Challenges in Mechanized Tunnelling

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1. Introduction

The feasibility of tunnel projects strongly depends on the knowledge about the subsurface conditions, water presence and other constraints such as the situation above ground, overburden and space requirements. For the realization of tunnel projects first all possible risks have to be analyzed before proving the technical feasibility and adapting suitable construction equipment. Accompanying the population growth there is a demand for flexibility and mobility, but more and more there will be the need for increased resources of water and energy. To cope with these essential requirements a quick realization of the planned projects is the focus for all projects in the transport infrastructure sector and also in supply infrastructure. In this respect mechanized tunnelling offers the technology and the solution for quick implementation.

With the Metro Line 7 Extension in New York a project will be executed within the inner city area. The construction of the structures within this contract will interface with existing buildings, infrastructure and utilities along the alignment. In Nevada, close to Las Vegas a water supply tunnel, the Lake Mead Intake No. 3, is under construction. The tunnel will be driven between the intake and the pumping station. One of the challenges here are potential groundwater pressures of 16 bar. In comparison the challenges of the longest rail tunnel, the Gotthard Base Tunnel, are demanding rock conditions with high overburden and rock-burst phenomena. The focus on the mentioned projects shows the challenges of each specific case with the adapted and well designed machine technology for a safe and reliable tunneling advance process.
2. Challenges in Mechanized Tunnelling

2.1 Metro Line 7 (Flushing) Extension, New York

The “Number 7 (Flushing) Line Extension” project is on Manhattan Island in New York. The project alignment is located about 244m east of the eastern shore of the Hudson River, about 6.4km north of its mouth at Upper New York Bay. The Hudson River estuary system is a major waterway of the northeastern United States.

In December 2007, the Metropolitan Transport Authority (MTA) awarded a contract to S3II Tunnel Constructors, a joint venture of J.F. Shea Construction, Skanska USA Civil North East and Schiavone Construction Co, to build the twin-tube running tunnels from the current 7 line terminus in Times Square and the station cavern at 34th Street at Hudson Yards in Manhattan's Far West Side.

(Fig. 1) - Tunnel alignment – Number 7 Line Extension, New York

For the excavation of the 2 tunnels of about 2.8km each two Double Shielded Hard Rock TBMs were ordered in December 2007. The machines are adapted to the specific project conditions, i.e. the geological and logistical conditions.

Manhattan is underlain by a glaciated and deeply eroded assemblage of metarmorphosed, folded, and faulted Proterozoic to middle Paleozoic age rocks. Topography is largely controlled by bedrock geology. The machines are excavating in hard rock comprising slate, granite and serpentinite underneath midtown Manhattan. The tunnel alignment runs under key infrastructure elements such as the 8th Avenue subway line, Amtrak/NJT tunnels to the west, Amtrak tunnels to the former New York central line going north, the Port Authority Lincoln tunnels and the Port Authority bus terminal and ramps.

The tunnel boring machines had been manufactured and tested by Herrenknecht AG at its workshop in Schwanau, Germany. After disassembly in three separate shipments they were transported by boat to New York. The first shipment arrived in early January 09, the second in early February 09 and the third later in February 09.

Both Double Shields were assembled in spring 2009 in the launching shaft at the corner of 25th Street and 11th Avenue. The cutterhead was assembled on surface and lowered in one piece into the chamber. After assembly both machines started excavation for the parallel tunnels of 2.8km each north along 11th Avenue to the current terminus of the 7 Line at 41st Street and Times Square.

The breakthrough of both machines is scheduled for Spring 2010. Then the follow on work will start, with the new service opening in December 2013.
The two identical Double Shielded hard rock machines with an excavation diameter of 6.88m are among the most technically sophisticated TBMs in tunnelling. This because two applications, Gripper TBM and Shielded TBM, can be combined within the same machine. The double Shield TBM comprises following components:

- Cutterhead with front shield
- Main bearings and drive
- Gripper shield with gripping device (gripper plates)
- Tailskin
- Ancillary thrust rams.

The requirement for the tunnelling equipment to be used on this project was for a full face hard rock TBM with the capability to negotiate short sections of mixed face and possible soft ground conditions. The initial tunnel sections on No7 with soft ground in the crown were pretreated by ground freezing from the surface. Moreover the machine must be capable of excavating very strong and extremely abrasive rocks such as the Manhattan Schist and Pegmatites. To fulfill TBM performance requirements the machines should be equipped with:

- Provisions for drilling probe and grout holes
- 17-inch or larger disc cutters
- Back-loaded cutter mountings
- Automated guidance system
- New or refurbished TBMs.

Both machines are equipped with a flat and closed hard rock cutterhead with back-loading cutters (Fig. 2). The cutterhead is equipped with 17-inch single and twin disc cutters and has a boring diameter of 6.88m. Each cutterhead is powered at 2,100kW and the total thrust is 25,722kN. The Double Shields can be equipped with drilling equipment, 1 drill feed unit and one rotary rock drilling unit which can be assembled on the erector head. The drill rig is not permanently installed and therefore one drill rig will be used for both TBMs.

(Fig. 2) - Double Shielded Hard Rock TBM for Number 7 Line Extension, New York

During the project, a total of 250,774m$^3$ of rock will be excavated. The excavated rock is transferred by conveyor belt from the cutterhead to the back of the tunnel boring machine where it will be loaded onto muck cars. The system to transport the muck from the TBM and to supply material to the TBM is a single track rail-bound transport.
The tunnel lining consists of precast concrete rings. One tunnel ring comprises 5+1 elements. For each tunnel tube 1,890 rings will be placed in parallel to tunnel excavation. The two machines have to pass the station cavern underneath 34th Street which was constructed using controlled drill-and blast. When reaching this station cavern, the machines will be walked through to finish the remaining section towards the reception shaft.

2.2 Lake Mead Intake No. 3, Las Vegas [1]

Two water intakes and two pumping stations are currently operated 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 Project, 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 of 4.8km in length is located about 24kms east of Las Vegas and will be excavated by a tunnel boring machine.

SNWA contracted the joint venture, known as Vegas Tunnel Constructors, to design and construct the intake tunnel and structure. The joint venture consists of Impregilo S.p.A (Milano/Italy) and S.A: Healy Co. (Chicago, Illinois/USA) and they selected Herrenknecht AG from Germany to design and manufacture the tunnel boring machine. The contract for the 7.22m-diameter convertible Hard Rock Mixshield TBM was signed on April 8, 2008. The machine was assembled in a 170m deep access shaft of 9.1m in diameter which is lined with a concrete lining.

The challenges for the execution of the project are the depth of the tunnel with corresponding hydrostatic pressures which are expected to amount to be approximately 16bar. This pressure is in the range of the groundwater pressure also predicted for the TBM excavation for the Hallandsas rail tunnel project in Sweden. The geological and hydrogeological conditions for the Lake Mead project are characterized by sedimentary and volcanic geology which lead to the design of a shielded machine that can be operated in open mode and closed slurry mode. It is capable of handling difficult hard rock conditions with a potential for high groundwater inflows and high hydrostatic pressures.

The TBM is equipped with drilling and grouting equipment. 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. 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 3 illustrates the possibility of drilling through the face and perimeter drill holes which are permanently available or available with minor disassembly. 

(Fig. 3) - Available drill pattern on the TBM
Further requirements for the machine design when operating in a depressurized 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 17 bar. The cutterhead of this 190m long Mixshield of dual mode has a diameter of 7.22m and is fitted with 17-inch back-loading cutters.

In open mode operation the muck is transported by buckets and muck channels to the muck hopper in the cutterhead. The muck hopper is 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 will pass through a stone crusher and will be transported out of the tunnel via slurry circuit through pipes installed along the tunnel. The muck will be then separated in a slurry treatment plant installed at the tunnel portal.

(Fig. 4) - TBM Operation open mode (left) and closed mode (right)

With hydrostatic pressures of about 16 bar maintenance and inspections for tool changes have to be guaranteed. The tunnelling system is therefore prepared for hyperbaric face access. 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 respectively 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 4.8km long Intake tunnel will be 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 17 bar.

2.3 World longest railway tunnel, Gotthard Base Tunnel [2]

The Gotthard base tunnel, which will be the longest rail tunnel in the world with a length of 57km, is currently under construction through the Swiss Alps. This future-oriented flat railway through the Alps will be put into service at the end of 2017. The two parallel rail tunnels will contribute to the improvement of travel and transport possibilities in the heart of Europe. In total there are four subsections that will be excavated by means of mechanized tunnelling. The remaining sections of the two parallel tubes will be driven by drill and blast.
Following four mechanized tunnel sections are excavated with 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)

(Fig. 5) - Gotthard Base Tunnel subsections driven using mechanized tunnelling technology

The first subsection driven by means of Gripper TBMs was for the Amsteg-Sedrun lot. The first tunnel was completed in June 2006, and the parallel section by the beginning of October, 2006, about half a year ahead of schedule.

From the south, two Gripper machines excavated and secured the two 14km long parallel tunnels for the Lot Bodio-Faido by the beginning of September 2006 and the end of October 2006 respectively. All four Gripper machines excavated through the demanding rock massif with the presence of local fault zones which extended over long stretches, especially in the southern lot starting in Bodio. Nevertheless the TBM drives which totaled about 50km were completed on time.

All four machines have been refurbished and modified after excavating their first stage and be put into operation for the follow on lots Erstfeld to Amsteg in the north and Faido to Sedrun in the south. The adaptations on the machines had been done to suit the predicted geological conditions but were also based on the experiences made along the first drives.

The geology along the subsection from Faido to Sedrun is characterized by two tectonic units, the Penninic Gneiss zone (approx. 5km) and the Gotthard Massif (approx. 10km). The predicted Piora zone is characterized by solid, compact and partially metamorphic dolomite anhydrite rocks at tunnel level.

Some modifications done on the two TBMs operating for the subsection Faido are listed as follows:

- Increasing of the excavation diameter to 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
- Replacement of 17-inch disc cutters by 18-inch cutters.
- Adaptation of the gripper and the walking legs to support a diameter of 9.50m.

Modifications were also done on the cutterhead dust control system, to increase from 600m³ per minute to 1,100m³ per minute.
The first Gripper TBM for the Faido east tunnel started tunnelling beginning of July 2007; the TBM start for the west tunnel was scheduled for October 2007. TBMs still operated by the joint venture Implenia of Zurich, Switzerland, Alpine Bau of Salzburg, Austria, Hochtief of Essen, Germany, Impregilo of Milan, Italy and CSC of Lugano, Switzerland which also carried out the excavation stage in the subsection of Bodio.

The geology along the two single-track tunnels of 7.2km each from Erstfeld to Amsteg is characterized by mainly solid and geotechnically favorable highly metamorphic gneisses (Erstfelder gneiss). The AlpTransit Gotthard AG administrative council awarded the subsection Erstfeld to the Joint Venture Gotthard Base Tunnel North consisting of the companies Murer-Strabag AG, of Erstfeld, Switzerland, and Strabag AG, of Spittal/Drau, Austria. The tunnels are being excavated and secured by the two TBMs that have driven the 2 x 11.35km long Amsteg section. This section includes an underground junction to permit a future extension of the tunnel towards the north without interrupting the operation.

![Hard Rock Gripper TBM at Amsteg.](image)

Challenges in connection with the TBM drives for this giant tunnel project are long tunnel drives with large overburdens (> 2,500m) and 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 in the start-up 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 manufactured by Herrenknecht proved, however, that they are in a position to technically overcome situations that were much more difficult than those envisaged in the contract.

### 3. Conclusion

The high demand for mechanized tunnelling for the construction of underground structures is shown with the examples of referenced projects in the immediate vicinity of existing buildings or traffic systems such as for the project Metro Extension Line 7 New York, the geological and structural challenges as shown with the Lake Mead Intake N° 3 project and the Gotthard Base
tunnel. The tunnel drives show the complexity of the projects of today and the adaptation or further development of available machine technology in order to complete the projects in a safe way for all people involved during the construction period but also in a reliable manner thus that time schedules are kept to bring the projects in operation in time.

Feedback from running projects along with on-going research and development allow the use of the newest or clearly advanced technology for an even more optimized tunnelling process.

Essential for the success of every large construction project is a close and constructive cooperation between client, contractor, supervisor of works and the enterprise.

References
