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## TBM APPLICATIONS FOR SHORT TUNNEL DRIVES

**K. Bäßler<sup>1</sup>, R. Angelov<sup>2</sup>**

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### ABSTRACT

Owners, planners and entrepreneurs but also users of tunnel structures in operation often question the use of mechanized tunnelling technology for the construction of short to relatively short tunnels. This topic had already attracted broad interest in the tunnelling industry especially among contractors and project planners about the minimum tunnel length, where the application of mechanized tunnelling technology is reasonable and commercially advantageous.

Within the context of this paper, a selection of reference projects is presented, showing that the use of tunnel boring machines (TBMs) can be quite viable even for relatively short tunnels and can be also crucial for the realization and secure implementation of a project.

### 1. Introduction

Mechanized tunnelling technology with solutions adapted to specific project conditions are in operation successfully worldwide. The high-tech state of the art tunnelling technology is used to construct arteries of life for the various means of infrastructure systems beneath the surface. This sometimes includes relatively short tunnel sections for road, rail and utilities for energy and water. The projects highlighted comprise bored tunnels of less than 900 meters in length that were excavated and lined using mechanized tunnelling technology. These tunnels are in use for sewage, water, service and metro trains all over the world.

Today large-scale projects are constructed in metropolises for metros and deep sewers that comprise numerous short bored tunnel sections of sometimes even less than 400 meters. The use of multiple TBMs for short drives is often necessary to comply with tight construction schedules.

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<sup>1</sup> Dr. Karin Bäßler, Herrenknecht AG, e-mail: baeppler.karin@herrenknecht.de

<sup>2</sup> Ralitsa Angelov, Herrenknecht AG, e-mail: angelov.ralitsa@herrenknecht.de

The paper addresses projects in South Africa, Europe, USA and Russia that have all in common that the built tunnels comprise bored tunnel sections of less than 900 meters using TBM technology.

## 2. Use of TBMs for Short Tunnel Drives

The projects highlighted are differing in respect of the geological, petrographic and geometrical conditions that are often decisive for the optimal choice of tunnelling method. If these conditions all enable the use of available tunnelling methods such as drill and blast, partial or full face excavation, then the tunnel length often becomes the deciding factor for the choice of tunnelling technology. The cited projects show that the use of TBMs was viable and commercially justifiable for these relatively short tunnel sections that could have also been excavated using other tunnelling methods and where the tunnelling length itself was not the determining factor for project realization.

### 2.1. Durban Harbour Tunnel, South Africa

In Durban a new service tunnel (ID = 4,4 m) was built for one of the continent's busiest ports, the Durban Harbour. Plans to widen and deepen the entrance to the Port of Durban to accommodate the depth of modern container ships necessitated the installation of a new municipal service tunnel. The new tunnel carries major sewage, water, electrical supplies and other utilities. It replaced an existing immersed tube.

The vertical alignment of the new service tunnel was governed by the proposed profile of the new harbour entrance channel and was designed as bored tunnel with a total length of only 515 meters. It has a steep gradient of 20% for about 100m at each side and a 300 m section at 0,5% across the main part of the harbour entrance. The minimum soil coverage to tunnel crown during construction was less than two tunnel diameters (9 m).

The geological conditions along the Durban Harbour tunnel comprise mainly Holocene and Pleistocene marine and lagoonal sediments classified as dense, fine cohesionless sand with clay and silt content. Only a small tunnel section was built in sandstone of varying strength between 0,5 and 50 MPa. The 515 m long tunnel was excavated and lined using a 5,17 m diameter Mixshield with liquid supported tunnel face (Slurry Shield). The machine from Herrenknecht was designed to operate with a maximum pressure of 3,5 bar. It was its fourth application after its prior use to excavate the Kai Tak Transfer Scheme in Hong Kong.

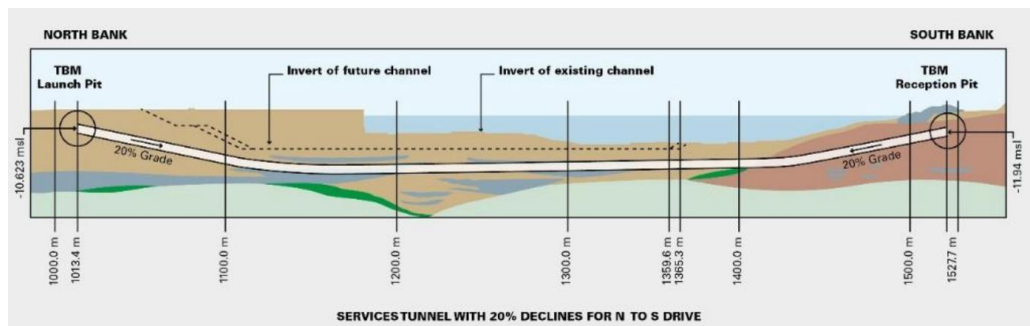


Figure 1. Durban Harbour Service tunnel – geological longitudinal section

The predicted geological conditions demanded a tool arrangement of both soft ground tools for the sandy clayey soils and disc cutters for the sandstone section. To cope with steep gradients of 20% a managed solution was offered with a trackless transport system by so-called Multi-Service Vehicles. These MSVs were designed and manufactured by Techni Métal Systèmes (TMS) in France. These vehicles supplied the TBM with lining elements and an adjusted mortar mix.

Tunnelling operation was based on a seven-day week due to a delayed start of tunnelling caused by problems such as a leak in the North Shaft. Three teams worked on a 12 hours shift on a 10/5-day rotational basis.



**Figure 2. Launching of TBM in the North Shaft**

Short tunnel drives such as the 515 meters as in the case of the Durban Harbour Tunnel have the challenge to get past the learning curve as quickly as possible to reach the planned tunnelling performance. The performance rate during the start of tunnelling was also influenced by the additional challenge of starting with a decline of 20% for the first about 100 m in soft ground and significant quantities of very stiff to hard clay along the sub-horizontal drive.

A total of 12 interventions were done during the construction period with planned interventions at the start and end of tunnel operation to check the condition of the cutting tools after excavating through the shaft walls at the launch shaft and again prior to excavating through the shaft wall into the reception shaft [1]. Interventions were also needed due to the accumulation of annular gap backfilling material on the outside of the tailskin during the declined drive and due to clogging issues in the excavation chamber or blocked slurry level sensors that occurred in the stiff to hard clay sections. These clay sections posed additional demands on the separation plant due to the amounts of very fine material that tested the capacity of hydrocyclones.

The tunnel-boring part of the project was completed in only four months so only a very short learning curve was available in this contract. The Durban Harbour Tunnel was the first tunnel project in South Africa that was excavated using a Mixshield (Slurry TBM).

The final part of the contract comprised the decommissioning and removal of the existing services in the old submerged tunnel tube.

It was not only the short bored tunnel length of about half a kilometer that interest owners and consultant engineers but also the specific project conditions with steep gradients and the use of a closed mode TBM operation with a Slurry Shield and its demand on logistics, material transport and annular gap backfilling.

## 2.2. Northern Lot of the North-South Urban Light Railway Cologne, Germany

In the city of Cologne in Germany a new, about 4 km long, North-South urban light railway route was built to connect the southern districts of Cologne with the city center.

Project challenges were the construction of the underground line in densely populated urban area with locally very low overburden, crossing beneath sensitive structures such as historic buildings, a storm water collector and railway embankments.

The overall project of the North-South link was split in two contract sections, the North and the South lot, with considerably differing lengths (see Fig. 3). The reason therefore was to accommodate the tunnelling concept with advance construction measures that were executed at the main station and the Museum Ludwig.

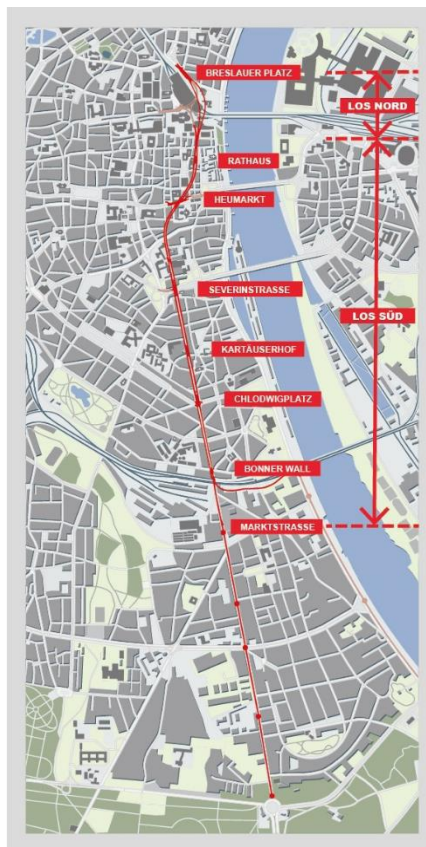


Figure 3. Tunnelling sections for the North and South lot [2]

In total three Mixshields were used for the North-South light rail project. The focus within this paper is on the two parallel 260 meters long sections for the northern lot that were excavated using a 6,8 m diameter Mixshield. This section comprised two very short drives that were realized as dead-end tunnels. The excavation started at the Breslauer Platz and crossed beneath sensitive structures and facilities of the Germany Railway to a jet grouted block that was located to the north of the museum complex. Tunnelling for the first single-track tube took place between July and September 2006. After the first section was completed, the 47 m long machine was retracted and fitted with a new shield skin to continue the second parallel section for the western tube. This section was excavated and lined between December 2006 and February 2007. The geology along the drives was characterized by Rhine deposits comprising water-bearing quaternary sands and gravels, blocks and boulders incorporated in the soil structure and sections of treated ground.

Tunnelling along this route alignment in a sensitive urban environment, mechanized tunnelling was focused on a settlement controlled process especially in sections with low cover. In one section, the minimum overburden between the crown of the TBM and the foundations above comprised no more than one meter. These challenging specific project conditions resulted in the design of the three machines. All three machines were equipped with [3]:

- An extensive data acquisition system that provides continuous information about the tunnel face support and relevant machine parameters that are essential for a controlled excavation process;
- An electronic wear detection system for the soft ground tools and cutting wheel structure;
- A system for seismic probing ahead of the cutting wheel to detect possible natural or man-made obstacles.

Tunnelling for the northern short sections also used a novel method for launching the shield. This new method, the “flying shield start-up”, was developed by Hochtief and was first applied for the northern section of the project in Cologne. [4] The system possesses major advantages compared to conventional TBM start-ups with a fixed rigid structure and requires several temporary segmental rings to be built in the open as the shield is launched. The new method requires less space for the start-up with the total system consisting of TBM, spacer pieces and push ring. This set-up is especially of interest for urban construction sites with constricted space conditions. For the northern tunnel drives, only about 33 m were available for the setting-up of the TBM.

### **2.3. Undersea Tunnel for the Flamanville 3 Nuclear Power Station, France**

The European Pressurized Water Reactor (EPR) de Flamanville 3 project includes an 867-meter long outlet tunnel for cooling water that was excavated using a 6,11 m diameter Mixshield from Herrenknecht. Tunnel excavation started on June 30, 2009 at the bottom of a deep shaft onshore and out under the sea for its entire length with a dead end at the discharge shaft where the TBM arrived on March 26, 2010.

The project area is divided into an eastern area with granitic rock and a western area with dark hornfels formation. The area includes additional late micro-granitic intrusions (dykes of several meter thickness). The entire outlet tunnel is situated within the metamorphic series that contain iron oxides in very variable portions. The first 450 meters of the tunnel was predicted to be in typical hornfels formation, the highly metamorphosed contact zone near to granite intrusion. Locally the hornfels has intercalations of quartzite. The remaining tunnel section was described to be partly in metamorphosed and partly recrystallized rocks.



**Figure 4. Prevailing geological conditions at tunnel face**

The rocks to be encountered in general were predicted to be extremely hard and abrasive. Rock mass discontinuities were mainly related to sedimentary bedding structures in the low grade metamorphosed rocks. Major fault zones were predicted with crushed sheared rock (clayey material). Based on the prevailing geological conditions and the tunnel construction beneath the sea level, a Mixshield was applied for the excavation and lining of the tunnel that has a length of less than one kilometer. The TBM was designed with a maximum operating pressure of 4 bars. It had a total length of 92 m including eight gantries. Due to the constricted space on site the excavation started with the assembly of the first 4 trailers and trailers 5 to 8 remaining at the shaft head.

The extremely hard and abrasive rock mass was decisive for the cutterhead design. It was equipped with 34 17-inch single disc cutters and 4 17-inch double disc cutters with a spacing of 67 to 98 mm, 6 buckets, grizzly bars and extensive wear protection in the face and gauge area. The machine had an installed maximum torque of 4,850 KNm. It was also designed to allow injection drillings for ground treatment in case this proved to be necessary. Therefore, the 11 ports were designed allowing divergent boreholes to be drilled at a 9° incline ahead of the machine. They were used only when the tunnel was connected to the offshore shaft.



**Figure 5. Mixshield (Ø 6,11 m) applied to construct the undersea tunnel**

The tunnel lining consists of reinforced concrete elements having an inner diameter of 5 m. The ring design is of a universal ring type (5+1) having a thickness of 400 mm. The high-precision segment moulds for stationary production of the concrete segments were supplied by Herrenknecht Formwork. The scope of supply comprised 3 sets of moulds for stationary production with vibration, spare parts and measurement instruments.

After tunnelling was completed, the area of rock between the shield edge and the shaft liner was consolidated and sealed with injections. Then the machine was disassembled with the shield shell left in place as part of the final formwork for the connection bend.

## 2.4. First Street Tunnel Washington DC, USA

The "Clean Rivers Project" in Washington, D.C. will ensure that 96% less untreated sewage is discharged into the Potomac River, the Anacostia River and Rock Creek. Three tunnel boring machines from Herrenknecht were in use to create huge tunnel structures with a total length of 11,85 kilometers. These tunnel structures will act both as temporary storage and efficient feeder lines to the Blue Plains Advanced Wastewater Treatment Plant in the south of the city, the world's largest wastewater treatment plant.

One of the three machines was in use to excavate the 800 m long tunnel section for the First Street tunnel. This tunnel will prevent further flooding of the neighborhood after heavy rainfall with additional temporary storage capacity underground. In the long term the First Street tunnel will be connected to the other tunnels in the Clean River Project. The machine that excavated the short tunnel section had a diameter of 6,95 meters and was operated between July to December 2015 by Skanska-Jay Dee JV. The EPB shield with backup was designed, manufactured and accepted after workshop assembly and test in the factory in Germany.

The geological conditions along the 800 m long bored tunnel section were characterized by fine-grained cohesive soils (hard and over-consolidated) and coarse-grained cohesionless soils (dense to very dense). The soils are interlayered groups, which vary from highly plastic fine-grained soil to coarse gravel [5].

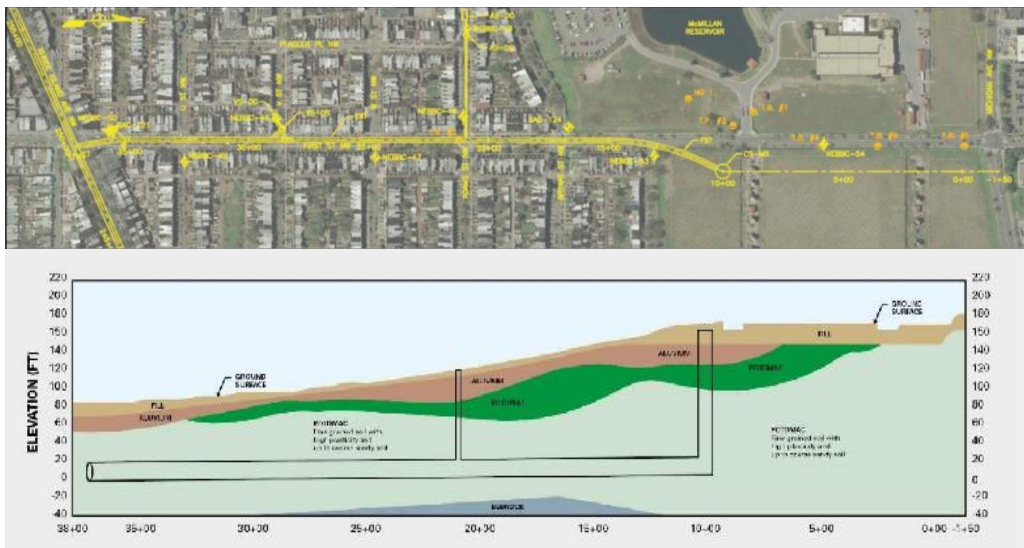


Figure 6. Layout Plan TBM tunnel and geological longitudinal section

The machine was assembled in a 49 m deep shaft (ID: 20 m) at Channing Street Construction Site located at the north end of the project. Launching of the shield started using umbilical hose connections with the backup still on surface.

The EPB Shield excavated at depths of 24 to 49 m beneath the surface for a total length of about 800 m and crossed beneath densely populated areas. The drive was completed in a dead-end thus the machine had to be retracted and disassembled. The cutterhead and shield with the main drive remained in the ground.

The machine was advancing about 15 meters of tunnel per day with best performances of up to 25 meters in this short tunnel section.

Tunnelling operation was characterized by multiple significant challenges ranging from technical to logistical to community concerns. The TBM excavated in extremely tight working areas and in an urban residential community. Apart from that the project was challenged by tight project schedules, and encountering a dense network of utilities locally more than 100 years old.

## 2.5. Escalator Shafts for the Metro St. Petersburg, Russia

In St. Petersburg three metro stations were connected by means of escalator shafts to the surface by using an EPB Shield of 10,6 m in diameter.

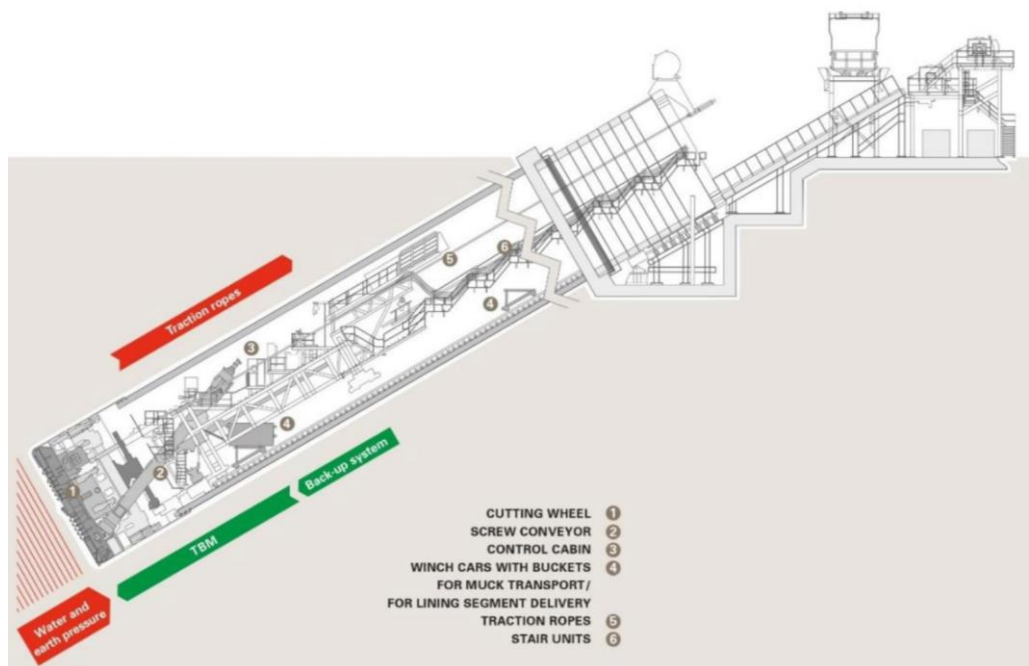


Figure 7. Declined drives of 30° in soft clay

The main challenge in the urban tunnelling project was to safely access three stations from surface with 30° declined drives in soft ground below the groundwater table. The specific project conditions included the decline in soft geology and very short tunnelling drives of only 105 m for the first, 116 m for the second and about 140 m for the third escalator shaft. The solution to cope with these demands was the use of technical advantages of mechanized

tunnelling technology with the ability to control settlements on surface. This is one of the main issues for tunnelling works in urban area.

In the past these sorts of conditions were dealt with the application of conventional construction methods that required temporarily frozen ground in sections for the excavation and cast in situ concrete lining. The old method was associated with substantial risks of heave or subsidence during freezing and thawing in the densely built-up city area of St. Petersburg. In addition, the conventional method was time consuming and costly.

The EPB Shield was selected to suit the predicted geological conditions of soft clay. Due to limited space in urban area and the short tunnel lengths a compact and short TBM design was considered. The TBM had a total length of only 35 meters. EPB Shields of comparable diameters are often ten times that length [6].



**Figure 8. Installation and near surface start of TBM**

For the realization of three 30° declined shafts the focus was on a safe and settlement controlled construction method. The basis for the successful excavation was a smooth interaction of logistics and job site installation behind the TBM. Special attention for the design of the 10,6 m diameter EPB Shield for the 30° decline was on [6]:

- Material handling and logistics;
- Backup;
- Control of the TBM;
- Recovery of TBM.

In respect of material handling and logistics the material transfer from within the excavation chamber to the back was done via screw conveyor. The excavated muck was then further processed with two rail-bound wagons that run on twin tracks hauled to the surface by a winch system. This winch system was also used to transport the lining segments to the machine. The annular gap backfill material consisted of a two component grout that was transported to the machine via lines carried on a cable garland.

The machine had a total length of 35 meters including the 21 meters long backup. Due to the winch house installation in the launching shaft the installation of the backup was limited and required the assembly in two steps. To comply with a short overall TBM length the transformers for energy supply of the machine hydraulics were not installed on the backup but were located instead on surface.

To control the TBM due to its declined drive of 30° in its position and to avoid any uncontrolled deviation of the machine respectively sinking of the machine a system of traction ropes and hydraulic cylinders was developed that kept the machine on course. These traction ropes were fixed to the shield and were conducted up to the escalator shaft to the surface. The tension ropes were anchored to hollow piston cylinders on the reaction frame.

Another prerequisite was the need to recover the machine for its threefold use to excavate all three shafts. This had to be considered already in the design phase of the TBM. The disassembly of the EPB machine took place underground and the main components of the machine were recovered from the dead-end shaft to be reused for the excavation of the subsequent escalator shafts. Therefore, the shield was designed with outer steel elements that were left in the shaft as part of the shaft construction and removable inner steel parts. The backup and the other machine components except the outer steel elements were disassembled in the shaft and retrieved using winches.



**Figure 9. Segmental lining as tunnel support**

The tunnel support consists of 500 mm thick reinforced concrete elements (7+1) of one meter in length. The segment moulds were manufactured and supplied by Herrenknecht Formwork.

### **3. Conclusion**

Numerous infrastructure projects are constructed using mechanized tunnelling technology even for relatively short tunnels where the tunnel length itself is not the determining factor for the choice of tunnelling method. More often the specific project conditions demand for tailored solutions guaranteeing primarily the safe but also reliable and timely realization of a project that is most often in focus of the public. Specific projects such as the construction of the escalator shafts for the Metro in St. Petersburg give new innovative directions of machine application for possibly even more complex geological conditions and for projects with space constraints.

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## ПРИЛОЖЕНИЯ НА ТПМ ЗА КЪСИ ТУНЕЛИ

**К. Баплер<sup>1</sup>, Р. Ангелов<sup>2</sup>**

**Ключови думи:** ТПМ тунелно пробивни машини, тунел

### РЕЗИОМЕ

Собственици, проектант и възложители, но също така и гражданите, които използват пуснатите в експлоатация тунели, често поставят под въпрос използването на тунелно пробивни машини при изграждане на къси, до сравнително къси тунели. Тази актуална тема вече привлече вниманието на тунелната индустрия, най-вече в лицето на изпълнителите и проектантите, относно минималната дължина на тунел, изпълнен с ТПМ, практически и ефективно, от търговска гледна точка.

В контекста на този доклад е представена селекция от референтни проекти, показващи, че използването на тунелно пробивни машини (ТПМ) може да има решаваща роля за реализацията и сигурното изпълнение на проекта.

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<sup>1</sup> Dr. Karin B ppler, Herrenknecht AG, e-mail: baeppler.karin@herrenknecht.de

<sup>2</sup> Ralitsa Angelov, Herrenknecht AG, e-mail: angelov.ralitsa@herrenknecht.de