Urban Tunneling in Settlement Risk Areas

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ABSTRACT

The paper introduces technology and methods for tunneling in urban areas with strong control of settlements. This includes the choice of TBM type, design of the face support system as well as application of support pressure with EPBs and Mixshield TBMs. Other topics covered are the sensor control of the excavation. The paper will introduce state of the art developments and case studies from recently completed TBM projects in Korea.

1. INTRODUCTION

More and more tunneling projects are executed in densely populated urban areas. Compared to early metro developments, this leads to new challenges to be met. Especially low overburden, sensitive infrastructure at the surface and difficult geological conditions increase the need for sophisticated machinery and operations control. Herrenknecht has developed and refined a number of technologies that have become the backbone of many modern tunneling projects. The first step in a TBM project is the machine selection. This paper highlights the recommended application ranges for different TBM types and explains recent technical developments. EPB machines, slurry TBMs and innovative machine types such as Variable Density TBM or convertible machines are covered. Furthermore, the application of an EPB TBM in the Seoul Metro Line 9 C919 project and a Mixshield TBM in the Wonju project in Korea are introduced. Project background, TBM technology and project highlights are discussed in detail. Both projects are showcasing the technological advances in the Korean tunneling industry.
2. TBM Selection in different Ground Conditions

Tunnel boring machines have to be designed to match the geological conditions of a project. Basically, there are three different shielded machine types:

a) Open single shield for stable and usually non water-bearing ground conditions with excavation under atmospheric pressure and dry muck removal with belt conveyor.

b) Closed earth pressure balance machine for fine-grained and usually unstable and water-bearing soils with excavation under controlled positive face support pressure and thick-matter-type muck removal from the excavation chamber with screw conveyor.

c) Closed slurry machine for coarse-grained and usually unstable and water-bearing soils with excavation under controlled positive face support pressure and muck removal from the excavation chamber with slurry circuit and above ground slurry treatment plant.

Generally, all three types have distinct, separate application fields. However, there are increasing overlaps between the possible geologies where these shields technically can be used which can be attributed to technical advance. Nonetheless, even if different methods are technically applicable, there are still economic boundary conditions that in different situations strongly favor one or the other method. Today, also more and more multi-mode machines with features of several types are built.

2.1 EPB Machines

![Components of EPB tunneling machines](image)

Fig. 1 Components of EPB tunneling machines
A major factor for TBM selection is the grain size distribution of the geology. EPB machines depend on two mechanisms, which can only function in a certain geological range. Firstly, the soil must create a plug within the screw conveyor, which dissipates the pressure. Only plastic soils with sufficient fines can achieve this property. If the soil does not contain enough fines to create this plug, material will gush out of the screw conveyor in an uncontrolled manner and the machine is not able to keep the desired support pressure. Settlements and sinkholes can be the consequence. The second important mechanism in EPB machines is the transfer of support pressure from the TBM to the tunnel face. To achieve this, the soil inside the excavation chamber should behave like a cushion. Conditioning agents such as foam, polymer and bentonite can be injected into the excavation chamber to adjust the soil conditions to the right properties. The EPB principle can be used in cohesive soil with certain minimum fine content. That means in ground consisting of clay, silt (in various grades) and fine sand. This cohesive soil can be easily agitated into soft and flexible muck material which can transfer support pressure to the tunnel face. In that range of soil, it is possible to control pressure and water inflow with the screw conveyor. However, it is possible to extend the EPB application range towards non-cohesive soil by using of additives like foam and polymer, but non-cohesive soil usually cannot get good muck material for pressure balance. Therefore, EPBs are normally not used in very high pressure or under rivers. Figure 1 shows an overview of the main components of an EPB TBM.

![Fig. 2 Grain size distribution for different TBM types](image-url)
2.2 Slurry Machines

Slurry TBMs or MIX-Shields are applicable in more non-cohesive soil range with reduced fine content. Typically these are weathered rocks, mixed ground, sandy soils or cobbles. Bentonite slurry is the material to transfer pressure to support the tunnel face. It has better flow ability to carry the muck and transfer the pressure precisely. Very high face pressure can be handled well by slurry TBMs. It is possible to extend the Mixshield application range towards cohesive soil also, although cohesive soil will lead to the difficulty of soil treatment (separation). Due to the air bubble pressure control, slurry TBMs are very precise with regards to support pressure control. In difficult ground conditions, this is an advantage over EPB machines.

![Components of slurry tunneling machines](image)

Fig. 3 Components of slurry tunneling machines

Due to the liquid support medium, slurry TBMs are able to provide stable face support in geology tapes such as cobbles, fractured or fresh rock, as well as mixed ground geology. When tunneling in high pressure environments, the slurry shield methods also allow a safer environment for cutterhead interventions as the bentonite filter cake supports the face safely even with air pressure.
In order to operate a slurry TBM, the jobsite is equipped with a slurry transport system (STS). A feed line transports slurry with pumps from the surface to the machine. A discharge pipe transports the slurry and excavated muck back to the surface. In long tunnels, booster pumps are equipped in both lines to cover the distance. In the shaft, both lines are equipped with flowmeters and densitymeters. From the readings it is possible to calculate the difference between the two lines and therefore quantify the amount of excavated material.

At the jobsite surface, a separation plant (or slurry treatment plant STS) is assembled. With the use of cyclones and centrifuges, the excavated muck is separated from the bentonite and disposed. The bentonite is the pumped to the TBM again. A bentonite mixing plant supplies fresh bentonite to compensate for losses.

### 2.3 Variable Density Machines

Variable Density TBMs allow switching operation modes between EPB type and Slurry type face support gradually. They utilize a screw conveyor to extract material from the chamber into a slurryfier box where the muck is mixed with bentonite to make it pumpable. Alternatively a belt conveyor can be used for transport. As a slurry circuit is available, it can also circulate through the excavation chamber and therefore regulate the density here. For difficult ground conditions, a special high density slurry can be used additionally.
Fig. 5 Operation and mucking modes of the Variable Density TBM

Usually economic considerations will dictate that a Variable Density TBM is rather equipped for one or the other mode to keep the invest low, but the technical possibility for all of this is there. Generally, a variable density TBM requires a comparable setup at the jobsite surface as slurry TBMs.

2.4 Convertible Machines

Considering the three different basic principles which were identified as relevant for convertible machines in section 2, there are different possibilities, how a convertible machine can be realized. Firstly this can be a conversion between Open Single Shield and Slurry Shield, secondly between Open Single Shield and EPB Shield and thirdly between EPB Shield and Slurry Shield. For all these types, there are different synergies between the operation modes and different difficulties to solve as well. Regularly concepts for a universal TBM which features all three operation modes are discussed in literature but economic and practical boundary conditions make this a rather unrealistic scenario.

4. Seoul Metro Line 9 C919

The city of Seoul is expanding its metropolitan metro network. For C919 jobsite of Line 9, Herrenknecht has supplied a 7.7m diameter EPB TBM to Samsung C&T Corporation. The Herrenknecht TBM S-971 has completed two tunnel drives of 371m each.
4.1 Project Geology

Both tunnels are bored with a very low overburden of 12m to 13m. The geology mainly consists of two different scenarios. Firstly, full face soil, consisting of alluvium and residual soil of fully weathered schist rock. Water permeability lies in a range between $2 \times 10^{-4}$ m/s and $9 \times 10^{-6}$ m/s. The second section encountered mixed geology of schist in various weathering stages with a maximum hardness of ca. 160MPa. Figure 4 shows a longitudinal cross section of the tunnel alignment.

![Fig. 4 Tunnel Alignment of Seoul Metro Line 9 C919](image)

4.2 Herrenknecht S-971 EPB Tunnel Boring Machine

The S-971 Herrenknecht EPB TBM has been designed for a maximum support pressure of 6 bar. Equipped with a hydraulic maindrive with a total power of 2000kW, the cutterhead is driven with a nominal torque of 10364kNm and a maximum rotation speed of 3.4rpm. The cutterhead is equipped with 17” single disc cutters and scrapers for soft ground. Full face wear protection is suitable to handle abrasive ground. The TBM is equipped with a simultaneous grouting system that mixes A and B component immediately before injecting into the ring gap. The grouting system is integrated into the TBMs tailskin. The following table summarizes the main technical parameters of the TBM:

<table>
<thead>
<tr>
<th>TBM Type</th>
<th>EPB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield Diameter</td>
<td>7700 mm</td>
</tr>
<tr>
<td>Maindrive Power</td>
<td>2000 kW</td>
</tr>
<tr>
<td>Nominal Torque</td>
<td>10364 kNm</td>
</tr>
<tr>
<td>Cutterhead Rotation</td>
<td>3.4 rpm</td>
</tr>
<tr>
<td>Thrust Force</td>
<td>54978 kN</td>
</tr>
<tr>
<td>Operation Pressure</td>
<td>6 bar</td>
</tr>
<tr>
<td>Screw Conveyor Diameter</td>
<td>900 mm</td>
</tr>
<tr>
<td>Screw Conveyor Power</td>
<td>315 kW</td>
</tr>
<tr>
<td>Foam Generator Lines</td>
<td>6 lines</td>
</tr>
</tbody>
</table>
4.3 Project Execution

Due the site’s location, in the middle of high traffic road, and its small size, the assembly of the TBM was conducted on a crowded site and through a very small shaft opening of 5x5m. The TBM design was adapted to this peculiar assembly situation. During the first drive the TBM encountered an unexpected bedrock of schist. The hard rock, not weathered, layer of schist rose up to 1m at the bottom of the excavation chamber on around 50m of the drive. This unexpected geology situation increased the wear on the cutting tools and the cutting wheel structure. This lead to two additional cutterhead interventions and repair works on the cutterhead structure in between the two drives. The fresh bedrock was not encountered during the second drive. The EPB machine has delivered a good performance of up to 10.5m per day and 55.5m per week. Figure 6 shows the advance rates of the second drive as an example.
As part of the preparation for the 2018 winter Olympics, the Wonju Kangneung railway line is being expanded. Herrenknecht has supplied an 8.41m diameter Mixshield to the project to construct a 1160m long railway tunnel. Dongah Geological Engineering Co., Ltd. was the contractor.

5.1 Project Geology

The tunnel has an over burden between 21.26m at the highest point and 7.62m under the river. A very diverse geology has to be passed. About half the tunnel trace leads through full face sandy soil with gravel and boulders. The other half leads through mixed face and different granite layers of various weathering grades. The maximum hardness is about 50MPa. All geological formations are highly permeable and due to the river crossing, high water flows could be expected. For this reason, a slurry type TBM has been chosen.
5.2 Herrenknecht S-962 Mixshield Tunnel Boring Machine

The S-962 Herrenknecht Mixshield TBM has been designed for a maximum support pressure of 4.5 bar. The machines air bubble technology for support pressure control allows a precise setting and control of the situation in the excavation chamber. The machines slurry feed and discharge lines are equipped with flowmeters and density sensors. The sensors allow permanently monitoring the amount of excavated material. A special software monitors the results. The following table summarizes the main technical parameters of the TBM:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Type</td>
<td>Mixshield</td>
</tr>
<tr>
<td>Shield Diameter</td>
<td>8410 mm</td>
</tr>
<tr>
<td>Maindrive Power</td>
<td>1280 kW</td>
</tr>
<tr>
<td>Nominal Torque</td>
<td>14680 kNm</td>
</tr>
<tr>
<td>Cutterhead Rotation</td>
<td>3.1 rpm</td>
</tr>
<tr>
<td>Thrust Force</td>
<td>59464 kN</td>
</tr>
<tr>
<td>Operation Pressure</td>
<td>4.5 bar</td>
</tr>
<tr>
<td>Slurry Flow Rate</td>
<td>1400 m³/h</td>
</tr>
</tbody>
</table>
5.3 Project Execution

The TBM has shown steadily increasing advance rates throughout the project. The learning curve for operation and maintenance has led to high performances of up to 70m per week in difficult ground conditions. Also the logistic supply has been improved throughout the project and thus allowed for higher performance.

![Weekly Progress
S-962 (Mix-DN8930): Korea, Gangneung Railwaytunnel (Dongah)](image)

Fig. 9 Herrenknecht S-962 TBM for Wonju Kangneung Railway

A number of lessons learned for face support pressure as well as slurry mode operation have led to stable face conditions and prevented major incidents. The TBM and related systems have proven reliable without downtime caused by major technical failures of equipment or components.

6. CONCLUSION

Modern TBM technology can deliver high performances in all ground conditions. The design of the TBM always follows the particular ground conditions of each project. Recent experiences in Korea have proven a good track record for TBM technology and further established Korean contractors and TBM operators in their leadership position. The TBMs presented in this paper are currently being refurbished and due to be deployed to further projects in Korea.