HERRENKNECHT AG

SOFTGROUND TBMs

> 40 FT

Project No.	Project name	Shield diameter [m]
S - 108	Elbtunnel Hamburg, Germany	14.20
S - 164	Lefortovo Moscow, Russia	14.20
S - 250	Silberwald Moscow, Russia	14.20
S - 252	Kuala Lumpur, Malaysia	13.21
S - 253	Kuala Lumpur, Malaysia	13.21
S - 300	M-30 Madrid, Spain	15.20
S - 317	Shanghai, China	15.43
S - 318	Shanghai, China	15.43
S - 349	Nanjing, China	14.93
S - 350	Nanjing, China	14.93
S - 352	Münster Wiesing, Austria	13.00
S - 381	H8 Jenbach, Austria	13.00
S - 483	Moscow, Russia	14.20
S - 534	Sochi, Russia	13.21
Pre-Design	Moscow, Russia	19.00

Reference Papers:

- *The making of the Mixshield.*
- *Lifting the lid on Mixshield performance.*
- *The latest technology in mechanized tunneling –*
  the design of the world's largest EPB and slurry shield TBMs.

PROJECT DATASHEET.

Updated: 5/15/2008

S-Number: **S-108**
Name: **4. Röhre Elbtunnel Hamburg**
Location: **Hamburg**
Country: **Germany**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-108
Project Name:	4. Röhre Elbtunnel Hamburg
Location:	Hamburg
Country:	Germany
Sales Region:	Europe
Diameter:	14200 mm
Total Tunnel Length:	2560 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Finished

MAIN **GEOLOGY** CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Max. Op. Pressure:	5.5 bar
Geology:	Sand, boulder clay, silt and gravel, erratic blocks

PROJECT DATASHEET.

Updated: 5/15/2008

S-Number:	**S-164**
Name:	**Lefortovo**
Location:	**Moscow**
Country:	**Russia**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-164
Project Name:	Lefortovo
Location:	Moscow
Country:	Russia
Sales Region:	Europe
Diameter:	14200 mm
Total Tunnel Length:	4112 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Finished

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Min. Overburden:	7 m
Max. Overburden:	30 m
Geology:	Fine to coarse sand, clay, limestone (medium strength, partially very fissured)

PROJECT DATASHEET.

Updated: 5/15/2008

S-Number:	**S-250**
Name:	**Silberwald**
Location:	**Moscow**
Country:	**Russia**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-250
Project Name:	Silberwald
Location:	Moscow
Country:	Russia
Sales Region:	Europe
Diameter:	14200 mm
Total Tunnel Length:	3010 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Finished

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Max. Overburden:	30 m
Geology:	Sand, clay, rock

PROJECT DATASHEET.

Updated: 11/12/2008

S-Number:	**S-252**
Name:	**Stormwater Management and Road Tunnel (SMART)**
Location:	**Kuala Lumpur**
Country:	**Malaysia**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-252
Project Name:	Stormwater Management and Road Tunnel (SMART)
Lot:	North Drive
Location:	Kuala Lumpur
Country:	Malaysia
Sales Region:	Asia Pacific
Diameter:	13210 mm
Total Tunnel Length:	5400 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Finished

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Min. Overburden:	10 m
Max. Overburden:	20 m
Max. Op. Pressure:	5 bar
Geology:	Limestone, marble, sand

PROJECT DATASHEET.

Updated: 11/14/2008

S-Number: **S-253**
Name: **Stormwater Management and Road Tunnel (SMART)**
Location: **Kuala Lumpur**
Country: **Malaysia**

MAIN | GEOLOGY | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

S-Number:	S-253
Project Name:	Stormwater Management and Road Tunnel (SMART)
Lot:	South Drive
Location:	Kuala Lumpur
Country:	Malaysia
Sales Region:	Asia Pacific
Diameter:	13210 mm
Total Tunnel Length:	3944 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Finished

MAIN | **GEOLOGY** | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

Min. Overburden:	10 m
Max. Overburden:	20 m
Max. Op. Pressure:	5 bar
Geology:	Limestone, sand, marble

PROJECT DATASHEET.

Updated: 12/12/2008

S-Number: **S-300**
Name: **Madrid M-30 By-Pass Sur Túnel Norte**
Location: **Madrid**
Country: **Spain**

MAIN | GEOLOGY | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

S-Number:	S-300
Project Name:	Madrid M-30 By-Pass Sur Túnel Norte
Lot:	Calle 30
Location:	Madrid
Country:	Spain
Sales Region:	Europe
Diameter:	15200 mm
Total Tunnel Length:	3526 m
Machine Type:	EPB Shield
Employment:	Road
Project Status:	Finished

MAIN | GEOLOGY | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

Min. Overburden:	12 m
Max. Overburden:	67 m
Max. Op. Pressure:	6 bar
Geology:	Peñuela, Peñuela + gypsum, massive gypsum

PROJECT DATASHEET.

Updated: 11/12/2008

S-Number: **S-318**
Name: **Shanghai Changjiang Under River Tunnel Project**
Location: **Shanghai**
Country: **China**

MAIN | GEOLOGY | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

S-Number:	S-318
Project Name:	Shanghai Changjiang Under River Tunnel Project
Lot:	Chongming
Location:	Shanghai
Country:	China
Sales Region:	Asia Pacific
Diameter:	15430 mm
Total Tunnel Length:	7472 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Finished

MAIN | GEOLOGY | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

Min. Overburden:	20 m
Max. Overburden:	23 m
Max. Op. Pressure:	6 bar
Geology:	Sand, clay, rubble

PROJECT DATASHEET.

Updated: 9/4/2008

S-Number:	**S-317**
Name:	**Shanghai Changjiang Under River Tunnel Project**
Location:	**Shanghai**
Country:	**China**

MAIN | GEOLOGY | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

S-Number:	S-317
Project Name:	Shanghai Changjiang Under River Tunnel Project
Lot:	Chongming
Location:	Shanghai
Country:	China
Sales Region:	Asia Pacific
Diameter:	15430 mm
Total Tunnel Length:	7472 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Finished

MAIN | GEOLOGY | CONTRACT | TBM SPEC. | TBM PROGRESS | BACKGROUND

Min. Overburden:	20 m
Max. Overburden:	23 m
Max. Op. Pressure:	6 bar
Geology:	Sand, clay, rubble

PROJECT DATASHEET.

Updated: 12/3/2008

S-Number:	**S-349**
Name:	**Nanjing**
Location:	**Nanjing**
Country:	**China**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-349
Project Name:	Nanjing
Lot:	Right Tunnel
Location:	Nanjing
Country:	China
Sales Region:	Asia Pacific
Diameter:	14930 mm
Total Tunnel Length:	2933 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Tunnelling

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Min. Overburden:	6 m
Max. Overburden:	30 m
Max. Op. Pressure:	7.5 bar
Geology:	Silt, sand, clay, gravel

PROJECT DATASHEET.

Updated: 12/3/2008

S-Number: **S-350**
Name: **Nanjing**
Location: **Nanjing**
Country: **China**

S-Number:	S-350
Project Name:	Nanjing
Lot:	Left Tunnel
Location:	Nanjing
Country:	China
Sales Region:	Asia Pacific
Diameter:	14930 mm
Total Tunnel Length:	2933 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Tunnelling

Min. Overburden:	6 m
Max. Overburden:	30 m
Max. Op. Pressure:	7.5 bar
Geology:	Silt, sand, clay, gravel

PROJECT DATASHEET.

Updated: 12/3/2008

S-Number: **S-352**
Name: **Inntalquerung**
Location: **Münster**
Country: **Austria**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-352
Project Name:	Inntalquerung
Lot:	H 3-4 Münster Wiesing
Location:	Münster
Country:	Austria
Sales Region:	Europe
Diameter:	13000 mm
Total Tunnel Length:	5840 m
Machine Type:	Mixshield
Employment:	Railway
Project Status:	Tunnelling

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Min. Overburden:	13 m
Max. Overburden:	44 m
Max. Op. Pressure:	5 bar
Geology:	Pebble stones, sand, coarse clay, brash, gravel

PROJECT DATASHEET.

Updated: 12/3/2008

S-Number: **S-381**
Name: **Inntalquerung**
Location: **Jenbach**
Country: **Austria**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-381
Project Name:	Inntalquerung
Lot:	H8 Jenbach
Location:	Jenbach
Country:	Austria
Sales Region:	Europe
Diameter:	13000 mm
Total Tunnel Length:	3470 m
Machine Type:	Mixshield
Employment:	Railway
Project Status:	Tunnelling

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Min. Overburden:	5 m
Max. Overburden:	24 m
Max. Op. Pressure:	5 bar
Geology:	Components of bunter, alternating sequence of gravel with sand and silt, sandy to silty gravel with stones

PROJECT DATASHEET.

Updated: 11/26/2008

S-Number: **S-483**
Name: **Zaryzino Südtangente Moskau**
Location: **Moscow**
Country: **Russia**

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

S-Number:	S-483
Project Name:	Zaryzino Südtangente Moskau
Location:	Moscow
Country:	Russia
Sales Region:	Europe
Diameter:	14200 mm
Total Tunnel Length:	2400 m
Machine Type:	Mixshield
Employment:	Road
Project Status:	Refurbishment

MAIN **GEOLOGY** CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Geology:	Sand, loam, limestone

PROJECT DATASHEET.

Updated: 12/19/2008

S-Number:	**S-534**
Name:	**Sotschi Straßentunnel Nr.3**
Location:	**Sochi**
Country:	**Russia**

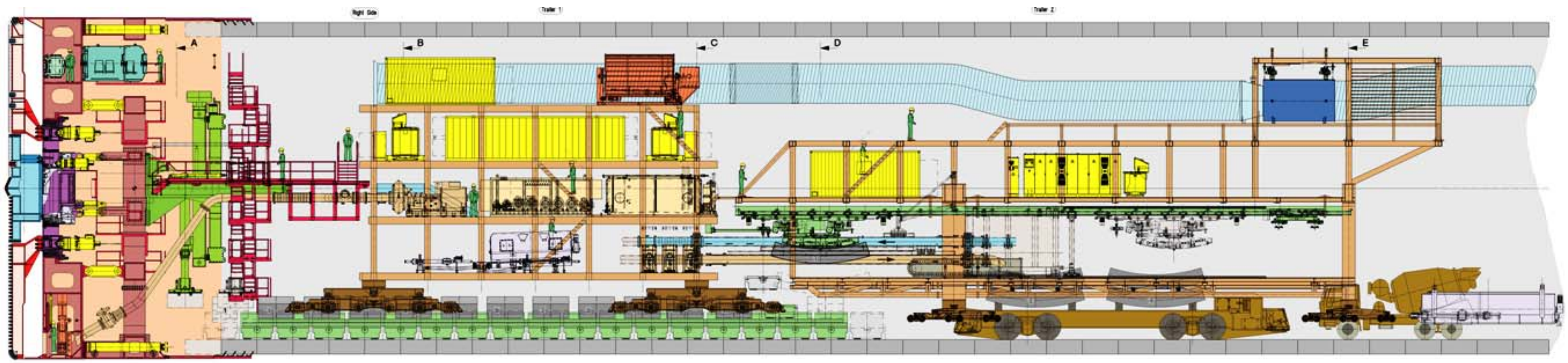
MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

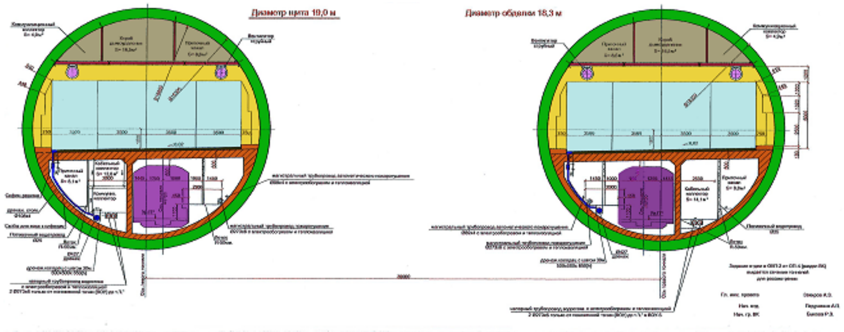
S-Number:	S-534
Project Name:	Sotschi Straßentunnel Nr.3
Lot:	Adler - Krasnaja Poljana
Location:	Sochi
Country:	Russia
Sales Region:	Europe
Diameter:	13210 mm
Total Tunnel Length:	4200 m
Machine Type:	Single Shield TBM
Employment:	Road
Project Status:	Contract

MAIN GEOLOGY CONTRACT TBM SPEC. TBM PROGRESS BACKGROUND

Geology:	Limestone

Moscow, Mix Shield Ø19m – Basic Design





Technical Data TBM:

Type:	Mix Shield
Diameter	Ø 19 m
Total Length	85 m
Total Weight	5.500 t
Shield Thrust	340.000 KN
Max Pressure	6 bar
Installed Power	14,0 MW
Tunnel:	Segmental lining, watertight
Type:	4 lane road + light rail
Segment OD:	18,45 m
Segment ID:	16,85 m
Segment length:	2,0 m

REFERENCE PAPER:

THE MAKING OF THE MIXSHIELD.

HERRENKNECHT
Tunnelling Systems

The making of the Mixshield – Part 1

In the first of a two-part series, Werner Burger, head of design and engineering, and Gerhard Wehrmeyer, director of traffic tunnelling, for Herrenknecht AG, examine the development of the modern Mixshield

Since its initial introduction, in 1985, the Mixshield TBM has taken on an essential role within the world of mechanical tunnel excavation. With its ability to operate as a classic slurry-shield, or change to Open or Earth Pressure Balance (EPB) mode mid-drive, the Mixshield offers a unique concept for dealing with mixed ground excavation conditions.

In order to appreciate how these machines have evolved, this article looks at the history and development of Mixshield technology over recent decades and the impact this has had on the underground construction industry.

Development of technology

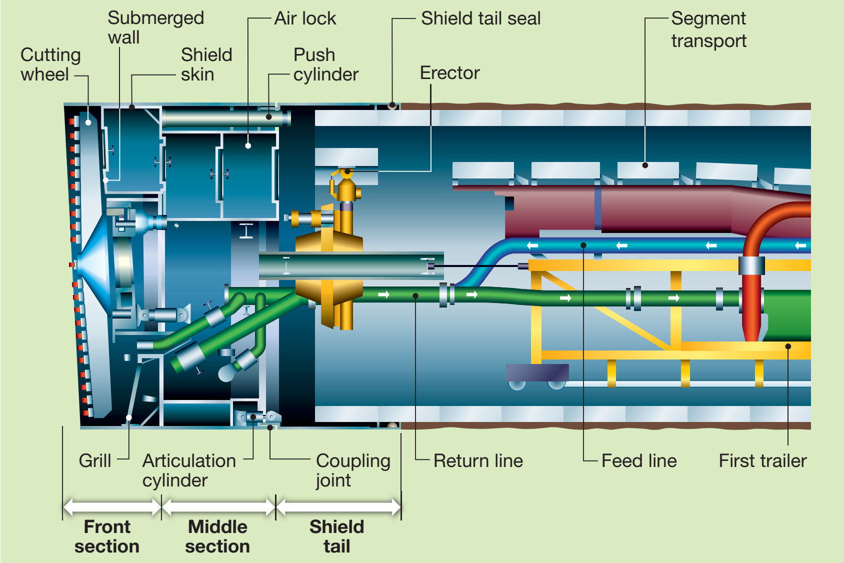
The first European attempts to develop a bentonite shield began in England in the early 1960s, leading to the excavation of a short experimental tunnel in London, in 1971. German contractor Wayss & Freytag took these initial ideas and built upon them, incorporating an air bubble principle to control and regulate face support pressure.

These early machines were mainly used in gravel and sand under lower water pressure, such as the Wilhelmsburg CSO tunnel, in Germany, which was completed in 1974. The shields were equipped with a centre shaft drive and light spoke-type cutterheads with square drag tools, reflecting their limited range of application at that stage.

With a view to finding an alternative to conventional compressed air excavations, which were common at the time, Wayss & Freytag concentrated on the design of face support systems and the development of a tail shield seal that would stand up to the rough conditions of mechanical excavation.

In parallel with these developments, the evolution of water-resistant single-shell concrete segmental linings occurred.

Early Mixshield concepts focused both on the development of a shield that would provide a slurry supported tunnel face and also an open shield that could enable a change of operational mode[1]. That is why, even today, the term “Mixshield” is still used for “slurry only” machines as well as for convertible shields. In all cases, however, the use of a submerged wall/pressure bulkhead combination, to create an air bubble for face pressure control, has remained an essential design feature for this type of machine.



Right & below: **Fig 1 - The HERA Mixshield**

The Mixshield is ultimately distinguished by the following features:

- A modular design that allows adaption to different modes of operation (slurry, open, and EPB) for different projects, or a fully-equipped machine for changes mid-drive
- Centre-free cutterhead drive with three-axis roller bearing for a centrally arranged muck transportation system (screw or belt)
- Centre-free cutterhead drive to accommodate various media (water, bentonite, hydraulics, electrics, etc) into the cutterhead and excavation chamber via a rotary joint
- Integration of a cutterhead support system with axial and radial articulation by means of a spherical bearing

The first application of a true Mixshield machine was at the HERA tunnel, in Hamburg, in 1985. This 6.2km-long project accomplished advance rates of up to 20m/day. The developments introduced proved successful, following a few adaptations during tunnelling, and confirmed the suitability of the new design.

Like other early Mixshields, the HERA machine had a cutterhead that tilted forward at 3°. The idea was that a slightly inclined face would help with face stability. However, with growing experience and confidence in the principle of a bentonite-supported face, this mechanically cumbersome configuration eventually disappeared in favour of vertically mounted cutterheads.

Table 1: Developments in Mixshield technology

Year	Project	Development
1985	**S-12 HERA**	• Mixshield: Centre free cutterhead drive Passive shield articulation joint Grouting through tail shield with external grout lines
1987	**S-21 Lille**	• Main bearing as three axis roller bearing • Centre flushing • Single lip tail seal type S1 • Double erector with semi-automatic mechanical gripping
1988	**S-41 Nuremberg**	• Fully-articulated cutterhead with spherical bearing • Cutterhead with mixed face tool arrangement including disc cutters • Grouting through tail shield
1988	**S-47 Duisburg TA 6**	• Jaw type rock crusher in invert (initially without grill in front of suction pipe - added later)
1989	**S-50 Grauholz**	• Mixshield as convertible shield: Changing operation mode slurry – open • Large diameter > 11m • Operating pressure 4bar • Cutterhead flushing • Fixed centre plate cutterhead drive with inner seal system • Compensation pipes excavation chamber – pressure chamber • Vacuum erector • Invert fill within backup area • Data recording
1989	**S-52 Mülheim BA 8**	• Hard rock cutterhead with disc cutters in pressurised slurry • Articulated suction pipe • Slurry supply in front of submerged wall • Hard rock TBM: Thrust cylinder skew controlled Hydraulic wing type stabilisers 17" backloading cutters only Bolt-on bucket lips
1991	**S-67 Strasbourg**	• Closed cutterhead with back loading scrapers • Hydraulically extendable gauge cutter • Agitator wheels in front of suction pipe • Re-circulation system to increase slurry flow within excavation chamber • Initial application of wire brush tail seals on a Mixshield • Segment supply in invert area • Automatic "weekend control" for slurry suspension supply
1992	**S-68 Essen Lot 34**	• Active centre cutter with independent slurry feed and suction lines • Extendable face plates • Submerged wall front gate
1992	**S-71 Köln Los M1**	• Floating thrust cylinders with hydraulic clamping system
1994	**S-85 Duisburg TA 7/8**	• Conversion of operating modes slurry – EPB via exchange of invert shield segment in shaft • Drill tubes through skin for pre-excavation grouting and probing • Open cutterhead centre with independent slurry feed and suction line
1996	**S-103 Sydney**	• Rotary crusher / sizer • Unidirectional mixed face cutterhead
1997	**S-108 4 Elbröhre**	• Accessible cutterhead for atmospheric cutter tool change • Face pressure 5.5 bar • World largest shield diameter: 14.2m • Preparation for diving activities • Hyperbaric rescue shuttle • Support pressure control to match tidal changes
1998	**S-127 Socatop**	• Conversion of operating modes slurry – EPB in tunnel
1999	**S-137 Westerschelde**	• Initial use of saturation diving up to 7.5 bar • Long-distance tunnelling with permanent face pressure >4 bar • Initial use of hyperbaric transfer shuttle and living chamber
1999	**S-150 Sophia**	• Continuous mining in soft ground with positive face support
2000	**S-152 Wesertunnel**	• Closed invert segment
2005	**S-246 Hallandsås**	• 13 bar max operational pressure • Convertible TBM with fines handling flushing circuit in open mode
2006	**S-317/318 Chongming**	• World's largest shield diameter: 15.43m • Improved cutterhead access for atmospheric cutter tool change

Another obvious design feature on early machines was the wide open, light cutting wheel design and a large submerged wall opening. It was thought that these were essential requirements to ensure the best possible bentonite circulation and therefore stability of the face. As with the inclined face, however, it became obvious these were not mandatory requirements and that cutterhead designs more appropriate to mixed face conditions could be employed without negative effects on face stability or settlement. The difference in layout between slurry shields and EPB cutterheads therefore started to disappear[2]. Today's cutterhead designs are driven by a much wider range of factors – including wear protection, muck flow, tool arrangement and tool access.

In the late 1980s, the potential of Mixshield machines became obvious to the tunnelling community. For the next 15 years, projects and orders were heavily influenced by the market enthusiastically embracing the concept. The development of other soft ground technology, such as compressed air shields and the membrane shield, were all but abandoned in favour of the Mixshield; which had already enabled the completion of projects previously considered impossible.

From a technical point of view, the step-by-step development of the Mixshield (Table 1) reads like a technical requirement catalogue for today's slurry shields. The only difference being that the initial introduction of any new feature on a given project required a huge amount of dedication and commitment from all parties throughout the learning curve.

Early milestones included the application of a Mixshield, used as a slurry machine, in Duisburg, which adopted a jaw crusher for boulders up to 500mm; the use of a hard rock cutterhead in Mülheim; convertible operation modes (closed mode with slurry circuit – open mode with centre belt conveyor discharge system) for the Grauholz tunnel; and Mixshield operation in Strasbourg with slurry support and closed cutterhead in coarse sand and gravel.

Additional progress was made in the mid-1990s with projects such as the fourth Elbe tunnel and the Westerschelde crossing. Since then, advances to larger diameters, higher water pressures and shallower cover have presented a whole new dimension of challenges. Many engineering questions, such as lowering the bentonite level for face access, had to be revisited and new innovative solutions such as accessible cutterheads for cutter tool changes under atmospheric conditions were created.

As well as direct improvements to Mixshield technology, several more general TBM developments have also contributed to the advancement of Mixshields, including:

- Articulated cutterheads to allow overcutting and full control of cutterhead and main bearing loads
- Floating thrust cylinder systems to address increased segment length and difficult tunnel alignments
- Mixed and variable face cutterhead and backloading tool designs
- High-pressure mainbearing, articulation and tailseal concepts
- Vacuum systems for segment erection
- Advanced systems for data recording and processing or process automation

Many of these more general developments have to be viewed in combination with related advancements, e.g. segment design and manufacturing, soil conditioning, sealant materials, alignment control and survey systems, IT systems and data transfer.

In addition to the coventional use of Mixshields for face support in soft ground, the growing use of closed mode operation in rock tunnels has also been seen in recent years. In water bearing rock with the potential for high water inflows and/or pressure, the control of water inflow through the cutterhead is essential for operational reasons (segment backfill grouting, muck discharge) and, in many cases, even more so for environmental reasons.

The traditional approach to such ground conditions is pre-excavation grouting from within the shield ahead of the tunnel face. Depending on rock conditions, pre-grouting activities can be time-consuming and do not always guarantee success, especially against flowing water. To overcome these problems, a closeable single shield rock machine was developed that would allow pre-excavation grouting using preventer systems against static water pressure. The next logical step was to install an additional slurry circuit muck transport system to deal with worst-case scenarios in closed mode.

Operational modes for such hard rock Mixshields include: a) Open mode with dry primary muck discharge system (e.g. conveyor); b) Open mode with (cyclic) pre-excavation grouting; c) Open mode with (cyclic) pre-excavation grouting in closed static conditions; d) Closed mode with hydraulic muck discharge system under reduced face pressure; e) Closed mode under full-face pressure with potential for positive face support.

Closed mode, high-pressure operation in hard rock provides the most adverse conditions of operation for all components of the machine, but having options d) and e) available is a significant advantage in terms of mitigating potential risk.

The machines for the SMART project in Kuala Lumpur, in 2004, produced the second series of large Mixshield machines, this time partially in medium soft rock conditions.

The spotlight regarding large Mixshield machines is now currently focused on the world's largest Mixshield machine, for the Chongming project, in Shanghai.

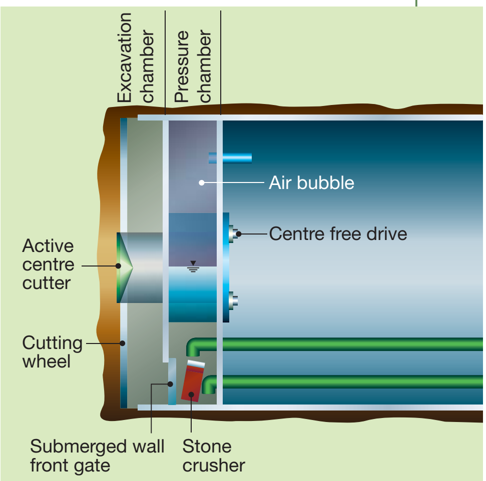


Fig 2: **Mixshield concept**

Face support

As a classic Hydro Shield, the Mixshield applies the necessary face support pressure via a pressure-controlled air bubble in the pressure chamber. A characteristic design feature of the Mixshield is the submerged wall, separating the pressurised front section of the shield into two areas. The area between the submerged wall and the pressure wall is called the "pressure chamber" (figure 2). The area in front of the submerged wall is defined as the "excavation chamber". The required pressure exchange between excavation chamber and pressure chamber occurs via an opening in the bottom of the submerged wall.

Additional compensating pipes that connect the invert area of the pressure chamber with the excavation chamber ensure pressure exchange, even if there is a blockage of the submerged wall opening.

The air bubble is maintained by a self-regulating air pressure control system (with a back-up available if necessary). When under water, where groundwater pressure is influenced by tidal activity, water levels and pore water pressure readings are taken into consideration as additional parameters in the pressure control. For large diameters, the slurry density and level in the pressure chamber may also be used as input parameters. The required face support pressure settings must be determined by calculations for each individual section of the tunnel alignment before the excavation.

Cutterhead access & tool changes

Integral to the general Mixshield concept is the ability to lower the slurry level in the excavation chamber for cutterhead or face access, either remotely from the atmospheric

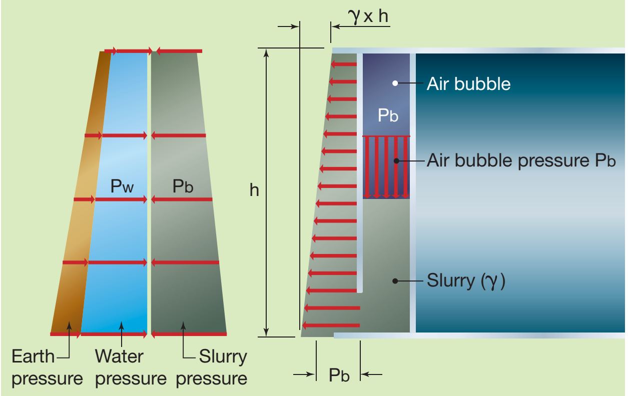


Fig 3: **Mixshield face support principle**

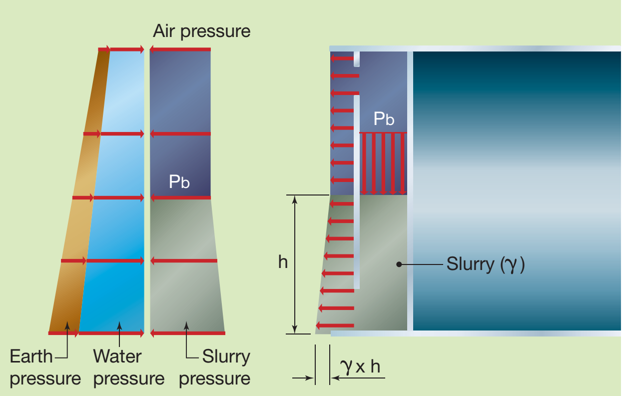


Fig 4: **Reduced front level for face access**

area behind the pressure bulkhead or from inside the pressure chamber (figure 4). In locations with shallow cover and high water pressure, the level of slurry can only be lowered by a third of the diameter for access to the excavation chamber, in order to maintain sufficient safety against the risk of a blow out. In such cases, the required balance between excavation chamber and pressure chamber has to be controlled from the atmospheric area behind the pressure wall.

The use of a submerged wall gate enables the isolation of the pressure chamber from the excavation chamber. By closing the gate, maintenance work in the pressure chamber can be carried out under reduced pressure or even free air conditions. In this scenario, pressure regulation of the excavation chamber is carried out via a remote pressurised bentonite tank air bubble, usually mounted on the back-up gantries.

A new development for areas of sticky soil with a high clogging risk is the separation of the suction area from the rest of the pressure chamber. This was successfully implemented in the Mixshield used for the Weser tunnel, in northern Germany. Here, the invert area was isolated from the rest of the pressure chamber. Separate connection lines (or "compensation pipes") provided the necessary pressure exchange to the excavation chamber for face support.

With this system, a large percentage of the total flow volume can be circulated through the excavation chamber reducing the slurry density in specific areas and making it more constant. This results in less muck accumulation/clogging, as well as less secondary wear and more even operational conditions for the slurry circuit and treatment plant. The isolated suction area created still accommodates the rock crusher and submerged wall gate.

Maintenance and service operations within working pressures of over 3.6 bar – and therefore outside of the normal framework of compressed air regulations – were successfully performed under special permits on the fourth Elbe tunnel and Weser tunnel at air pressures of up to 4.5 bar.

Professional divers can be employed for underwater operations or pressure levels beyond 3.6 bar for access into the suspension filled excavation chamber and/or for work to be performed in the invert area of the pressure chamber. Requirements for diving operations need to be established at an early stage of the project and have to be addressed in the design and installation of the TBM. Different applications also have to be defined. For example:

Short-term, submerged dives to explore the tunnel face or to inspect cutter tools: Divers enter the bentonite suspension from the air bubble in the pressure chamber. Submerged wall doors are used to access the excavation chamber. These are located below the suspension level in the pressure chamber. This procedure was successfully implemented at the fourth Elbe River tunnel.

Long-term, for major maintenance and repair work and/or pressures beyond 4.2 bar: Special dive techniques, such as those used in the offshore industry are used (involving mixed gas or saturation diving). In the case of saturation diving, dive crews remain under pressurised conditions for extended periods. The divers are transferred from an above ground "living chamber" to the TBM via a mobile shuttle lock. Depending on their tasks and the pressure levels at which they are operating, the divers can work for several hours before returning to their "living chamber".

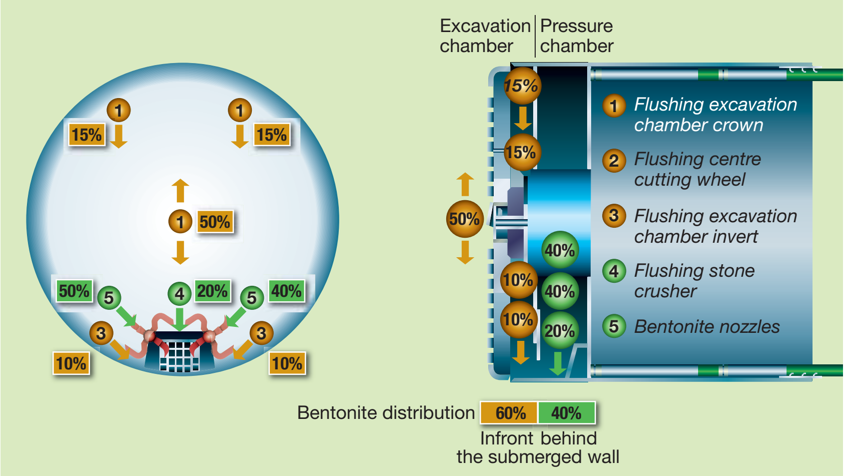
Whenever possible, maintenance work in the pressurised area is done in a dry compressed air environment using masks for the breathing gas mixture. The entire process, including breathing gas mixtures, atmosphere, durations, or individual pressure levels, has to be precisely planned and supervised by experienced specialists. Saturation diving for tunnelling operations was used for the first time on a large scale at the Westershelde project, in the Netherlands.

Crushing rocks and boulders

In principle, there are two ways to handle rocks and boulders. Firstly, if the matrix of the tunnel face is strong enough, disc cutters excavate rocks and boulders. In most cases, this excavation mechanism can be used successfully down to boulder sizes of 400mm to 600mm. The remaining rock entering the excavation chamber is then crushed into smaller particles by a rock crusher located in the invert of the machine. The maximum allowable grain size after crushing is dictated by the design of the slurry circuit, especially the size of discharge pipe, pump type and slurry flow speed.

As a rule of thumb the practical maximum grain size can be considered to be about 30-40% of the discharge pipe diameter. The typical arrangement in the suction area for conditions with boulders and cobbles is the installation of a grill for grain size limitation in front of the suction pipe and a hydraulic jaw crusher in front of the grill. Different size jaw crusher capacities are used in different machine diameters:

Jaw crusher (left) and rotary sizer with agitators (right)



Above: Fig 7 - Example of suspension supply to excavation and pressure chamber

Left: 17" monobloc cutter, on the ESCSO Project in Portland, USA

- 4m-6.5m: max boulder size 500mm
- 6m-10m: max boulder size 800mm
- 9m: max boulder size 1200mm

Early attempts to use "in-line" crushers or boulder traps in the discharge pipe were unsuccessful and have therefore nearly disappeared from modern designs.

The amount, size and consistency of the anticipated rock influences the choice of cutterhead configuration and cutter tools. Disc cutters are the most effective tools for excavating hard rock. However, the cutting tools for handling rocks and boulders with a Mixshield require different features in order to operate under pressurised slurry conditions. In particular, the cutter seal and seal gap design differs, to effectively prevent the penetration of muck and slurry (mud packing), but also provide the least possible friction to ensure the cutters are rolling properly across the tunnel face. For face pressures above 4 bar, compensating disc cutter systems have been developed that can handle high outside pressures as well as significant pressure variations, which on a 12m slurry machine is in the range of 1.5 bar from crown to invert.

If rolling is restricted due to inner friction, or the cutter is jammed, it will no longer be available for regular excavation and will only grind on one side. Two-ring cutters provide a better performance at lower single-ring thrust capacity, as they enable several cutting or face contact patterns for the same number of bearing seals and therefore a better relationship between cutting ring- and inner friction. The use of two-ring cutters also requires fewer housing positions on the cutterhead and, for this reason, provides more options for cutterhead openings to optimise muck flow.

In many cases, the use of two-ring cutters in the inner face and centre area and single-ring cutters for outer face and periphery area is a good compromise. Grain size limiters in the muck openings are installed to keep loose rock or large boulders at the tunnel face, so they can be broken down by the cutters. The design and layout of the size limiters has to be decided on the basis of anticipated ground conditions and installed crusher capacity. Special care also has to be given to the working levels of the different tool types on a mixed face cutterhead. Disk cutters should be positioned 30mm to 50mm ahead of the soft ground tools to ensure that hard rock or boulders are first attacked by the appropriate tool type.

Positive results have been achieved on several mixed face slurry machines using specially designed Monoblock cutters, with a reduced risk of secondary wear to non-cutting related elements of the cutters, such as split rings or hubs.

The combination of mixed face cutterhead tool arrangements and jaw crusher-suction grill arrangements has proven effective when dealing with variable face conditions or cobbles and boulders. The need to manually intervene in order to remove or split boulders has been reduced dramatically and can be considered an exception these days.

Clogging risks

The problem of clogging can be addressed in several ways: choice of tools, quantity of fresh suspension supply, flushing and/or agitation systems in the excavation chamber, flow in the chamber and the geometrical design and shape of cutterhead, excavation and pressure chamber.

The preferred method in adhesive ground conditions is the use of wide cutting tools, in order to achieve bigger cuttings or clay chips. This also reduces the number of tools required to cover the full face. The use of fewer cutting tools increases the free areas between the individual tool sockets and therefore reduces the risk of "bridge building" and adhesion at the cutterhead.

A high circulation or flushing quantity in the excavation chamber, in combination with a suitable cutterhead design, encourages free flow of excavated muck and reduces the time cuttings remain in the chamber to a minimum. Optimisation of the flow and a reduction in the time taken for muck to pass through the excavation chamber also have positive effects on wear reduction. This was demonstrated on the CTRL's Thames Tunnel drives, in London, where two Mixshields were used to mine through chalk layers containing a large amount of abrasive flint.

Flushing nozzles at the centre of the cutterhead supply fresh suspension close to the tunnel face where the soil excavation takes place. These feed lines in the rotating cutterhead are supplied via single or multiple channel rotary joints in the cutterhead centre. Feed line outlet arrangements in front of the submerged wall ensure a sufficient quantity of supply to the rear face of the cutterhead in the excavation chamber. For Mixshields operating in adhesive ground, there is a general tendency to feed fresh suspension in front of the submerged wall.

Each individual supply line into the excavation chamber or the cutterhead can be controlled from the TBM's cabin, with information about the flow and pressure of each individual line being fed back to the operator. Depending on the ground and the direction of cutterhead rotation, adaptation and optimisation of the feed-line flushing pattern is also possible. The installation of mixing arms behind the cutterhead is also a common solution to assist flushing.

There are two ways to avoid adhesion or muck settlement in the pressure chamber area. Mechanical agitator wheels in the invert area can assist muck flow. Alternatively, rotary sizers (see p39) can be used to cut clay chips to size, while not obscuring continuous conveying into the suction pipe. Additional flushing nozzles in the pressure chamber can also assist flow. T&T

Part 2 of this article, due to be published next month, will focus on potential future developments of Mixshield technology.

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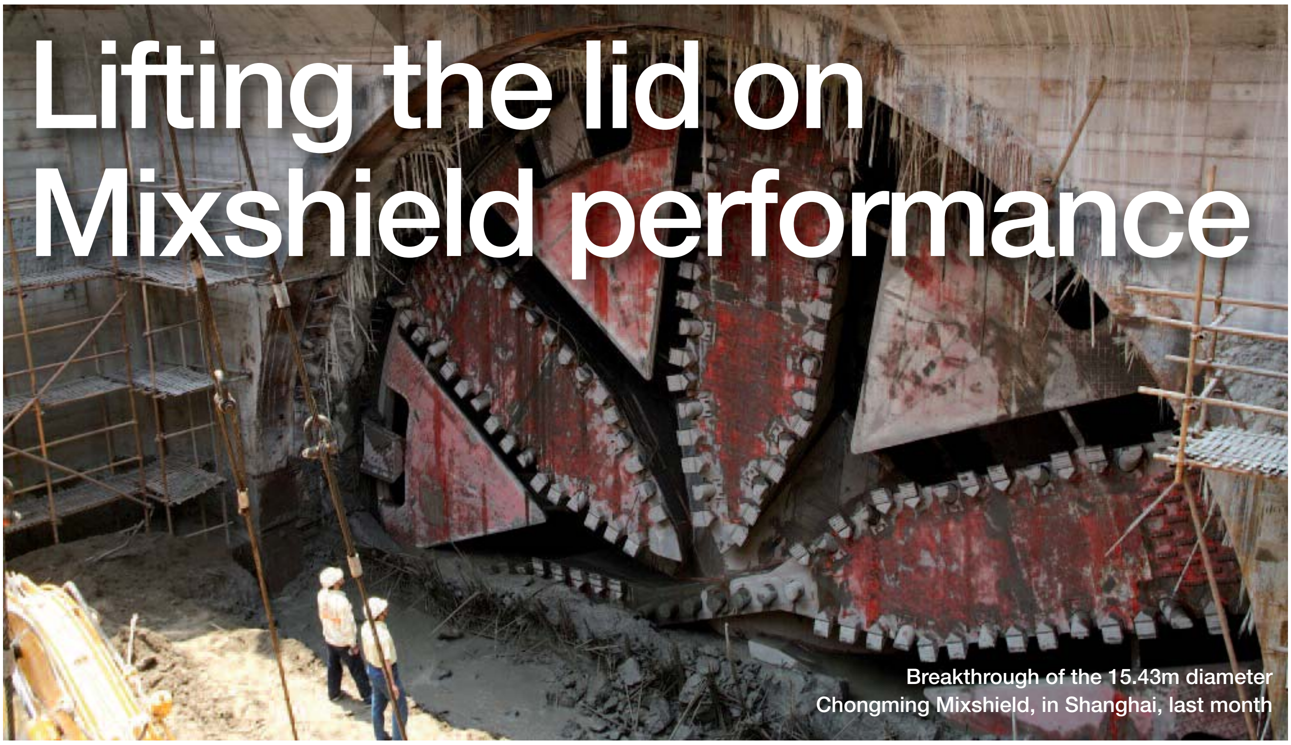
REFERENCE PAPER:

LIFTING THE LID ON MIXSHIELD PERFORMANCE.

HERRENKNECHT
Tunnelling Systems

Lifting the lid on Mixshield performance



Breakthrough of the 15.43m diameter Chongming Mixshield, in Shanghai, last month

There remains much potential for the future development of Mixshields, particularly in terms of increased diameters and higher face support pressures. In part two of their article, Werner Burger and Gerhard Wehrmeyer, of Herrenknecht AG, look at two particularly influential projects and their impact on future Mixshield technology

A glance at the development of Mixshields over the past two decades (figure 8) shows an impressive increase in tunnel diameters. What's more, from a TBM technology and manufacturing point of view, there is no obvious technical limit on further increases.

Diameter increases are closely connected to the planned purpose of a tunnel. Two and three lane road tunnels have now been constructed with diameters of 11.2m (A86 Road Tunnel, Paris) and 14.2m (Lefortovo Tunnel, Moscow), and a three-lane road tunnel is currently being built in China with a diameter of more than 15m (Chongming, Shanghai).

With these diameter increases, multi-purpose or combined-use tunnels such as road/water storage (SMART, Kuala Lumpur) or road/subway (Silberwald, Moscow) are also becoming more widespread. The ability to excavate very large diameters also creates additional potential for new usage concepts, like subway station platform tunnels.

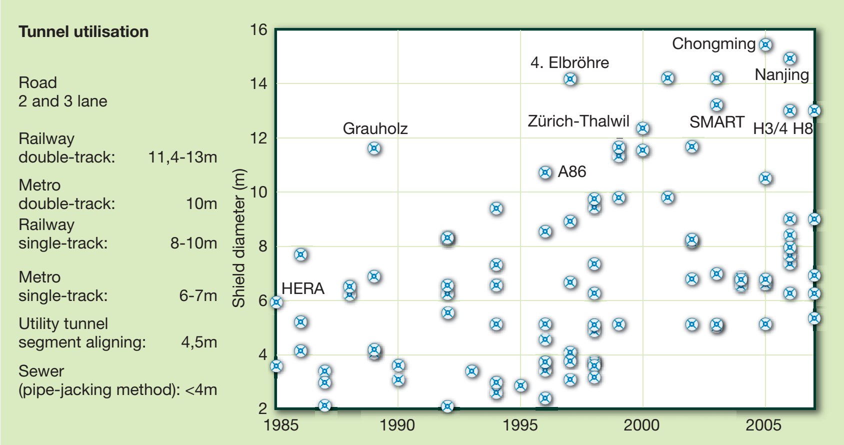
Twin-track rail tunnels with diameters of 11.4m-12.6m already exist, and the increasing speed of trains and higher demands of operational safety (emergency rescue/escape concepts) will create further need for larger tunnel and machine diameters.

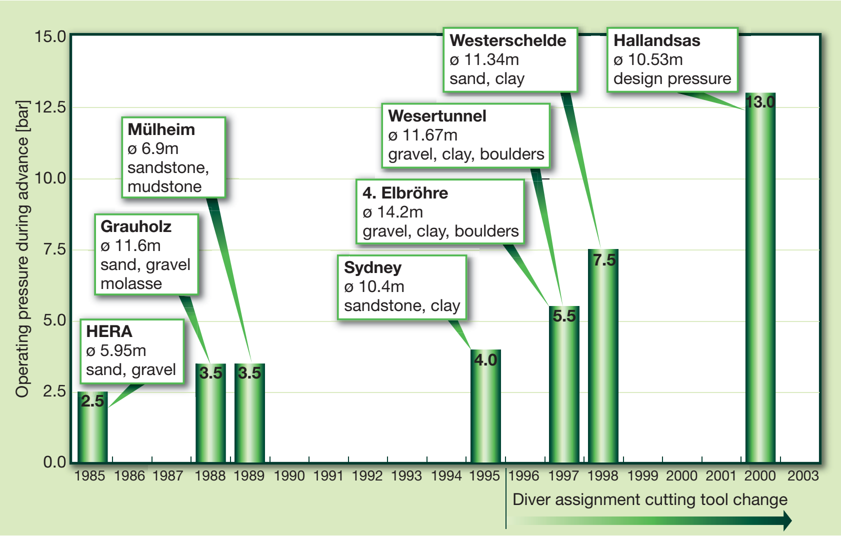
Increasing performance demands, combined with experience from past projects, has also contributed to a continued increase in Mixshield operating pressures (see figure 9). Compared with EPB machines, the Mixshield's use of a closed slurry circuit as the mucking system enables higher face pressures to be effectively dealt with. Controlling a large pressure drop in a continuous mucking system is also easier with a slurry circuit than with a screw conveyor, especially in heterogeneous or highly permeable ground conditions.

A significant increase in face pressure affects all components of the shield that are exposed to the surrounding soil or groundwater. In particular, it affects:

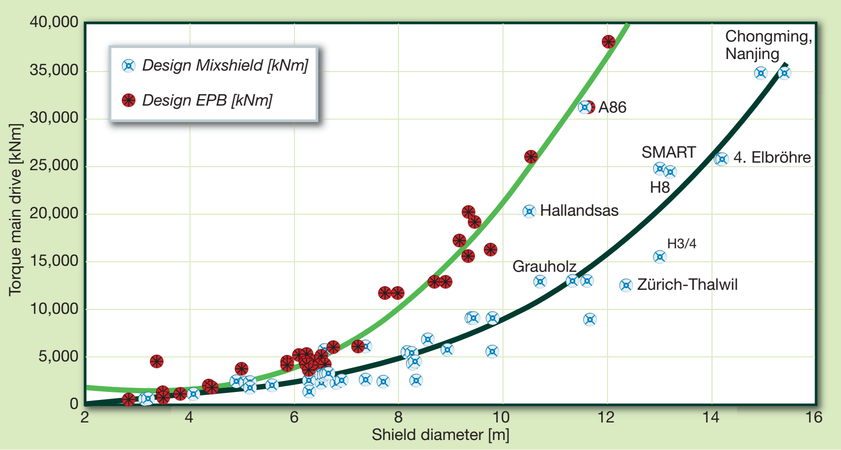
- Shield structure
- Tail seal systems
- Main bearing seal systems
- Articulation seals
- Shield thrust system
- Slurry circuit
- Equipment (and procedures) for face access

Below: Fig 8 - Diameter development of Herrenknecht Mixshields





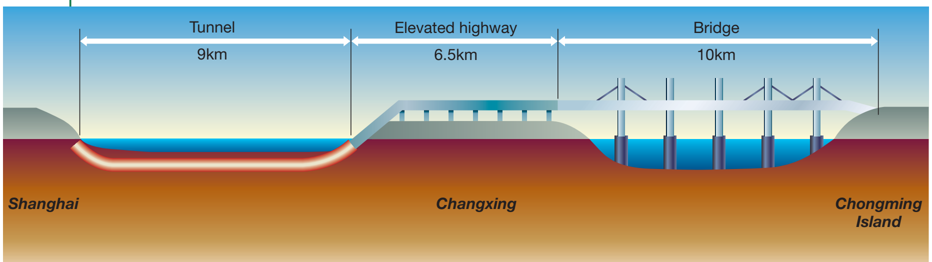
Above: Fig 9 - Operating pressure of Herrenknecht Mixshields



Above: Fig 10 - Torque comparison of cutterhead drives (Mixshield vs EPB-shield)

While it is possible to accomplish the required shield thrust by changing the number or diameter of the thrust cylinders, far more sophisticated technical solutions are required for seal systems. This is especially true of the main bearing seal system, which is one of the most sensitive design elements in high-pressure applications. For support pressures beyond 4 bar, pre-stressed cascade systems are used with the individual cascade chamber pressures automatically following the face pressure.

Below: Fig 11 - Chongming alignment



These systems can handle pressures far beyond 10 bar for an extended period of time in dynamic mode without the risk of overloading the individual lip seals. Long-term field experience with large diameter drive systems (bearing diameter range of 6m) with face pressures of 7 bar to 10 bar already exist and full scale workshop and commissioning test programmes with pressures of 15 bar have been performed successfully. In emergencies or extended stoppages (long-term static mode), additional inflatable seals are included.

While it is now possible to address high-pressure operations by using appropriately designed equipment, the key questions relate more to the potential and the limitations for chamber access under hyperbaric conditions.

Technical solutions to reduce the need for man access to the excavation chamber are available and currently include:

- Accessible cutterheads for atmospheric cutter tool change (larger machines only)
- Remotely activated standby cutter tools
- Load detection and wear sensor systems

However, these technical features will not totally eliminate the need for a “Plan B” for manual intervention to cover unforeseen conditions or worst-case scenarios.

Based on the system of excavation and face support, a Mixshield requires lower cutterhead torque compared with an EPB shield (figure 10), as the cutterhead is only excavating the ground at the tunnel face into the suspension-filled excavation chamber. The excavated soil sinks towards the submerged wall opening in the invert due to gravity, assisted by the flow direction of the circulated slurry, and is carried to the suction pipe after clearing the rock crusher and suction grille.

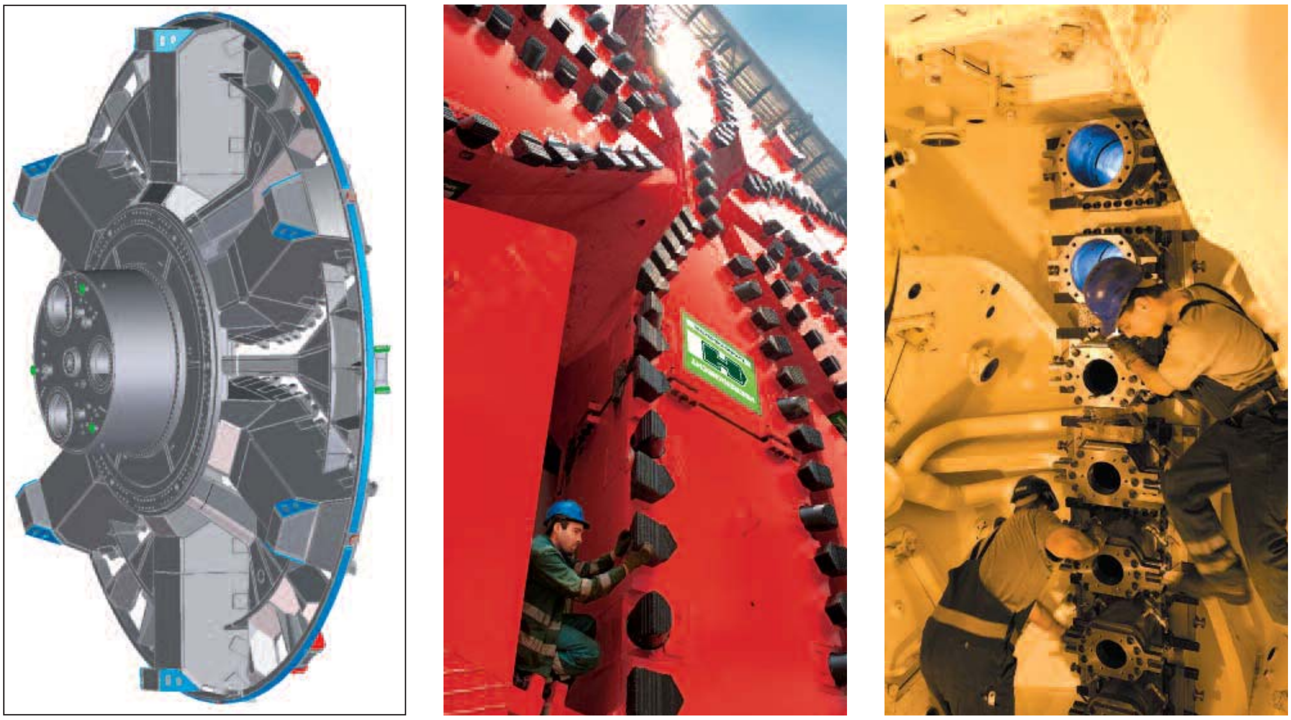
An EPB shield requires a comparatively high torque at the cutterhead because, in addition to the soil excavation, the cutterhead itself acts as a mixing tool inside the excavation chamber, which is completely filled with muck.

Therefore by adopting high torque EPB drive systems that have been developed for large diameter machines, such as that used on the M30 project, in Madrid (with 125,000kNm), there is huge potential for the development of larger diameter Mixshield machines.

Examples of projects

The following presentation of the Chongming and A86 tunnel projects demonstrates the efficiency of current Mixshields and the value of development.

Mixshield used as a shield with slurry supported face – Chongming, China: A twin tube road tunnel is currently being built beneath the Yangtze River in the city of Shanghai, comprising two 7160m-long bores with three lanes each. The tunnel, along with a new bridge, will link the islands of Changxing and Chongming to the freeway system and city. The geology of the tunnel is defined by its position in the river delta, consisting of soft clay deposits and thin sand layers. The tunnel has an outside diameter of 15m. The pre-cast concrete ring consists of 9+1 segments with a length of 2m. The segments are 640mm thick and weigh up to 16.7 tons. The basic concept of the two Mixshield machines for the project is based on experiences from the Mixshield used at



Above: Fig 12 - Accessible cutterhead: Design (left); front view (middle), view from inside (right)

the fourth Elbe Tunnel and advancements in large diameter shield developments in high water pressure conditions. With a shield diameter of 15.43m, the two machines are currently the world's largest diameter shields.

The Mixshield machines have following technical features:

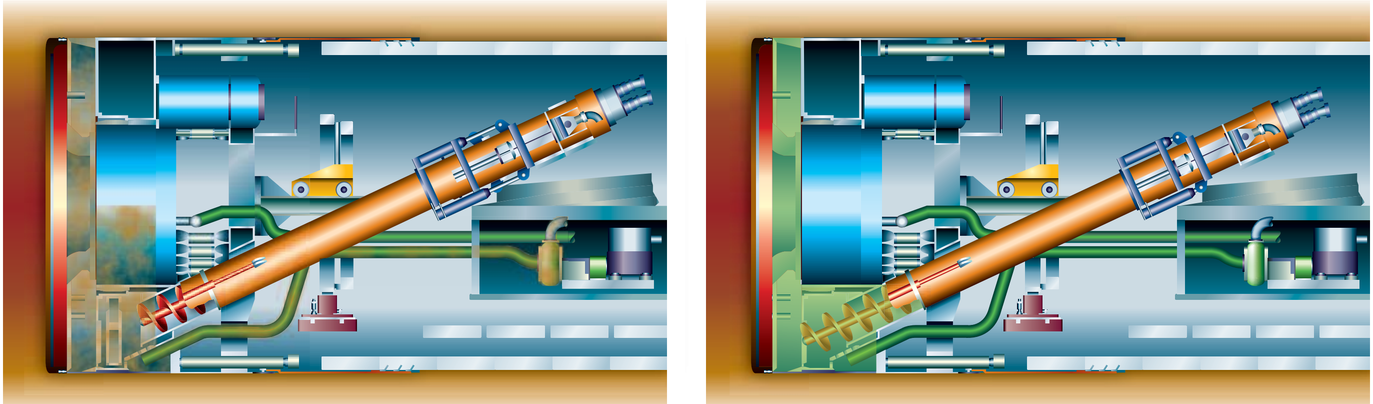
- The shields are designed for an anticipated operational pressure of 6 bar at springline level. Due to the underwater application, and nearly straight alignment, (Rmin = 4.000m), a shield articulation joint was not included
- The invert area of the Mixshield is equipped with two agitator wheels (Ø1.900mm), which assist the material flow to the grille and a 500mm diameter suction pipe. Submerged wall gate, bentonite nozzles, cutting wheel and extensive excavation chamber flushing arrangements complete the Mixshield configuration to address the soft soil conditions and potential clogging risks
- The double shell tailskin with integrated grout lines has a three-row wire brush seal and an inflatable emergency seal system. Furthermore, freezing lines are integrated into the tail shield, which, in case of emergency, can be used for ground freezing around the machine to minimise the risk of water inrush during brush seal changes or repair works
- The cutterhead is designed with six main spokes accessible under atmospheric pressure. To reduce the need for pressurised face access, one complete set of cutting tools (covering the entire face area) is exchangeable under atmospheric conditions from within the cutterhead spokes. To suit to the anticipated geology, the cutterhead was equipped with massive scrapers. Two hydraulically operated overcutters can create an overcut of 40mm in radius. The cutterhead front and outer areas, as well as the rear, are designed to be durable and wear resistant to cope with the single drives of more than 7000m (see p31).

As an additional safety feature, the Mixshields are equipped with all components – such as air locks and installations – necessary for pressurised face access including saturation diving activities.

The installed cutterhead drive power is 3750kW and the bearing diameter is 7.6m. The torque of the variable frequency electrical drive is 34800kNm, the shield thrust capacity is 203000kN and the TBM system is designed for a nominal mining speed of 45mm/min.

The three-section backup system has an overall length of 118m and is divided into primary backup, bridge section and

Below: Breakthrough of the Westerschelde machine, in The Netherlands



a) Operation mode slurry

b) Operation mode EPB

Above: Fig 13 - Machine concept of the A86 Mixshield, used in Paris, France

secondary backup.

The primary backup, or first three-deck trailer, contains all the hydraulic power packs and electrical systems for the supply and operation of the shield, along with slurry pumps and backfill grout system. For an even distribution of the wheel loads the trailer contains an integrated support system of auxiliary rail elements (steel invert slabs) and multi-wheel sets. The prefabricated 35 ton invert elements are installed in the area under the 67m bridge section. The supply crane system is installed inside the bridge cross-section to transfer segments, grout and other consumables to the TBM. All installations and workplaces for extension of services are located in the third section, along with ancillary equipment.

The machine is supplied with segments and grout by rubber-tired transport vehicles, which travel in convoy and carry either segments only or segments and grout tanks. The segment transfer on the backup is done by segment crane and a segment feeder. The grout is supplied in transfer tanks to the first backup.

The shield structures and assemblies of the 132m-long and 2,300 ton TBMs were manufactured in Shanghai. Cutterheads and other main components such as drive assemblies and thrust cylinders were manufactured in Germany and shipped to China. After shop acceptance, the TBM was disassembled and transported to the start shaft about 6km from the workshop.

Tunnelling started for the first tube in September 2006, and in January 2007 for the second. In March 2008, the first 7160m tunnel was about 90% complete and the second about 70%. Constant weekly performances of 90-120m are now being achieved by each TBM. Both drives are scheduled to finish in 2008 (the first TBM in May, and second in September), almost a year ahead of the project schedule.

Mixshield used in differing operational modes – A86 tunnel: To close the gap in the A86 orbital motorway, a 10.1km-long, two-deck road tunnel for cars has been built to the West of Paris. A second tunnel for trucks is planned for construction at a later stage. Two levels, with three lanes each, require an outer diameter of 11.565m. The tunnel crosses the entire spectrum of geological formations under Paris: Marl, clay, limestone, chalk and sand as well as three different groundwater levels. For optimum adaptation to the geological conditions, the machine had to operate in different modes:

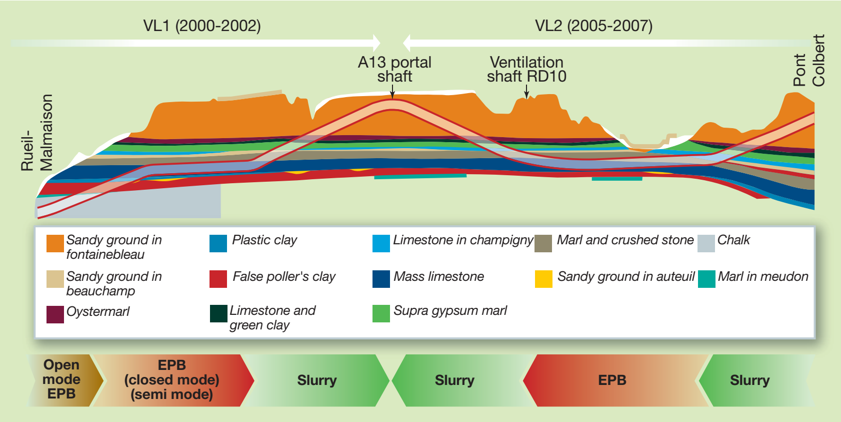
- As slurry shield with slurry supported face (slurry operation - see figure 13a)
- As earth pressure balance (EPB) shield with face support provided by conditioned muck (see figure 13b)
- In Semi-EPB, or compressed air, mode
- In open mode (muck discharge via screw conveyor, non pressurised excavation chamber)

The change between different operational modes is carried out within the tunnel. Shield and backup are equipped with the full range of equipment for each mode. For slurry mode, this included a full slurry circuit with submerged wall/pressure wall installation and also a rock crusher. For EPB mode, components such as screw conveyor and TBM conveyor were installed.

The cutterhead is designed for use in all modes of operation without the need for modification. The cutterhead concept is a closed wheel type with a full set of mixed tool equipment including 17” backloading disc cutters and ripper tools for two directions of rotation.

In slurry mode, the excavation chamber and the lower part of the pressure chamber are filled with bentonite slurry; the upper part of the pressure chamber contains the air bubble, and the entire area is pressurised. In EPB mode only, the excavation chamber is pressurised so the submerged wall becomes a pressure bulkhead. The pressure chamber is then at atmospheric pressure and can be used as a working chamber, only pressurised during

Below: The A86 machine breaks through



Above: Fig 14 - A86 Tunnel alignment

face access. To change from EPB to slurry mode, the entire screw casing is moved back, thus clearing the submerged wall opening in the invert and the suction grille below. After this, a specially designed jaw crusher moves from parked position to operational mode.

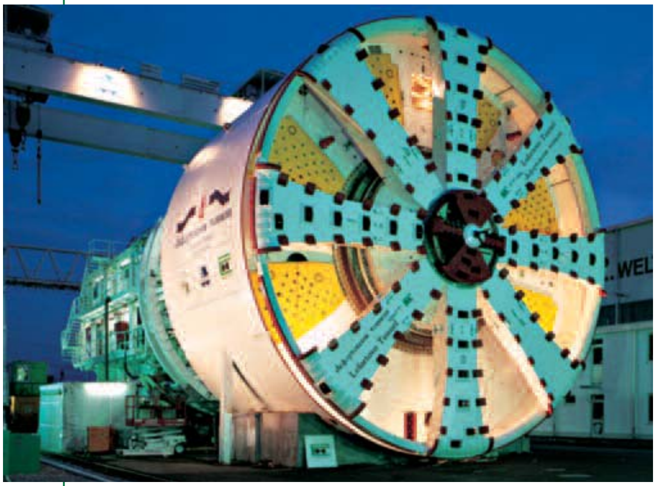
Some of the slurry mode installations, such as the air bubble pressure regulation system or the bentonite circulation systems, can also be used in EPB mode when required. Having the two systems permanently available provides potential synergy.

Apart from the ability to change modes of operation, the TBM also has the following technical key features:

- To cater for EPB mode, installed cutterhead power is 4000kW and the available cutterhead torque is 35000kN/m. Shield thrust is 150000kN, and the designed advance speed is 80mm/min
- The slurry circuit with 1900m^3/h flow volume is designed for a mining speed of 50mm/min in slurry mode. The tunnel is runs uphill and the largest difference in height between portal and TBM is 160m. This configuration needed to be addressed in the design of the slurry circuit as, under some conditions, the friction losses in the discharge line are less than the geometrical height between TBM and treatment plant
- A specially designed camera system for the excavation chamber was installed for the first time and successfully tested in semi EPB/compressed air or open mode
- Due to the steep tunnel gradient of 4.5% rubber tired vehicles were used for segment and grout transport. At the tunnel portal a semi-automatic loading station for the vehicles was installed loading one complete multi stack truckload at the same time, which together with a quick unloading system in the gantry reduced the turnaround cycles

The pre-cast invert slab elements for the final lower road deck were installed 200m behind the trailing gear, concurrent to the advance of the TBM. In November 2000, the machine started excavating the VL1 tunnel (figure 14) in open mode EPB configuration. The first 150m in an incomplete starting configuration through chalk containing a high amount of flint was excavated in two-shift operation, quickly reaching mining speeds of 80mm/min. After having installed the TBM and portal systems in their final configuration, the operation was changed to three shifts.

Following a fire in the rear section of the tunnel in 2002, mining activities were halted for three months. By October 2002, the TBM was operated in open mode, closed mode EPB with face pressures of 1-2 bar and semi EPB mode. The semi EPB mode proved to be the most appropriate method for excavating the stable but water bearing material, using the compressed air to control the water and achieving dry excavated material.



Left: **The 14.2m diameter Lefortovo Mixshield, before it was shipped to Moscow, Russia**

With the ground conditions changing into Fontainebleau sand, the machine was changed in-tunnel to slurry mode and operated in that mode for one year achieving mining speeds of 50mm/min. The breakthrough of the first tunnel was in October 2003. The TBM was disassembled, transported and reassembled at the Pont Colbert starting portal for the VL2 tunnel.

For the VL2 tunnel the TBM began excavation in slurry mode. Immediately, around 10m after the portal, a major six-lane motorway had to be passed beneath with shallow cover. Launch and passing under the freeway was completed after just nine days with no problems. After 1.2km in slurry mode, the TBM was changed back to EPB mode, and after passing an escape and ventilation shaft at the deepest point of the VL2 tunnel the TBM mode was changed back to slurry again. The machine arrived at the portal in August 2007.

Conclusion

Initiated by the requirements of numerous large scale projects around the world, the development of Mixshield technology has taken major steps forward, as illustrated in this and the previous article (*T&TI*, May p35). Numerous additional features are also currently on the drawing board or being used for the first time. These include:

- Advanced wear detection systems for cutting tools and structure
- Positive ground support of the tunnel wall along the shield skin
- Advanced ground improvement scenarios for closed mode from within the machine
- Total integration of the whole package of above ground and underground measurement, process and alignment control data for a controlled boring process (CBP)
- Approaching diameters of 18m to 20m
- Fully variable, multi-mode concepts (EPB/HD slurry/LD slurry)

The ability to handle high water pressures, the potential for crusher installation, low power requirements, high accuracy of face pressure and settlement control, and favourable face configurations, are just some of the current advantages of Mixshield technology. The combination of these advantages along with the ability to change modes of operation, brings the concept close to combining the best of both worlds. Nevertheless, there is also still huge potential for future development of the technology, that will see even greater tunnelling challenges conquered. T&T

REFERENCE PAPER:

THE LATEST TECHNOLOGY IN MECHANIZED TUNNELING – THE DESIGN OF THE WORLD'S LARGEST EPB AND SLURRY SHIELD TBMS.

HERRENKNECHT
Tunnelling Systems

Underground Space – the 4th Dimension of Metropolises – Barták, Hrdina, Romancov & Zlámal (eds)
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The latest technology in mechanized tunnelling – the design of the world's largest EPB and slurry shield TBMs

Dr.-Ing. E.h.Martin Herrenknecht & Dr.-Ing. K.Bäppler
Herrenknecht AG, Germany

ABSTRACT: The general increase in growth is a result of a worldwide growing need for an efficient infrastructure in the areas of transport, supply and disposal services. Topographical conditions in large cities and towns encourage tunnelling solutions, particularly by mechanized methods. The mechanized tunnelling process has captured the attention of the public sector. As a safe, settlement controlled tunnelling process it offers a beneficial alternative to other tunnel excavation methods. Innovative solutions are increasingly required for tunnelling projects with a high level of difficulty in terms of construction, such as large diameter inner-city tunnels in heterogeneous grounds with high water pressures or the construction of long-distance tunnels integrating combined traffic systems in the tunnel cross section. Mechanized tunnel excavation moves into new dimensions especially regarding complexity of ground conditions, diameter, length and depth of underground constructions where the feasibility of other tunnelling methods is limited. This paper focuses on the design and technical challenges of the three largest soft ground tunnel boring machines, two Slurry Shields (ø15.4 m) for the Shanghai River Crossing project and one Earth Pressure Balance Shield (ø15.2 m) used for a road tunnel project in Madrid in Spain.

1 INTRODUCTION

The tendency of the tunnel projects of today show the innovative move of using full-face TBMs with diameters larger than 14 metres.

The resulting larger effective tunnel cross sections enable the possibilities of integrating more than 2 lanes of traffic or more than one traffic system in the tunnel or as shown with the example of the Storm Water Management and Road Tunnel project in Kuala Lumpur in Malaysia that the tunnel can take over more complex service functions.

With the example of the two largest soft ground tunnel projects in the world the latest technology in mechanised tunnelling will be described. The current largest Earth Pressure Balance Shield (Ø15.2 m) was in use for a road tunnel project in Madrid. The tunnel takes three lanes of traffic side by side on one level in the tunnel cross section. The two largest Mixshields (Ø15.4 m) designed for the Shanghai River Crossing Project in Asia are in use for the construction of a road tunnel carrying three lanes of traffic on one level and a safety passage and a rescue lane in the bottom of the tunnel cross section.

2 LARGEST EARTH PRESSURE BALANCE SHIELD (Ø15.2 M) USED FOR THE M30 ROAD TUNNEL PROJECT IN MADRID

Within the framework of the project Calle M30, the largest Earth Pressure Balance Shield (EPB) was in use for the construction of the north tunnel of the south bypass on Madrid's highway M30.

The tunnel route passes through a densely populated area and crosses beneath several structures such as three metro lines and railway tracks with minimal cover. The lowest distance from the tunnel crown to the structure is only 6.5 meters and this with an inside diameter of the tunnel of 13.37 m.

The tunnel is constructed with reinforced concrete segments. One tunnel ring is composed of 9 + 1 segments and has a length of 2.0 m.

The EPB-Shield with a diameter of 15.2 m has been designed to suit the prevailing cohesive soil conditions, which have been predicted along the designed tunnel alignment. Clay and gypsum of stiff to hard consistency are characteristic of the geological conditions at tunnel level.

Large diameter EPB machines, and very large diameter EPB machines such as the one used on the south bypass tunnel for M30, require a very high cutting wheel torque compared for example to slurry TBMs.

Machine technical and process technical factors such as drive unit and bearing unit, cutting wheel design and rotational speed have a relevant effect on the torque of the cutting wheel. The EPB-Shield for the Calle M30 project has a very high cutting wheel torque which amounts to 125,000 KNm. Therefore the cutting wheel is equipped with two concentrically arranged cutting wheels.

The inner cutting wheel is installed in the free centre of the outer cutting wheel as a flat disc-type wheel. It is installed in the working surface of the outer cutting wheel and it is longitudinally displaceable relative to the outer cutting wheel.

The rotational drives of both cutting wheels are completely independent with different rotational speeds in both directions of rotation.

Part of the high torque is consumed in the mixing chamber, which is neutral with respect to the rolling of the machine. The torque is consumed between the cutting wheel and the tunnel face, it is the active part regarding the rolling of the TBM and can be resisted in loose soil by means of the skin friction or by transfer into the tunnel lining (reinforced concrete segments). If the torque rises beyond the value which can be resisted by the moment of friction of the shield shell, the machine will show a tendency to roll.

With a diameter of 15.2 m and a torque of 125,000 kNm the Herrenknecht EPB Shield beats all dimensions which have up to now been available on the mechanised shield tunnelling market.

The drive unit of the inner cutting wheel comprises 10 motors with a total power of 2,000 kW. To summon up the required power of 12,000 kW for the outer cutting wheel a new design was conceived. Altogether 50 motors are necessary for the outer cutting wheel drive. They have been distributed around the main drive in two rows of 29 motors and 21 motors.

The double cutting wheel design also improves the excavation process and the soil conditioning. The material excavation in the outer and inner area of the tunnel face can to a large extent be carried out at an optimised cutting tool speed. This is achieved by adjusting the differences in peripheral speeds, which can be applied to the cutter tools.

The design of the outer cutting wheel area facilitates the arrangement of various cutter positions, which is normally not possible at all in the inner area as a favourable opening ratio must be maintained. A great difference in the cutter penetration depth between the outer and the inner area can be avoided by a higher rotational speed in the inner area, which has also the effect of reducing wear on the cutting tools.

With regard to the soil conditioning with the double cutting wheel design and in particular with respect to the material removal and kneading or mixing effect, the mixing chamber can be divided into two zones. Both can be handled independently from each other.

The areas of the inner and outer mixing chamber are in direct contact with each other so that an exchange of material between both zones is possible but not necessary. Because of the individual handling of the outer and inner mixing chamber, a homogenous consistency of the material in the chamber can be achieved.

The cutting wheel is equipped with eight independent injection points at the front face of the centre cutting wheel and with 14 independent foam lances installed in the outer cutting wheel. Thus the injection of plasticizing agents such as foam is possible. Thereby 36% of the total volume will be injected through the injection points, which are provided on the front face of the centre cutting wheel and the remaining 64% will be injected in the outer ring section.

The start-up of the excavation process of the currently largest EPB-Shield begins when the inner cutting wheel starts rotating. The soil will be conditioned with foam through the rotary union, which is attached to the centre cutting wheel and above the stators. The stators are positioned in the centre area behind the cutting wheel in order to reduce the friction on the inside. To increase the mixing effect in the centre area, the displacement cylinders will be slowly extended.

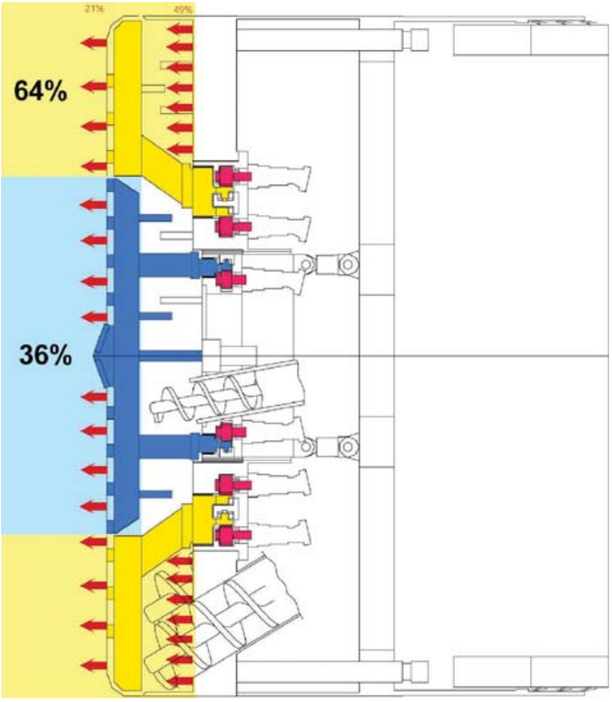

Figure 1. Injection of plasticizing agents through the two concentrically arranged cutting wheels of the EPB-Shield (Ø15.2 m) for M30.

It can be assumed that the soil will be well-conditioned up to a diameter of approximately 9 m and this will considerably reduce the starting torque of the outer cutting wheel.

As soon as the centre area is conditioned, the outer cutting wheel starts turning and simultaneously adding foam. Thus, the complete excavation area will be homogeneously conditioned and the advance process can commence.

The excavated material is transported out of the excavation chamber via three screw conveyors, which are integrated in the shield. They handle an excavated volume of 565 solid cubic meter per ring. There are two parallel screw conveyors (Ø1,250 mm), which are located in the lower part of the shield to remove the excavated material from the outer cutting wheel and to transport it back to the belt conveyor. The third and smallest screw conveyor (Ø600 mm) is arranged in the lower third of the central cutting wheel. It will remove the excavated material from this area and convey it back to the belt conveyor.

The complete transport of the TBM from the manufacturing factory to the jobsite took two months. The main components of the Shield TBM were first transported with a river boat to the port of Rotterdam and then with two ships to Spain. For unloading the components a crawler crane with a capacity of 600 tons was necessary. The transport on the road lasted approximately nine days (50 km per night accompanied by the police).

The excavation of the 3,525 m long north tunnel of the south bypass on Madrid's highway M30 started on November 15, 2005 and could successfully be completed, on July 12, 2006, by the team of the contractors Acciona Infraestructuras S.A. and Ferrovial-Agroman S.A. in cooperation with Herrenknecht AG, after only 8 months of construction time.

During advance the giant boring machine achieved convincing performances, which could be increased week by week and pushed to a best weekly performance of 94 rings or 188 m. The best daily performance amounted to 18 rings or 36 m and the strongest monthly performance could be reached in May 2006 with considerable 758 m.

After the assembly and learning phase, weekly performances, which were clearly higher than 50 rings or 100 m, could be achieved permanently. The tunnelling cycles were 30 minutes and the construction of a ring, consisting of 10 concrete segments, 13.9 tonnes each, could be carried out in approx. 50 minutes. During tunnelling a cycle time of less than 100 minutes could be achieved for the advance and the installation of a 2,000 mm long ring. The TBM supplier's and construction firms' skilled personnel helped to reduce learning curve effects.

After approx. 1,000 m, 2,000 m and 3,000 m of tunnelling, a standstill of approx. 4 days was each scheduled in order to inspect the cutting tools, install tunnel belt boosters and carry out other maintenance operations that could not be done parallel to the advance. The target construction time of 12 months could clearly be underrun, and the 8-month tunnel construction time equals an excellent TBM performance of more than 450 m per month.

3 LARGEST MIXSHIELD (Ø15.4 M) IN OPERATION IN SHANGHAI

With the construction of the gigantic project "Shanghai Changxing Under River Tunnel" the region of the Yangtze delta near Shanghai will be further opened.

The Yangtze is Chinas biggest river. Its yearly flow of 951.3 billion cubic metres of water amounts to approx. 52% of the total yearly quantity of all Chinese rivers.

The greatest challenge of this project is the connection of the two river banks from the Pudong mainland with the island of Chongming. Two parallel motorway tunnels with a length of 8,950 m each will be built between the mainland Pudong and the island of Changxing. A bridge will connect the island of Changxing with the island of Chongming.

Since the waterway between the mainland Pudong and the island Changxing is a very busy main shipping route, the tunnel solution was preferred instead of a bridge construction.

With a length of 80 km and a width of 20 km, Chongming is the third biggest island of China. The island Changxing with a population of about 30,000 is characterised by the establishment of industries with three large shipping services.

The two parallel tunnels will run beneath the largest river of China with the currently largest two tunnel boring machines. The Mixshields have a shield diameter of 15.43 m. Each of the tunnel tubes will integrate two levels, of which the upper level will contain three lanes for motor traffic and the lower level is planned to integrate a rescue lane in the centre and a safety passage.

The planned construction period of the Chongming Yangtze River Crossing Tunnel near Shanghai amounts to four years.

The challenges for the design of the two largest Mixshields for the river crossing were on the one hand the large shield diameter of 15.43 m and on the other hand the predicted geological and hydrological conditions. Each tunnel will have a total length of approx. 7,170 m with a gradient of ±2.9%.

The two Mixshields are adapted to the local geological and hydrological conditions featuring clayey formations and very high groundwater pressures. The entire tunnel will be built in very weak, clayey soils below the groundwater table. Characteristic of the

Figure 2. World's largest Mixshield Ø15.4 m for Shanghai.

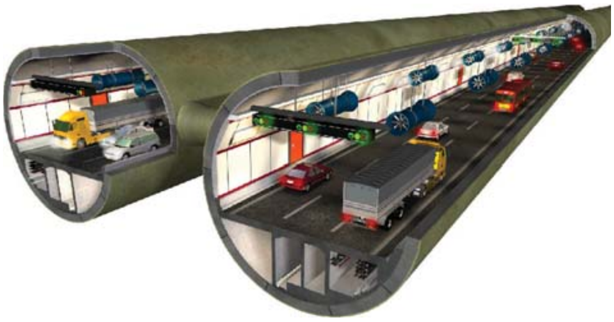

Figure 3. Changjian under River Tunnels, Shanghai.

expected geology are local intercalations of silty and sandy layers and shell residues.

Due to a ground-water level of up to 47 m above the centre of the tunnel, the TBMs are designed for a maximum working pressure of 6.5 bar. At the deepest point the tunnel will run about 65 m below the surface.

The tunnel lining consists of precast reinforced concrete segments with an inside diameter of 13.7 m. One tunnel ring consists of 9 + 1 segments and has a length of 2 m. For both tunnels altogether 7,500 segment rings are needed. They will be delivered with two special trucks from the segment fabrication yard, which is about 1.5 km away, to the jobsite.

A feature of the cutting wheel design are six accessible main spokes, which are sealed against the water pressure. To avoid adhesion of sticky clay at the cutting wheel, the centre area is equipped with an own slurry circuit. Large openings in the cutting wheel optimise the flow of material and reduce the risk of blockage of material in the centre.

In order to get reliable information about the condition of the soft ground tools and buckets, especially in the loaded outer area of the cutting wheel, ten cutting tools (2 buckets and eight soft ground tools) are equipped with an electronic wear detection system.

The system generates online data on the state of the selected cutting tools and gives early warning of possible wear to the TBM staff.

With this electronic wear detection system maintenance works can be planned and the service life of the tools can be optimised, thereby minimising costly chamber accesses under compressed air.

The heart of the system is a new tool support with integrated sender electronics. This is permanently connected to the soft ground tool through induction loops and "detects" whether the wear limit is reached. For this purpose the sender is electrically connected with a power supply. If the probe is intact a certain current flows but if the probe is destroyed due to wear of the tool this is "sensed" by the sender through a significantly higher fault current. The sender is inductively connected with the receiver and the tool probe through a small gap. A LED informs the machine driver of the wear. With this automatic method of wear detection unnecessary maintenance could be avoided.

The design of the cutting wheel was conceived in order to allow man access to its interior space under atmospheric air pressure, sealed from the ground water pressure outside.

Tool change devices, which are integrated in the cutting wheel, allow the personnel to replace tools under atmospheric conditions from the interior of the cutting wheel.

The tool change device has two functions:

1 To serve as receptacle for the tools.
2 To allow the outward and inward airlock transit of the tools.

In order to flush the devices there are flushing connections installed on the rear case.

This tool change device consists of the following main components:

1 Front casing. This forms the connection to the steel structure of the cutterhead and is circumferentially welded to it.
2 Rear casing. It is flange-mounted to the front casing and assumes in connection with the front casing the guidance of the slider and of the sliding pipe.
3 Slider.
4 Sliding pipe. The sliding pipe receives the cutting tool.

The sliders are opened in the working position. In this position the cutting wheel is made water tight by the front seal. In case of damage of this seal, the circumferential profile seal located around the slider and the rear seal would assure the leak tightness.

A further feature, which has to be mentioned, is the installation of road elements by the back-up of the Mixshield. The back-up is composed of three trailers. The first one contains all necessary equipment and supply material for the functioning of the excavation process. The second trailer is a bridge construction to allow free space of ±20 m for placing the road elements, which are precast concrete parts of 2 m length in dimension, 4.30 m in width and 4.56 m in height. Each element has a weight of approx. 35 tons.

Supplies will be delivered to the TBM with trucks. They will drive along these rectangular road elements which are placed along the centre of the bottom of the tunnel. The trucks will be unloaded in the back-up trailer number 3.

Back-up number 1 will run on invert slabs. These are placed on the already built segment ring and will be taken out and moved to the front as soon as the first back-up trailer passed this section. Back-up trailer number three runs on auxiliary rails.

The tunnel excavation for the about 7,170 m per tunnel tube is expected to take about 34 months. The commissioning of the BOT-tunnels is planned for 2010.

4 CONCLUSION

The two cited Shield TBM projects are characteristic of demanding conditions like the under river crossing near Shanghai and the inner-city tunnelling for the M30 project in Madrid. Both projects illustrate the feasibility of large diameter tunnels and are pointing the way for future projects regarding the excavation of even larger tunnel cross sections, long-distance bored tunnels and even deeper excavations.

In general, it is important to have a good understanding of all the conditions of a project already in the planning stage. The geological information is of particular interest because the machine design will be adapted to the predicted geological conditions. It is increasingly important to avoid possible risks when tunnelling in urban areas and also in the open country when underpassing existing structures or rivers and to further adapt the technology to make it even more safe and efficient.