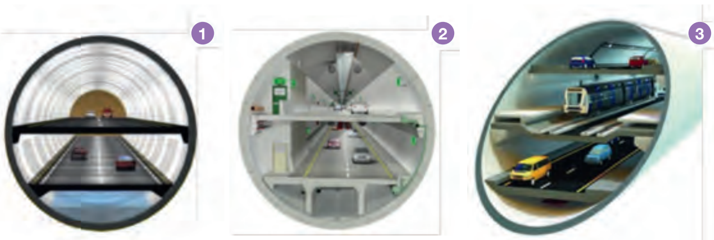


Figure 20 : Development of operating pressure based on pressures measured at the tunnel face of selected Mixshields.

With a view to tomorrow and the knowledge of the past, neither the development of the maximum operating pressures nor the diameters of tunnel boring machines has reached an absolute limit. It is important here to gradually adapt the project requirements in order to master the challenges arising from these issues. The supersize diameters offer the opportunity for different tasks (Combination of road tunnel and storm water reservoir like SMART, KL) as the bundling of different traffic systems in one tunnel (Figure 21).



Innovative TBM concepts as the Variable Density TBM will increase their mode of application further. For the mechanized shaft construction different shaft sinking methods are available already and will be developed further

- VSM technology for bigger diameters (currently 12 m) with active support of the shaft walls
- SDD rigs for up to 1,000m

and for hard rock and medium strength rock :

- Shaft Boring Machine (SBM) and
- Shaft Boring Roadheader (SBR)

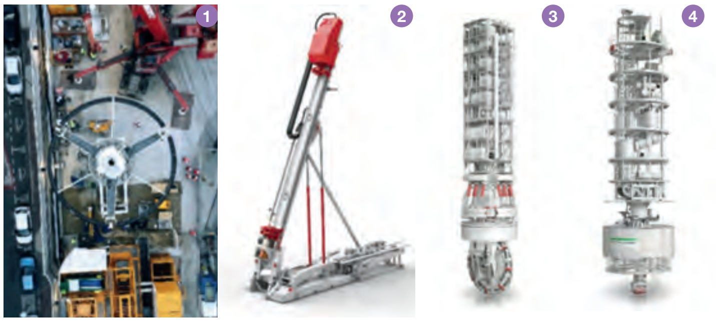


Figure 22 : Overview of the different vertical & shaft boring Machines: 1 Vertical Shaft Machine (VSM), 2 Slant Directional Drilling (SDD), 3 Shaft Boring Machine (SBM) and 4 Shaft Boring Roadheader (SBR).

We are also pushing hard towards automation, robotics, digitalization and IoT. TBMs produces a high amount of data and with the use of machine learning and data analytics, we can achieve predictive maintenance. By equipping our machines with sensors, data can be generated and by the use of data analytics and machine learning, patterns of equipment usage are understood, allowing the extension of a component´s lifetime. The smart machine will support the operator to recognize and decide if it requires intervention works before reaching any critical failure and to decrease unnecessary interventions and avoid failure of components. We are already doing that with our disc cutters rotating monitoring (DCRM).

Figure 21 : Possible utilization of tunnel supersize diameters: 1 Combination of road tunnel and storm water reservoir, 2 Two-lane, two-storey tunnel and 3 Bundling of different modes of transport in one tunnel [4] [8].

7 >> Final remarks

To be successful in future, you must be able to have a dream today, but you must also keep both feet solid on the ground. We keep pushing, we keep progressing and then, we can make a difference in this world. In technology, all that matters is tomorrow !

It is essential also to understand that each tunnel requires a specific tailored machine, mainly because of the huge variety of the ground conditions. From the history of tunnelling, many times the choices of a machine type, or even excavation type, were done incorrectly, leading into a misapplication of the tunnelling method, even with disastrous effect. This has lead into the misinterpretation that the failure was of the tunnel boring machine and not from the choice made. This is why we insist in the tailored-made aspect, each project requiring the uttermost care, aiming to achieve the most efficient design for that particular case.

And this is why education in mechanized tunnelling is indispensable. A TBM is a moving factory, where many processes are happening at the same time. This factory is inserted in an extremely complex surrounding environment, the underground, therefore, we need first to understand the underground. Then, the machine is a complex set up of various components, from different disciplines, interacting with each other, requiring a comprehensive approach. The tunnel boring machines require to be looked at with a multidisciplinary vision. We need to implement a new discipline in tunnelling, a holistic mechanized tunnelling engineering, where all the aspects of shield tunnelling are considered, applying this integrated concept from design to execution. We need also to keep pushing in incorporating the innovations of other industrial fields into our own tunnelling world, and only with cooperation between all parties that will be feasible.

Innovative construction of efficient infrastructures underground is a highly complex and interdisciplinary task. Each project is unique, with its own topographical, geological, technical, financial and economic requirements. In every project, the smartest solution and technology are key – for the benefit of the customers and society. There is still enormous potential for progress in the mechanized tunnelling.

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ITA Secretariat - c/o MIE2 – Chemin de Balexert 9 - CH-1219 Châtelaine (GE) - Switzerland
Tel. : + 41 21 693 23 10 - Fax : + 41 21 693 41 53 - Email : secretariat@ita-aites.org - Web : www.ita-aites.org