Mixshield technology

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1. Introduction

The patent for liquid face supporting technology was already registered in the nineteen hundreds and has been successfully applied since the 1960s.

The original single chamber design of the traditional Slurry shield was developed into a two-chamber system (Mixshield) in Germany by the companies Wayss& Freytag and Herrenknecht in the 1980s. This way, the pressure conditions at the tunnel face can be controlled more precisely. Hence, the risk of settlements in city areas was reduced immensely.

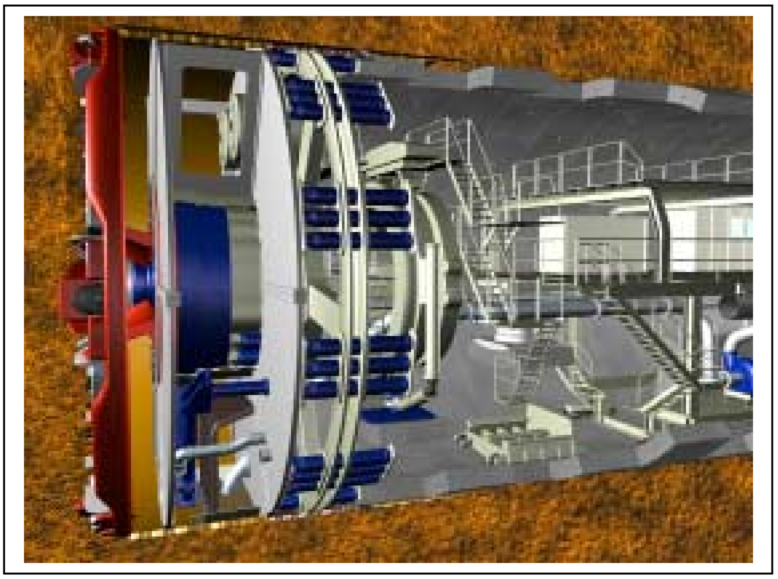

Fig.1: Mixshield with double--chamber system

The Mixshield is mainly used in non-cohesive soil conditions, which require liquid face support (bentonite). Bentonite serves as a support and conveying medium and has a crucial influence on the function ability of the Mixshield. An efficient operation of a Mixshield requires extensive separation technology to reduce the density of the bentonite. In addition to specific know-how about suspensions extra space for a separation plant is needed at the surface.

In solid clay soils, the use of bentonite is not necessary and water may be used as a muck transport and conveying medium.

An important advantage of a Mixshield in comparison to the EPB-shield is the use of a stone-crusher at the invert area to crush boulders. This characteristic qualifies the Mixshield for operation in mixed geologies of hard-rock and glacial soil formations, which contain the entire grain distribution spectrum including big boulders. Due to the center-free drive of the cutterhead, the Mixshield can be changed into hard-rock excavation mode with conveyor belt in the tunnel.

Fig.2: Typical spoke type cutterhead of the Mixshield
(Hamburg ∅14,2 m*, Berlin* ∅8,9 m*)*

With a Mixshield, the existing ground is excavated via a rotating cutterhead (see fig. 2) in a full face excavation process. The rotation speed and turning direction of the cutterhead is changed in most cases during tunneling to avoid a rolling of the shield.

The excavated soil flows with the support of a bentonite suspension through the opening of the submerged wall into the rear chamber and through a rake-type classifier via centrifugal pump out of the tunnel and into the separation plant.
Various openings in the excavation and working chamber provide continuous mixing of the soil with fresh bentonite.
In principle, the pressure at the tunnel face is determined by the volume balance between the suspension supplying line and discharge line as well as the excavated

material at the tunnel face. A crucial support pressure control is achieved by an air bubble in the upper part of the working chamber (see fig. 3) which is coupled to an automatic compressed air regulation. Thus, changes of the density of the suspension can be quickly compensated.

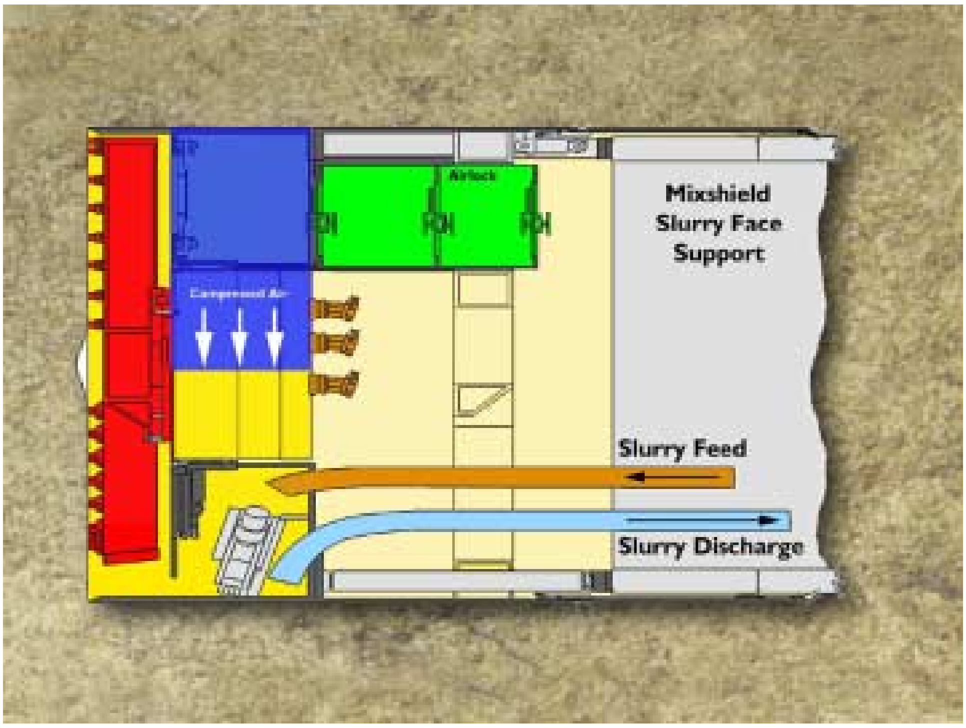

Fig.3: Compressed air cushion for precise support pressure control

Experiences in extremely sticky soils led to a problem solution using an active center-cutter as an independent micro machine with an extra slurry circuit and a cone-crusher (see Fig. 6), that reduces the clogging in the center.

2. The double-chamber system

The slurry-shield, originally developed by the Japanese, possesses of one working chamber, which is filled with the bentonite suspension. Density variations of the suspension by uncontrolled material break-down at the tunnel face lead directly to instabilities, since the density correlates with the pressure at the face. Therefore, at the beginning of the 1980s, the double-chamber system was developed. Via an air cushion in the rear working chamber, the pressure at the tunnel face is regulated by a compressible medium -air - (see fig. 3). The rear chamber and the front excavation

area are connected by an opening in the submerged wall. The air cushion above the bentonite column acts thereby as a flexible spring, which is connected to an automatic compressed air control system that quickly adjusts the pressure within an accuracy of minimum 0.1 bar.
The chamber can be separated completely by closing the opening in the submerged wall, the bentonite is lowered and access is possible under atmospheric conditions. The support pressure in the excavation chamber in front of the cutterhead is controlled by air pressure and bentonite equilibrium. Thus maintenance works can be accomplished e.g. at the crusher, without complete lowering at the face, whereby the risk of instabilities of the tunnel face is reduced.

2. Stone-crusher

The cutterhead type of Mixshields traditionally consists of spokes, which gave a high opening degree for efficient face supporting by the bentonite (s. fig. 2). Thus big boulders can enter into the machine and become a problem regarding further transportation through the slurry-pipes and pumps. Tunneling in heterogeneous ground with boulders therefore resulted in the innovative solution of the stone-crusher (s. fig. 4).

Fig. 4 : Jaw crusher

Fig. 5: Roller crusher with rotators

The first time, it was positioned in the cutterhead center in a machine operating in Switzerland (Grauholz Tunnel), which turned out to be not the optimum location.

State of the art meanwhile is the location of the stone crusher in the invert area of the Mixshield in front of the rake-type classifier and the pressure intake line. Stones of high strength and diameters up to 1.2 m can be crushed by hydraulically operated jaws (see Fig. 4). The crusher does not only serve size reduction, but - as in the case of the roller crusher used in Holland/Westerschelde (see Fig. 5) - to split clay lumps which can stick together in front of the sucking line due to adhesive and cohesive mechanisms and thus block the hydraulic transport. Another innovative development are rotators in front of the sucking line (see Fig. 5) to add kinetic energy in order to achieve a homogeneous low density of the bentonite. The design of round sheet metal transitions as well as the aerodynamically design of the working chamber are additional measures to ensure an optimized suspension flow and efficient tunneling in sticky ground.

3. Active Center Cutter

Experiences in sticky ground conditions showed that clayey soils predominantly settled around the cutterhead center. This is caused - among other things - by the peripheral speed along the cutterhead, which increases linear with the radius and is zero in the center. Here, there is almost no relative motion between soil and metal and that is why clay prefers to adhere in the center.

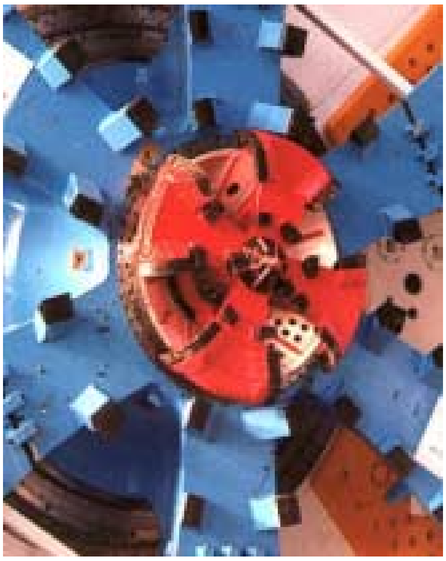

Fig. 6: Active center cutter (Essen / Germany)

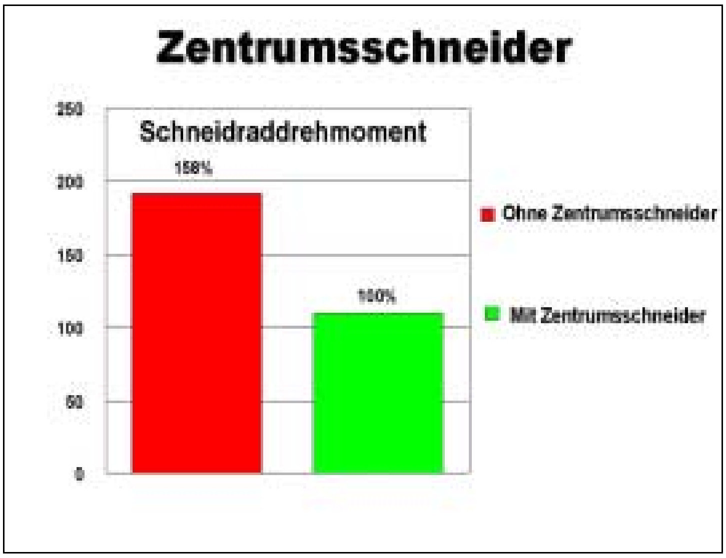

Fig. 7: Comparison cutterhead torque with/without center cutter (Essen / Germany)

With a use of a self contained micro machine with high number of revolutions, its own slurry circuit, the shearing speed between ground and cutterhead is increased, whereby a blocking of the cutterhead is prevented as much as possible. A positive effect of the active center cutter is also the reduction of the necessary torque for the cutterhead (see fig. 7).

5. Bentonite and Separation Technology

The efficiency of the Mixshield is dependent to a considerable degree on the bentonite technology. Bentonite, as a rule, is a three-layer silicate, which can store water in between the individual mineral layers which causes swelling. An efficient swelling process takes several hours and requires a high frequency mixer, in order to solve the clay minerals homogeneously in water. The fresh bentonite suspension has a density, depending on of the mixing recipe, slightly above water, to support the hydrostatic groundwater pressure within the soil.

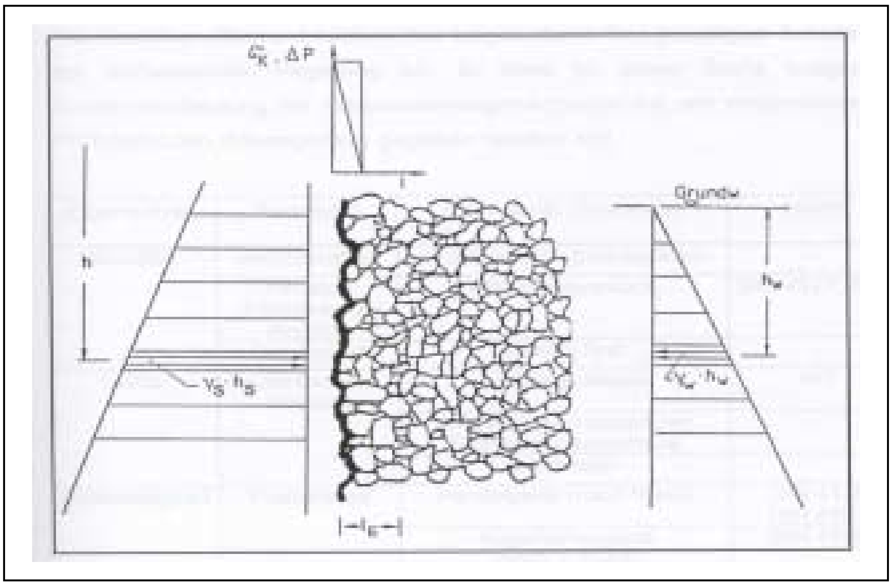

Fig.8: Creation of a mud cake

The dissolved bentonite suspension seals the tunnel face with a mud cake, which can only result from a pressure gradient between excavation chamber area and tunnel face (s. fig. 8). With a slight positive over-pressure in the suspension compared to the existing groundwater pressure, the bentonite displaces the pore water and activates shearing stresses between the soil particles, which stabilizes the face.

An additional mechanical support of the tunnel face are the hydraulically extendable support plates (see Fig. 9), which are perforated in order to supply the tunnel face with fresh bentonite in case of personnel enter into the working chamber.

The clay minerals of the suspension seal the pores at the tunnel face, whereby an almost impermeable filter cake is developing, which is comparable to a plastic foil. In the case of an entrance, it forms the important basis for admission with compressed air for the personnel.

Fig.9: Mechanical support plates for stabilization of the tunnel face

Due to its bipolar particle charge, bentonite is susceptible to changes of charge in the ground and/or in the groundwater. When mixing negative (e.g. chlorine anions) or positive (calcium cation) carriers, it may come to the flocculation (clumping) or liquefaction of the suspension, and thus to a sudden stability loss of the tunnel face. The quality of the bentonite must therefore be controlled regularly. Substantial control parameters are the filtrate water discharge, the yield limit and the density of the bentonite, which must be examined at the jobsite.

The used bentonite is conveyed by a centrifugal pump to the separation plant and should not exceed a maximum density of $1.5 t/m^3$, since the conveying capacity of the pump and the wear increase extremely. Investigations showed that the bentonite density represents a substantial control instrument for the reduction of stickiness. The Separation of the used suspension forms an important part for the efficient operation of a Mixshield. In the case of an under-dimensioning of the separation plant, the bentonite can only convey some parts of the excavated material out of the working and/or excavation chamber, which thus is accumulating in the front of the machine. The consequence is a time and cost-intensive cleaning of the tunnel boring machine. In dependence of the particle size distribution and the performance rate of the Mixshield, filters, hydro cyclones, centrifuges and filter presses are put in operation to separate the solved portions from the bentonite. Modern separation plants are supplied in module type, mobile or stationary. Chemical additives (polymers) can be partially added the loaded bentonite suspension for flocculation, in order to optimize the separation expenditure of fine particles. Depending upon size of the machine the first separation stage can be installed on the backup of the machine.

6. Slurry Circuit

The application area of the Mixshield regarding the face pressure lies with up to 8 bars above the EPB shields due to the enclosed system of the pipes.

Fig.10: Radiometric density and magnetic-inductive flow meters

The pipelines and centrifugal pumps are to a certain extent exposed to a lot of wear and have to be checked regularly. After a certain completed tunnel section, the entire pipe system is extended with the support of bypass and/or lock systems in the backup area.

Radiometric density meters and/or magnetic-inductive flow meters are mounted to the pipes, to perform a muck control in the excavation and working chamber, which also has an big effect on the stability of the tunnel face (s. fig 10).

7. Seismic Probing

Tunneling in glacial soils bear an increased risk of unforeseeable obstacles within the tunnel route, which can cause substantial damage to the tunnel boring machine.

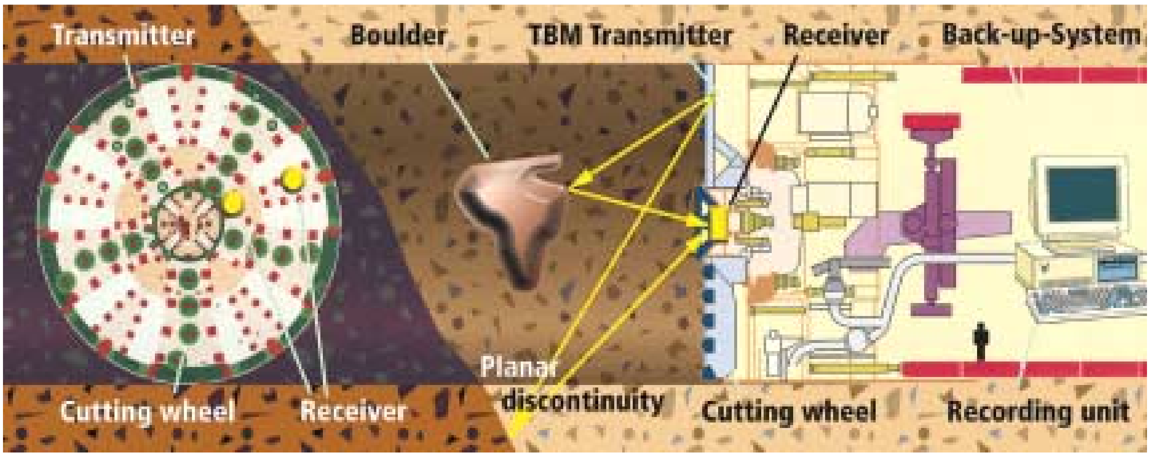

Fig.11: Seismic Softground Probing (SSP)

Due to the good coupling of the cutterhead and the ground via the bentonite a seismic softground probing system can be applied which gives the possibility to detect the density changes within the soil in front of the machine by an acoustic wave (see fig. 11). The wave velocity of the output/input signal is depending on the density of the medium in which it moves and therefore changes when finding fault zones, caverns etc. Based on the correlation between the output and input signal of the system, information are obtained regarding obstacles within the ground.

Newest developments for Mixshield provide a safety and control system of the tunneling process (SÜB), which as an expert system, provide the operator with special machine parameters, to reduce the risk of settlements at the surface.

Another innovative technology is the continuous tunneling of the Mixshield for the Project Sophiaspoor-tunnel in the Netherlands. The utilization of two erectors (s. fig

12) make it possible to set the rings without interruptions in the tunneling process – continuous excavation is accomplished. This means that during the usual down time of the machine, due to building the ring, the excavation can continue. This is achieved by the thrust cylinders, which have a stroke length of two segment, as well as an intelligent hydraulic control program which enables an asymmetrical startup of thrust cylinders. The result is a theoretical time gain multiplied by the duration of the ring time per ring multiplied by the number of rings.

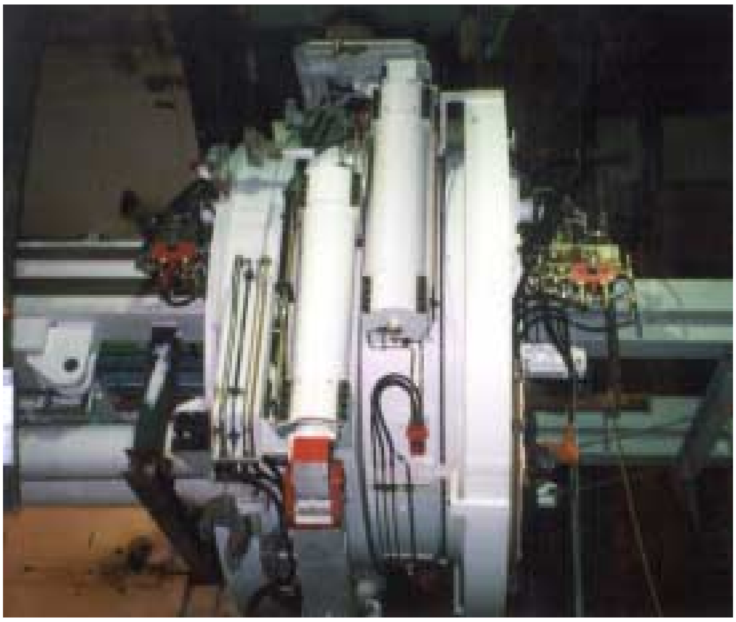

Fig.12: Double-erector-system for continuous tunneling at the Sophiaspportunnel / Netherlands

8. Jobsite Experience (worldwide application of Herrenknecht Mixshields)

8.1 Hamburg Hera

The first Herrenknecht shield machine was used for the construction of the ring tunnel of HERA in Hamburg in 1985. This tunnel has a coverage of 10 to 20 metres below surface and lies mainly in sand and partially below ground-water level. A Mixshield with a diameter of 5,95m (s. fig.13) was selected which could be adapted to the geological conditions. This first Mixshield had a installed cutterhead torque of 1800 kNM and a total installed thrust force of 2400 tons. The 6,3 km long tunnel had an average performance of 20m with a maximum monthly rate of 400 m.

During the tunnelling in the Hera Project blockages in the form of stones were encountered which had to be removed by hand. The cutter bits of this early machine were mounted at the centre of the cutter head spokes.

Fig.13: First Mixschild Hamburg Hera (∅ 5,95 m)

8.2 LILLE - France

For the construction of the metro in Lille, France, the call for tender for contract section 3 was for shield tunnelling with a single shell tunnel lining.
A slurry shield with a diameter of 7.7 m was used (s. fig. 14). A 3600 m section was excavated. After overcoming small difficulties at the start a tunnelling speed of up to 16 rings (equivalent to nearly 20 running metres) per day was achieved. Heavy bonding occurred while transversing plastic clay layers (a high proportion of cohesive ultra-fine grain). The cutting wheel had a tendency to stick between the spokes on the hub and the input rake. Tunnelling breaks or ring construction times were used by personnel who entered excavation chamber to remove the bonding in the excavation chamber by hand. Efforts were taken to combat the bonding as much as possible by special shaping and coating of the spokes of the cutting wheel and alterations to the rake, as well as the flushing nozzles. Obstructions in the hydraulic circulation were avoided by reducing the tunnelling speed.

Fig.14: Mixschild for Metro Lille / France (∅ 7,7 m)

A dual erector which enables two lining segments to be positioned at the same time was used for the first time in this project. Each erector is equipped with a newly developed erector arm which meets the end plate of the lining segment and brings it fully mechanically into position without bending or twisting it and then releases itself from the lining segment again. This improvement in placement technology reduces the assembly time for a segment ring and increases the economic efficiency of the construction technique.

The Mixshield proved itself in the various types of soil which emerged along the route, such as chalk, marl and sand. The bonding problem could also be resolved to a large extent through modifications such as, the shaping and coating of the spokes of the cutting wheel.

8.4 Cairo – Egypt

The Cairo Project involved the construction of Line 2 of the Cairo underground, a 6 km long underground railway tunnel which connects the city centre to the northern suburbs.

In order to determine the design for the mixshield in Cairo the experiences, further developments and innovations from preceding projects were incorporated in the tunnelling machine. An evolutionary trend has already been seen in the projects described above. The Herrenknecht company, in co-operation with a Joint Venture (in this case a working group made up of the companies Spie Batignolles, SGE, Dumez, Bouygues, GTM International and Fougerolle), drew up a specification list for the Cairo Project. The following points formed the basis:

- Technical data from the projects up to 1993
- Previous experience/deployments
- Geology
- Tunnel profile
- Hydraulic conditions
- Logistics

Fig.15: Mixschild for Metro Cairo / (∅ 9,4 m)

It is only by co-operating with other parties and conducting practice oriented pre-trials that highly innovative machines can be planned as possible focal points for development. For the mixshield in Cairo the following innovations contributed to the construction of the machine.

- Agitators
  (Function: to spiralise and mix the burden with bentonite and make this mix

transportable)

- Injection through the tailskin
- Vacuum erector (gripping device for 6 ton lining segments)
- Automatic program for the slurry circulation

These further developments and innovations proved successful in the machine used in Cairo.

8.5 Metro Essen / Germany

Geological and Hydrological Conditions

The tunnel route of the underground project in Essen is primarily situated in marl. The ground water is roughly 3 m under the upper edge of the terrain and may not be lowered.

Tunnelling and machine design

In view of the upcoming marl, particular attention had to be paid to the bonding problem in the excavation chamber. This led to the development and deployment of the active centre cutter, in order to reduce the load in the extremely critical area next to the cutting wheel.

Rounded edges and reductions towards the back on the cutting wheel prevent the risk of the sticky marl soil impeding the excavating capacity of the cutting wheel. They improve the flow of material in the area of the cutting wheel.

Another special characteristic is the implementation of hydraulically extended face supporting plates in the cutting wheel. These serve to protect the personnel when entering the excavation chamber. The face supporting plates can only be extended in the tunnelling direction and pressed onto the working face when the cutting wheel is stationary. Beforehand, the cutting wheel has to be moved into a prescribed position. The pressing procedure exerts an influence on the flushing mud. When retracting the supporting plates it is possible to immediately refill this section of the working face with supporting liquid via the openings in the face supporting plates. For reasons related to the technical procedure it is not yet possible to position a supporting plate in the lower area.

A submerged wall gate, used for the first time in Essen, made it possible to work safely in the suction pipe area under atmospheric conditions without the working face being submerged.

Fig.16: Mixschild for Metro Essen /Germany / (∅ 8,3 m) with active center cutter

The experience gained in previous projects was applied during the design of the machines.

8.6 The Grauholz Tunnel

A tunnel machine with a diameter of 11.6 m was deployed for the Grauholz Tunnel (railway tunnel) near Bern in Switzerland.

Geological and Hydrological Conditions

The Grauholz Tunnel runs through very complex geological conditions with strongly fluctuating permeability and varying pressure ratios. It crosses through glacial, very heterogeneous soft ground zones (clay, silt, fine and medium grained sand through to nearly clean gravel) above and below the groundwater level, molasse formations (soft rock) and numerous sections with a mixed face.

Tunnelling and machine design

A convertible shield with two function modes was deployed. Conversion allowed the machine to be switched between liquid supported face and soil removal via liquid conveyance, to unsupported face with belt removal.

The rock sections were driven with a hard rock machine and the excavated material removed via a conveyor belt. For both of the soft ground sections a slurry shield was deployed with liquid support and, in part, compressed air support of the face and hydraulic conveyance. Existing rocks and boulders were broken down in slurry operation with the assistance of a central stone crusher.

Fig.17: Convertable Mixschild for Grauholztunnel / Switzerland / (∅ 11,6 m)

The large diameter of the tunnelling machine enabled the installation of separation equipment in the backup system. This proved advantageous for slurry operation, due to the fact that the costs for pumping and conduits could be reduced. This produced considerable cost savings over a tunnel length of 5.5 km.

The arrangement of the slurry shield as a double chamber makes maintenance significantly easier. With the slurry shield it is possible to actively control the face support. The slurry pressure has to compensate the water and soil pressure. Design processes to determine the supporting pressure were set up and verified. In order to prevent loss of air pressure, special slurry mixtures and entry procedures were developed.

The cutting wheel was driven from the periphery. As a result, the centre of the machine remained available for the implementation of a conveyor belt in hard rock operation. The material excavated from the tunnel was transferred to a belt located behind. For conversion from liquid supported operation to TBM operation, the conveyor belt was pushed into the crusher housing located in the cutting wheel centre and the submerged wall opening closed.
When converting from TBM to liquid operation, after pulling back the material belt, the conveyor belt opening could be closed with the assistance of a rapid closing mechanism, thus enabling the change over to hydraulic conveyance.

Course of the project
As a result of the experiences which were gathered during the construction of the Grauholz Tunnel, the Mixshield procedure could be further developed into an efficient method for dealing with complex soil (mixed working face and rock formations).

8.7 ELBE TUNNEL Hamburg / Germany

Taking the size of the machine with a diameter of 14.20 m and the special requirements of the Elbe Tunnel Project (at the most critical point the tunnel roof is separated from the Elbe stream channel by only 7 m of ground material) into consideration, the following technical innovations were developed for the mixshield:

- The cutting wheel is equipped with a separate centre cutter. It can be operated completely independent of the cutting wheel.
- Atmospheric or pneumatic changeover of machines enables machines to be exchanged without a lowering procedure in the working chamber. The changeover of tools is achieved through the ability to enter the cutting wheel internal space, as well as the decompression equipment situated behind the tools. This development represents part of the safety plan.
- Seismic advance investigation: with the SSP System (Sonic Soft Ground Probing System) it is possible to investigate the ground conditions up to 50 m in front of the cutting wheel.

- Supporting pressure adjustment: an automatic control circuit processes parameters such as the water level of the Elbe, the suspension level behind the submerged wall and the density ratio in the excavation chamber.
- Ring construction: due to the large diameter of the tunnel the steel cement lining segments weigh up to 20 tons. As this was new territory it was decided to deploy a ring shaper. The ring shaper stabilises the ring while the machine is moving forward until it is embedded by the grout injection
- Fresh ground was also broken with the installation dimensions for the stone crusher and the submerged wall gate valve.

With the tunnelling machine for the 4^{th} tube of the Elbe tunnel there is the possibility of allowing the active centre cutter with an external diameter of 3 m to proceed up to 600 mm in advance of the solid soil excavation by the cutting wheel.

Fig.18: Mixschild for Hamburg / Germany / (∅ 14,2 m)

8.8 WESTERSCHELDE /Netherlands

The two machines for the Westerschelde Project in Holland are interesting in particular from a technological point of view. The experiences which were gathered in Sydney regarding the bonding problem contributed to the design of the machines for the Westerschelde Project. Two machines are deployed with a diameter of 11.3 m and a length of 175 m. Characteristics of this project are the sections with extremely high working pressures and the sections with highly adhesive clay. For this reason, the flow of the excavated material and the bentonite suspension are arranged in such a way that the adhesion of the clay is reduced to a minimum. A centre machine was installed in the centre of the cutter head to reduce the bonding of the cohesive clay material in this critical area. In view of the expected high working pressures of up to 8.5 bar (world record) special requirements were made regarding the seal on the main bearing and the tailskin seal.

Fig. 19: Mixschild for Westerscheldr / Netherlands / (∅ 11,3 m) entering the reception shaft

9.9 Zurich-Thalwil, Switzerland

The Zimmerberg Base Tunnel (Zurich main station - Thalwil) in Switzerland is a central project in the Swiss Railway's Bahn 2000 (Railway 2000) scheme. It forms part of the European transit axis between Frankfurt - Zurich - Milan.

Geological and Hydrological Conditions

The construction ground in the tunnel area can be roughly divided into the categories: soft ground section, rock route and mixed face route.

The soft ground section has a length of approx. 860 m, of which 160 m of the tunnel will be produced with opencast methods. The soft ground consists of crushed stone, i.e. highly permeable gravel which conducts groundwater, gravelly sand and sand.

The rock section is 8.4 km long and consists of rocks from the upper fresh water molasse. It is characterised by alternating deposits primarily consisting of sandstone, marl and silt. The overlying rock strata extends from 3.5 m up to 80 m.

Tunnelling and machine design

The 2.7 km long northern section of the Zimmerberg Tunnel will be driven in the direction of Zurich with a Mixshield (∅12.29 m). The Mixshield is capable of excavating in rock, as well as in soft ground. Once the upper fresh water molasse, with overlying ground of roughly 20 to 30 metres, has been crossed, the hard rock TBM will be converted to a Hydroshield (underground without a chamber) for the advance in the water saturated soft ground.

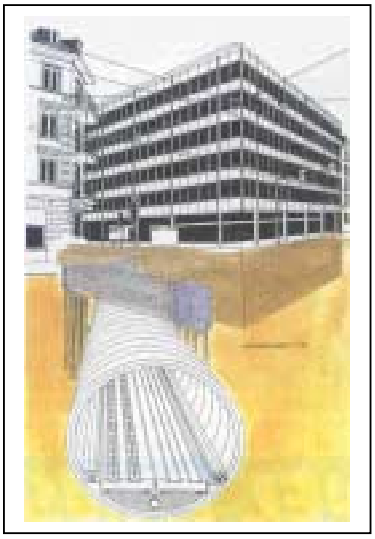

Fig. 20: Mixschild for Zürich-Thalwil / Switzerland / (∅ 12,63 m) at very low coverage (left picture)

Course of the project

After advancing 350 metres in hard rock operation the TBM was converted to hydro operation for the next 150 metres. The remaining approx. 1900 m in hard rock were driven with daily performances (working day = 16 h) of between 20-21 metres and without problems. The machine was then converted back to hydro operation. The conversion, including the replacement of the wire brush tail seal, as well as the assembly of the spade type cutting teeth and the centre nozzles, took 3 weeks.