TBM Vortriebe im Hartgestein - maschinentechnische Umsetzung von Penetrations- und Verschleißprognosen

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In der Folge sind eine Reihe von Konferenzbeiträgen aus den Jahren 2006 bis 2010 zusammengefasst die sich im Wesentlichen mit konstruktiven Aspekten der Auslegung von Hartgesteinsbohrköpfen sowie Schneidrädern für Lockergestein befassen.

Eine ideal angepasste Auslegung ist natürlich bei vorgängig bekannten und gleichbleibend homogenen Baugrundverhältnissen am besten möglich und die real erzielten Werkzeugstandzeiten entsprechen der Prognose. Bei einigen Projekten aus der jüngeren Vergangenheit sind sogar vermehrt Abweichungen der mittleren Standzeiten nach oben hin festzustellen.

Ursächlich hierfür sind die stetigen Weiterentwicklungen der letzten Jahre bei den Schneidringen selbst, den Schneidringlagerungen und deren Dichtungen sowie des gesamten Maschinensystems, z.B. variable Bohrkopfdrehzahl. Einen Einfluss dürften aber auch die verbesserten Inspektions- und Wartungsmöglichkeiten durch den verstärkten Einsatz von „Backloading“ Bohrköpfe haben.

Die überwiegende Mehrzahl heutiger Projekte bzw. Trassierungen ist jedoch weit entfernt von gleichbleibend homogenen Gebirgsverhältnissen sondern bewegt sich in vielen Fällen über die gesamte Bandbreite von vollflächig anstehendem Lockergestein, oftmals unterhalb des Grundwasserspiegels, bis hin zu vollflächig anstehenden Felsformationen. Die eigentliche Herausforderung für den Konstrukteur sowie den Betreiber der Maschine wird dann die ideale Kompromisslinie zwischen den diametral gegenüberliegenden Anforderungsprofilen zu finden. Ein Projekt was diese Problematik sowie ihr letztlich erfolgreiches Meistern besonders verdeutlicht ist der Hallandsås Eisenbahntunnel in Schweden.

Hard Rock Cutterhead Design

(North American Tunneling Conference 2006, Chicago)

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ABSTRACT

In light of an increasing demand of big diameter hard rock TBMs in Spain and especially for the NEAT project in Switzerland, major efforts have been made by the Herrenknecht AG in improving mechanized hard rock excavation. The structure of backloading cutterheads, as state of the art solution for big diameter machines, especially looking on the interface cutterhead structure – cutter housing has been improved significantly based on theoretical analysis and extensive full size test programs. The reduction of downtime due to cutter change was identified as major development target for big TBMs mining in hard and abrasive rocks. Accessibility and cutter exchange philosophy are introduced as additional design criteria for cutterheads. Methods to quantify access quality as well as simulation software to evaluate design variants have been developed and successfully used.

1. BACKGROUND

Herrenknecht AG produced since 1990 a large number of Single Shield Hard Rock TBMs which successfully operated on different road and railway tunnel projects in mostly sedimentary rocks. At the same time Herrenknecht AG commenced building a significant number of open style gripper TBMs and double shields.

In the late 1990s an extensive research program was launched in order to improve mechanized hard rock tunneling. Four major fields of activities were considered to be the main topics:

- rock support possibilities in the TBM area
- cutterhead structure
- downtime due to cutter change
- cutters

The following paper will concentrate on the points “cutterhead structure” and “downtime reduction”.

2. CUTTERHEAD - HOUSING STRUCTURE

Based on Herrenknecht’s own experiences as well as on different reports from other projects it appeared to be that in TBM applications in extremely hard and blocky rock conditions the cutterhead - cutter housing structure seemed to be more and more the weak point of the excavation system.

After analyzing the “status quo” it became obvious that two things happened in the last 10-15 years:

- The development of the disc cutters pushed the cutterload close to 280kN for 17” cutters and even more than 350kN for 19” cutters.
- Front loading designs for new cutterheads above 5,0m in diameter nearly disappeared due to safety requirements.

Therefore the cutter loads increased and by the same time it was necessary to accept compromises for the cutter fixing systems (housings) and the global cutterhead structure. The back loading design of the cutter housings caused an opening in the cutterhead front structure close to the location where the cutter loads were induced. At the same time the need for cutter access from within the cutterhead caused a widely open hollow structure (of the drum type) cutterheads with negative impacts on the structural stiffness.

There is no question that especially for bigger diameters the requirement for back loading systems is mandatory to achieve the best possible solution for workplace safety. Both of the relevant European Safety Standards which are the EN 815 for Gripper TBMs and the future EN 12336 for shielded TBMs are asking for backloading designs whenever the size of the TBM allows this.

3. TESTING PROGRAM

In light of this background, a testing program was set up to achieve a better understanding of the mechanism causing cracking or damages, and based on this knowledge to find improvements. The program consisted of a theoretical part done by finite element analysis as well as a practical part with full size components on a large dynamic testing machine. The testing was carried out in collaboration with the technical University of Karlsruhe, Germany.

The different work packages were:

- Analyzing cracks and damages from different jobsites.
- Back analysis of existing cutterhead structures to define the shape of the original size test components and the applicable test load cycles.
- Testing of reference components to create cracks comparable to the real experienced ones to verify the test bench arrangements and the sample configuration and creating the “zero line” for the future design improvements.
- Backing the reference tests by finite element analysis to check the validity of the theoretical calculation results.
- Running finite element analysis on design variants.
- Testing different original size variant components against the “zero line” of the reference sample tests.

The criteria for the bench test was to create a damage or crack configuration that on a real job would have caused the need of an intervention to do a major repair.

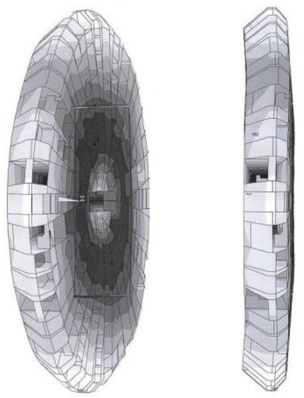

Fig. 1: FE Analysis of typical cutterhead deflection under nominal concentric cutterload

After the first stage of practical and theoretical analyzing the past experiences it was not possible to determine the real reason causing damages in between the cutterhead and housing structure. Besides the general thinking that the individual cutter load creates damages in the area of the related housing, it also seemed to be likely that the global cutterhead deflection caused by the total cutterhead thrust may be a reason for cracks in the area of individual housings.

Based on this assumption, the reference samples were tested in two different arrangements one of them simulating the individual “cutter load” and the other simulating the “global deflection” of the cutterhead. After running both tests with the reference components it appeared clearly that the nature of damages and crack development that was achieved with the “global deflection” test gave nearly an identical image to what was experienced in reality. The "cutter load” tests also produced some matching results but predominately in limited local areas of the cutter fixtures and shaft seats. This helped to improve these local areas for the new design.

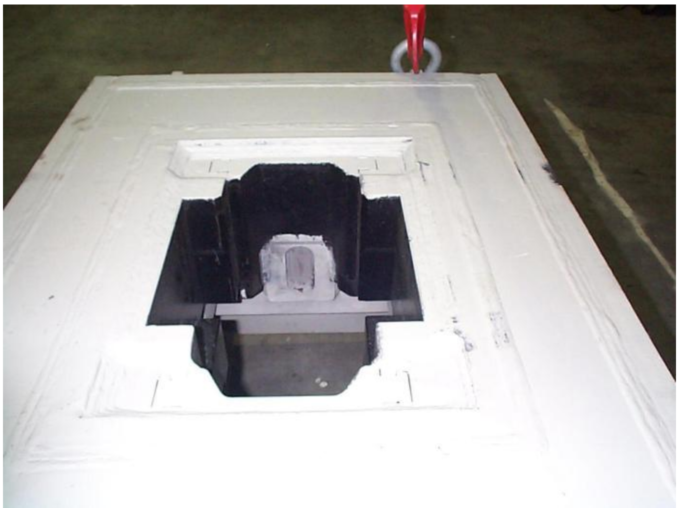

Fig. 2: Reference sample of a 17” backloading cutterbox

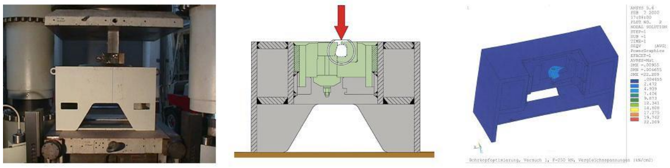

Fig. 3: “Cutter Load” reference test

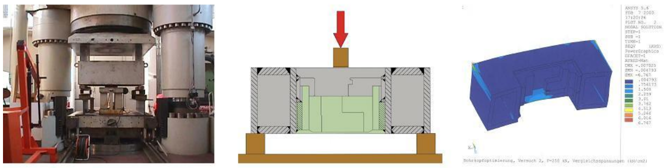

Fig. 4: “Global Deflection” reference test

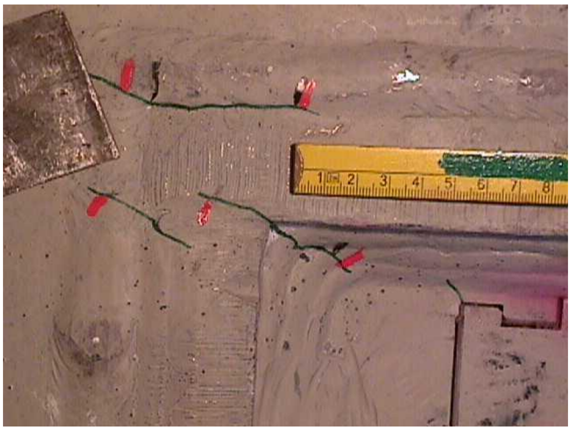

Fig 5: cracking on reference sample

After finalizing the reference tests, there resulted a clear definition of the “zero line” for design improvements as well as in a better understanding of the complex reasons for creation and development of cracking. A number of improved designs were tested. The improvements were based on modified geometrical designs of the housing and the surrounding structure as well as on modified manufacturing / welding procedures and housing materials.

Fig. 6: one of the modified test samples

The extensive test program finally resulted in major modifications of the housing design and manufacturing process. Also major modifications were applied to the interface cutterhead – housing and to the welding process. For both load cases “cutter load” and “global deflection” improvements by a factor of 4-5 could be reached. As a secondary effect the manufacturing of the original size components also allowed to optimize the manufacturing process under real shop conditions. Especially for the welding procedures, this was of some help not to create sophisticated procedures impossible to adapt to site conditions.

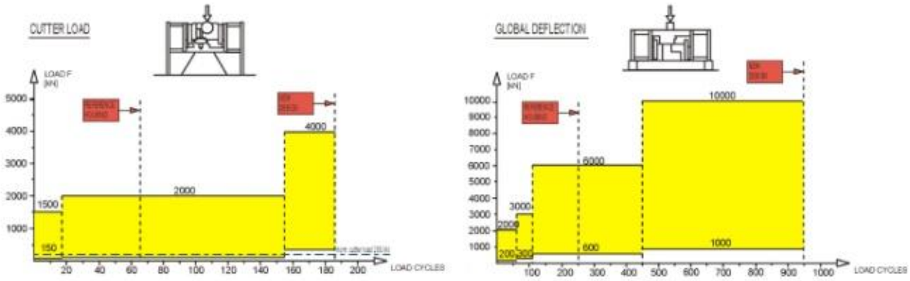

Fig. 7: typical test results for “cutter load” and “global deflection”

Fig. 8: modified cutterhead interface and housing design

4. FIELD EXPERIENCE

The new housing design was first used on both 9,4m TBMs for the Lötschbergtunnel in Swiss. The two TBMs had to excavate approx. 9/10km of tunnel predominately in hard granite, granodiorite and gneiss. In some sections of the tunnel extremely blocky rock conditions were encountered causing high loads for cutters and cutterhead structure.

Fig. 9: Lötschberg, TBM S-167 Steg

Fig. 10: Lötschberg, blocky face conditions

Fig. 11: Lötschberg, face cutter

Both TBMs finished the tunnels with great success. The S-167 TBM (Steg) excavated a total of 8,9km, the TBM S-174 (Raron) a total of 9,99km of tunnel. None of the two cutterheads needed, besides the normal wear protection replacement major structural repair or welding during the excavation. The implementation of the test results into the cutterhead design proved to be a complete success.

Based on the manufacturing and field experience from the two Lötschberg TBMs additional detail improvements were implemented in the cutterhead design for the following machines. These were besides others two double shields 9,5m for the Guadarrama project in Spain, two 8,8m Gripper TBMs for the lot Bodio – Faido and two 9,55m TBMs for the lot Amsteg on the Gotthard Tunnel. In 2004 / 2005, the Guadarrama TBMs have finished their job having excavated a total of 28,5km. The four Gotthard TBMs have done a total of 40km by January 2006. The general experience with all of the 6 cutterheads is generally confirming the positive results of the first application on the Lötschberg TBMs.

Fig. 12: TBM S-201 (S-202) Guadarrama

Fig. 13: TBM S-210 (S-211) Gotthard, Bodio-Faido

Fig. 14: TBM S-229 (S-230) Gotthard, Amsteg

All of the above mentioned TBMs where equipped with 17” cutters. This was due to the fact that at the time those TBMs where designed there was no or only little experience with 19” backloading cutterheads in comparable TBM sizes and rock conditions. However the positive test results as well as the encouraging field experiences provided a solid background for the second step of development towards the 19” backloading designs.

Fig. 15: TBM S-288 (S-289) 8,23m, 19” backloading cutterhead, West Area CSO Atlanta, USA

5. DOWN TIME REDUCTION, CUTTER HANDLING

Besides all other activities to reduce the cutter exchange frequency like increasing cutter ring life, cutter diameter or variations of spacing and profile, still the time necessary to exchange cutters has a major influence on overall economy of a tunnel drive.

Past development activities related to disc cutters have been mainly aiming for higher cutter thrust (production) and extended cutter life (wear cost, exchange frequency). As a result of this the cutter technology for hard rock excavation reached a level where potential improvements are still achieved but the individual steps are getting smaller for the 17” and even for the 19” cutters. However, development efforts for mixed face or closed mode applications of disc cutters still have potential for considerable improvement.

For today’s high performance rock TBMs used in highly abrasive rock conditions cutter ring life can easily drop down to average values below 100m³/cr resulting in the need of 10-20 cutterchanges per day on a 9,0 m TBM. Especially for big jobsites with a number of secondary construction activities taking place parallel to the excavation and being related at the same time to the excavation progress a highly industrialized overall process is needed. Unplanned stops for cutter changes or extending the scheduled maintenance shift due to cutter change is not acceptable and could create significant cost.

For this reason the cutter exchange philosophy including cutter change prediction, preventive cutter changes and changing in groups becomes an important factor.

In light of this situation accessibility and group arrangement of cutters have become important additional requirements for the cutterhead design besides the well known classical ones like balancing, spiral arrangement of cutters or pure structural needs.

Independent from whatever quality the cutter handling tools are, the best effect in minimizing time can be achieved by having the best possible access to the individual cutter locations. It is clear that also the quality of access is a result of a compromise between all the relevant requirements determining the cutter location.

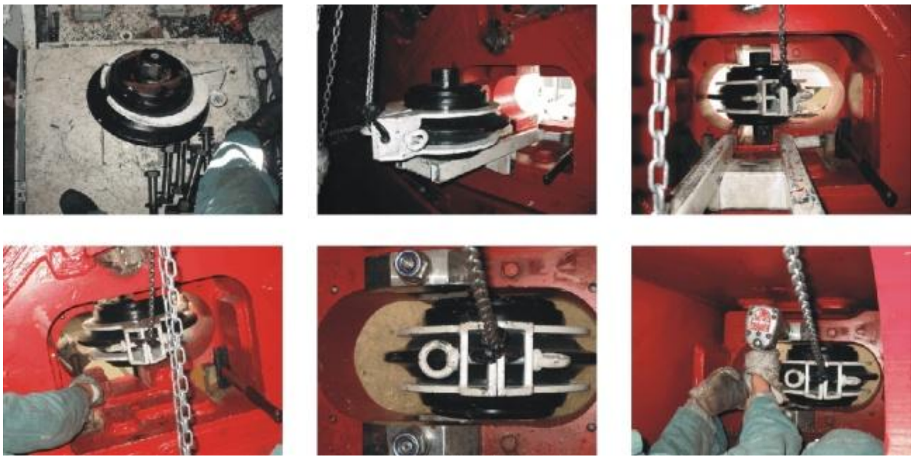

Fig. 16: special tools for cutter handling

To achieve a positive effect on time savings the cutter positions with the highest expected exchange frequency should be in the locations with the best possible accessibility, whereas cutters with a expected low exchange frequency could still be placed in locations with poorer access quality.

To determine an access quality baseline specifications with three levels where defined.

Level 1: best accessibility (green)

1. The disks can be transported directly, radially from the centre; there is no deflection of the crane chain and only little transverse pull.
2. The position from which the work is carried out is accessible via at least one entrance ≥ ∅ 500mm situated in the interior of the cutterhead.
3. The working area in the interior of the cutterhead is sufficiently dimensioned to allow at least a stooped working posture in the worst case.

Level 2: medium accessibility (blue)

1. The disks can be transported directly, radially from the centre; there is no deflection of the crane chain and only little transverse pull.
2. The position from which the work is carried out is accessible via at least one entrance ≥ ∅ 500mm situated in the interior of the cutterhead.
3. The available working area in the cutterhead is highly limited and allows only a very stooped or kneeling working posture.

Level 3: worst accessibility (red)

1. The transport of the disks cannot take place directly from the centre and requires at least one deflection of the crane chain.
2. The position from which the work is carried out is accessible via at least one entrance ≥ ∅ 400mm (≥ 0,2m²).
3. The available working area in the cutterhead is highly limited and allows only a very stooped or kneeling working posture.

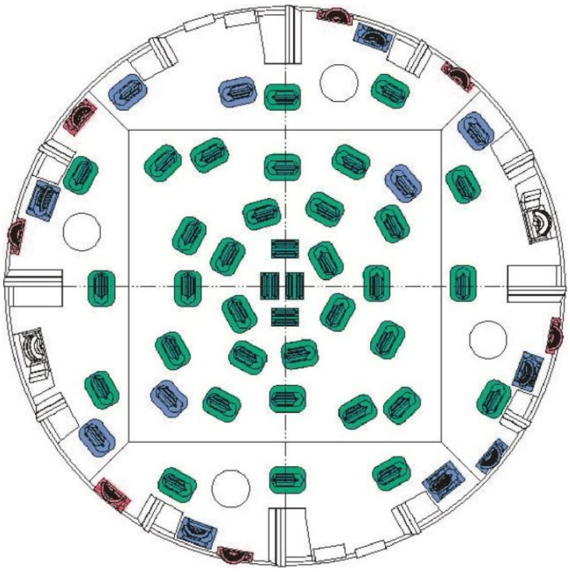

Fig 17: Cutter access qualities on a 9.5m backloading cutterhead (Level 1 = green, Level 2 = blue, Level 3 = red). The requirement for extendable cutters and spare housings limits of access optimization resulting in a significant number of level 2 and level 3 locations.

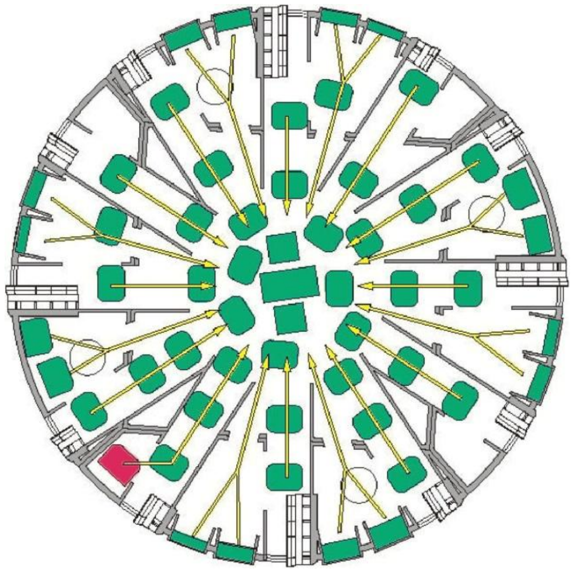

Fig 18: Optimized cutter access on a different 9,5m backloading cutterhead. Rear view section showing also the internal cutterhead structure and access ways to the individual cutter locations. Only one level 3 location (red) remaining.

Based on design or functional requirements it is not possible to avoid in all cases level 2 or 3 qualities. In those cases this locations should preferably be used for cutter positions with a expected low exchange frequency. Typical cutter exchange rates show a linear increase along the radius on the face, higher exchange rates in the transition zone and again decreasing exchange rates in the outer gage area.

Establishing a relation between the access quality level and a unit time needed to change a cutter gives the possibility to create some sort of access quality index for a cutterhead design defined by the ratio of total number of cutter changes for a given cutter position to total number of time units.

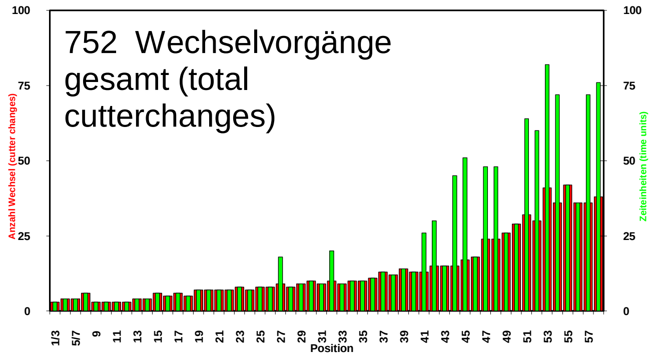

Fig. 19: typical exchange rate profile (red) for a cutterhead with related time units (green) for the individual cutter positions

Whereas good methods for overall wear prediction are state of the art, no methods have been available up to now for “relative local wear” prediction. There has been no need for up to now to estimate the cutter costs.

The individual exchange rate of each cutter position along the profile is predominately caused by its geometrical location or parameters on the cutterhead. Based on this knowledge and a large database from different projects and geometrical profile arrangements a calculation tool has been developed that allows to some extent a relative local wear or exchange rate prediction based on geometrical parameters. Having this tool available it is possible now to optimize new cutterhead designs for downtime reduction or to run simulations for different cutter exchange philosophies like changing in groups or preventive changes.

Changing of cutters in groups may be recommended especially in highly abrasive rock conditions with high exchange rates. When doing so it is of major advantage for efficiency when several cutters of the same group can be changed at the same time with little or no need to rotate the cutterhead in between.

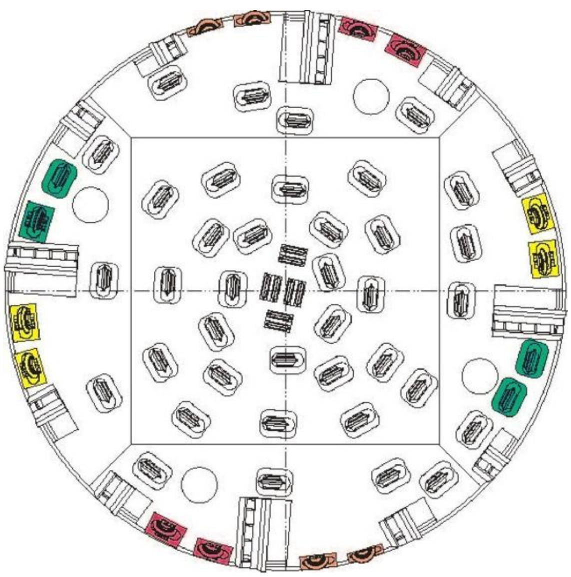

Fig. 20: typical cutter group arrangement on a 9,4m cutterhead

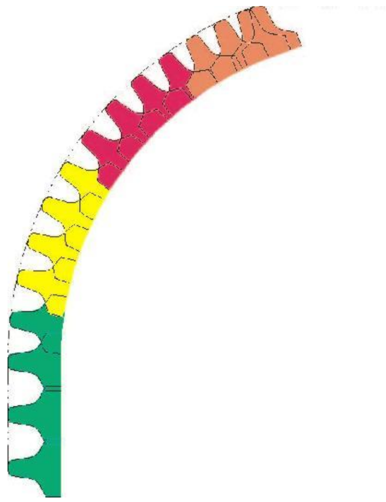

Fig. 21: typical cutter group arrangement in transition and gage area

Based on this considerations modern back loading cutterhead designs not only address the issues of optimized excavation process ,structural integrity and safety requirements for maintanace but also take into account the reduction of downtime needed for cutter change and therefore have the potential for a higher overall efficiency.

Design Principles for Soft Ground Cutterheads

(Rapid Excavation and Tunneling Conference 2007, Toronto)

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ABSTRACT

The last decade has witnessed a rapid development and application of slurry and EPB type tunnel boring machines. Both soft ground types are able to excavate tunnels in unstable ground conditions below the water table with positive face support. The most significant component of the excavation process is the cutterhead and tool configuration were the excavation and face support meets the geological challenge. The TBM downstream processes cannot take place unless the cutterhead and tools effectively do their job. This paper will review the current state of the art design for both slurry and EPB cutterheads and highlight both common as well as geological specific design features.

FACE SUPPORT PRINCIPLES

Two different situations should be considered with respect to cutterheads for soft ground applications:

- Stable tunnel face with no or little water inflow, predominantly above the ground water table
- Unstable tunnel face mostly in combination with significant potential water inflow below the groundwater table

In the first case full face (rotary cutterhead) or partial face (digger / roadheader shield) excavation could be used. This should most likely be done in combination with breast doors for mechanical support during stoppages or even compressed air for ground water control.

The second case requires “positive” face support during excavation or stoppages and chamber access for cutterhead inspection or tool change.

The general principle of the positive face support is that the tunnel face is supported by a pressurized slurry (STBM) or conditioned muck (EPBM) whereas the difference between the two is only the density of the pressurized support medium. The pressurization of the support medium is controlled either by the flow (EPB and STBM without air bubble) or a separate air cushion (STBM with air cushion).

Pressure control in an EPB is based on a low volumetric flow which results from the volume of the excavated ground and injected conditioning materials. The pressure control in a slurry TBM without air bubble is based on a high volumetric flow of the circulating bentonite slurry and the excavated ground. The pressure control in slurry TBMs with air bubble is completely independent from the flow volume and purely based on an air pressure control.

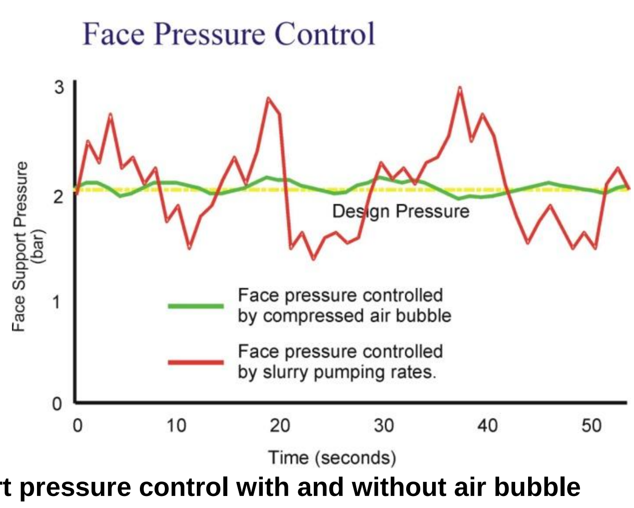


Figure 1. Face support pressure control with and without air bubble

To control the pressure by flow becomes more difficult the higher the flow volume gets. The air pressure control independent from the flow provides the fastest and most accurate reaction. For both principles it is essential that the controlled pressure of the support medium is transferred to the entire tunnel face area in the best possible way. Thus isolating the face from the support medium by closing the cutterhead produces a high risk for non controlled face behavior resulting in settlement or even sinkholes in the worst case.

Whatever attempts are made for mechanical face support during excavation, they may not be successful under difficult and unstable ground conditions. In any case there must be a working gap for the tools between the tunnel face and the cutterhead front plate. Even if this gap is kept small it creates sufficient volume for potential ground losses in the range of 5% or more.

The decision to use EPB or STBM technology is strongly influenced by the ground conditions. This topic has been extensively dealt with in numerous publications and is not examined in greater detail here.

EVOLUTION OF CUTTERHEAD DESIGNS

STBMs

In the late 1970s and early 1980s when the first slurry TBMs with remote air bubble were buildt in Europe the idea was to allow the best possible exchange and contact of the supporting slurry fluid to the face. These machines were developed to excavate permeable sands and gravel below the ground water table. For this reason the cutterheads were “star - type” designs carrying simple square tools either in the middle of the arms or a sort of cutting tools at the outer edges of the arms. These type of design worked quite well in sand or gravel and even later when designing the first mixed face cutterheads the cutter discs were mounted onto the arms. Based on the design principle of these cutterheads the implementation of backloading cutters on the arms is difficult for smaller diameters. In the center area it is not possible at all for disc cutters or any type of soft ground tool.

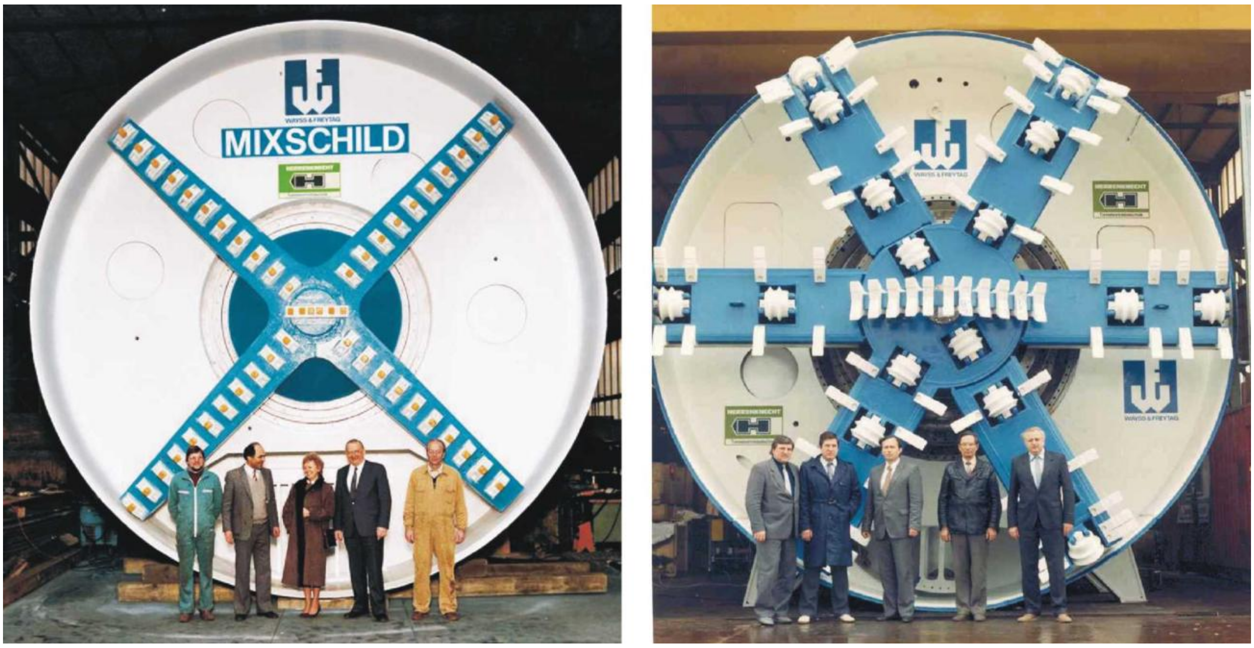


Figure 2. Early Mixshields: HERA Hamburg 1984 (left), Metro Moscow 1985 (right)

For large diameters like the Grauholz TBM in 1988, arm cross-sections big enough for man access were realized, providing the possibility to install fully back-loaded cutters over the entire profile (Fig 3). This principle was used later for the atmospheric cutterchange, keeping the interior area of the arm under atmospheric conditions while changing the cutters from inside. These cutterhead types worked quite well regarding the face support during excavation but had the disadvantage that large face areas were completely open during chamber access under compressed air. And even if the support principle slurry cake–compressed air worked well, there was no additional mechanical protection for the workers which created an “unsafe feeling” especially in diameters over 6-7m. For this reason extendable face plates were developed for the use as a mechanical protection during chamber access (Fig 4).

Figure 3. Grauholz 1998 with back-loading cutters

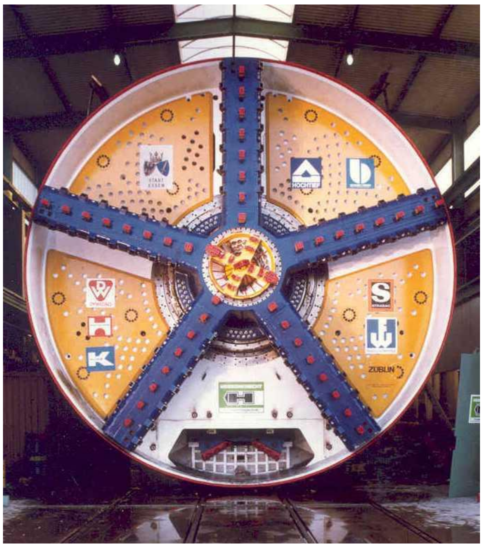


Figure 4. Essen 1994 with extendable face plates and active center cutter

In 1990 the first closed cutterhead on a slurry TBM was used in Mülheim for a tunnel in mostly hard rock conditions and in 1991 in Strasbourg for pure sands and gravel (Fig 5). These projects finally were followed by numerous other applications of closed face cutterheads in all kinds of ground conditions demonstrating that the face support principle with slurry works also with disc type or closed cutterheads.

This development and knowledge opened the door for further improvements especially for mixed ground applications or even hard rock cutterhead configurations with back-loading cutters on slurry machines. Parallel to the development of this wider variation of cutterhead designs improvements on the slurry circuit were achieved. New STBMs allow to inject slurry not only into the air bubble chamber, as on the very first machines, but also into the excavation chamber or through the cutterhead. These modern designs allow a wide variation of flushing configurations and provide sufficient supply of fresh bentonite slurry to the tunnel face (Fig 6).

Figure 5. Early closed STBM cutterheads: Mülheim 1990 (left), Strasbourg 1991 (right)

Figure 6. Modern STBM cutterheads: West Side CSO Portland (left), East Side CSO Portland (right)

EPBMs

Developed for the excavation of fine grained soils with mostly low permeability cutterheads for EPBMs not only have to carry the tools for soil excavation but also have to act as a “mixing paddle” to create the soil paste that is needed for face support. As a result of this dual function the majority of the EPBM cutterheads closed disc type designs, creating a primary excavation and mixing area between tunnel face and cutterhead front plate and a mixing chamber between cutterhead back side and shield bulkhead. In very soft and ideal ground conditions that require only little mixing and conditioning even star type designs are occasionally used.

The twin function excavation and mixing creates additional design requirements for EPBM cutterheads. This is related to injection of soil conditioning materials in front and behind the cutterhead as well as all kinds of muck flow considerations to enable the mixing and conditioning process to be optimized. The better this process is put into practice, the easier the face and settlement control can be realized.

As was previously for the slurry TBMs the use of the EPBMs was also extended towards mixed coarser grain sizes or even mixed face ground conditions based on great improvements in conditioning materials and technology (Fig 7). This required the implementation of mixed face tool arrangements with disc cutters and soft ground tools causing additional difficulties to fulfill the mixing and muckflow requirements.

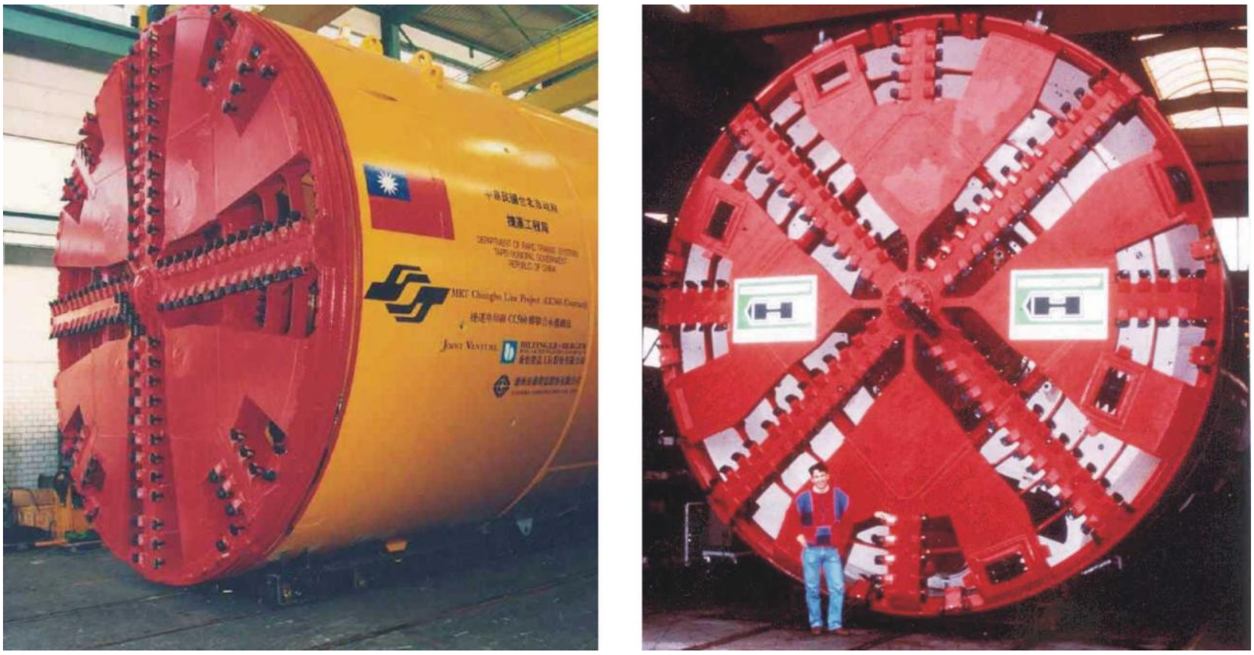


Figure 7. Early EPBM cutterheads: Taipei Metro 1992 (left), Valencia Metro 1995 with partial mixed face tool arrangement (right)

Some of today’s EPBM applications even show a full hard rock design for the cutterhead being used on tunnel alignments with variable ground conditions reaching from full face hard rock to mixed face intersections to full face soft ground (Fig 8). These TBMs operate in the hard rock sections in open mode and closed mode in the mixed and soft ground sections. Based on the design requirements for hard rock excavation it is inevitable that the closed mode EPB operation has to accept compromises related to mixing and muck flow considerations finally resulting in lower performance and higher wear compared to a pure EPB design in the soft ground sections or the use of a STBM for this type of variable ground alignments.

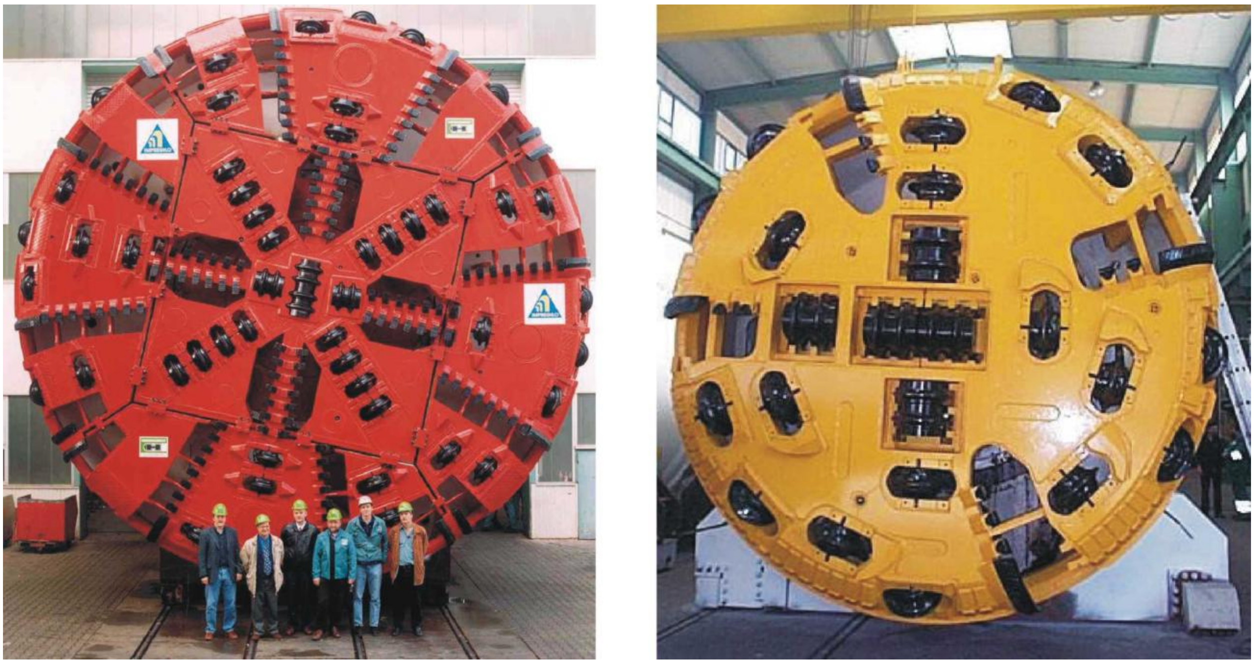


Figure 8. EPB cutterheads for variable ground: Porto Metro 2000 (left), Singapore DTSS 2003 (right)

SPECIAL DESIGN CONSIDERATIONS

Openings, opening ratio

The opening ratio is the percentage of openings of the total face area. This value is of greater importance for EPBMs than for STBMs. The mostly used range for the opening ratio is between 25 and 35 percent. The size and location of the openings on a cutterhead openings are the result of a compromise involving a large number of aspects.

The openings have to be large enough to assure the passing of the excavated and in front of the cutterhead already preconditioned soil into the rear mixing chamber without the need of a substantial pressure drop. The measurement of the support pressure is done with pressure cells installed in the rear wall of the mixing chamber (shield bulkhead). Major fluctuations of the earth pressure in front and behind the cutterhead are not acceptable if an accurate face pressure control is required. Pressure cells have occasionally been installed in the cutterhead front plate in the past but the readings are not of such accuracy that they can be used as primary input signals for earth pressure control.

The individual size of the openings has to limit the grain or boulder size that is allowed to enter into the mixing chamber. The basic rule is in most cases that only grain sizes should be able to enter the mixing chamber that could also pass through the follow-up conveying equipment (usually a screw conveyor). This recommendation often results in conflicts in mid- or small size EPBMs with only limited possibilities for big diameter augers. The use of grizzly bars to limit opening cross sections is common in such cases, but also causes often plugging of the small remaining muck passages.

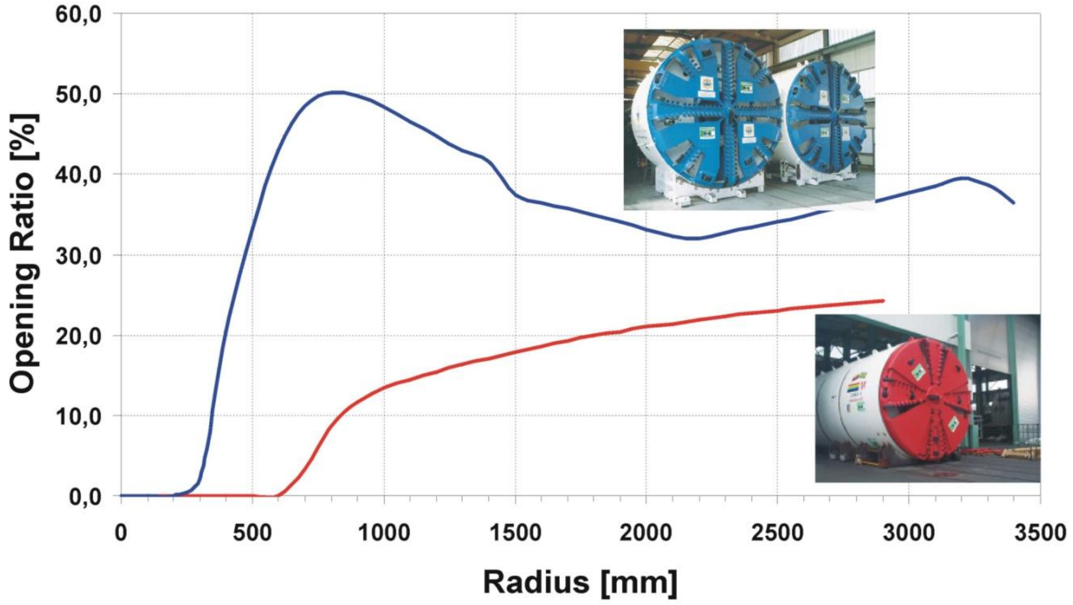


Figure 9. Opening ratio of different EPBM cutterhead designs with similar specifications – soft ground cutters for full coverage, backloading twin disc cutters in outer face and peripherie

More important than the overall percentage of the openings is the their location or in other words the set-up of the opening ratio along the radius (Fig 9). Especially the centers of cutterheads are the most critical areas for plugging in slurry and even more in EPB machines. There is very little mixing dynamic close to the center in EPB machines. On slurry machines this can be compensated to some extend by center flushing nozzles reducing the density in the center area.

Certainly, the openings close to the center are of considerably greater importance than the ones at the outer face area. In particular when there is a potential need for disc cutters in the center a compromise has to be found. The cutterhead used for the machines for the East Side Extension in Los Angeles for example kept the possibility to install center housings for disc cutters but started (and finished) using the center openings as muck openings (Fig. 10)

Figure 10. EPBM for the East Side Extension Los Angeles during shop assembly and at the arrival shaft

Muck flow

The muck flow in the excavation chamber is of major importance for both STBM and EBPM cutterheads. When mining in cohesive and sticky materials clogging of the cutterhead or excavation chamber is one of the major risks for production. Wherever possible the cutterhead design has to avoid “dead corners” or pockets allowing the muck to stick to and start building bridges and should be as smooth as possible on the front as well as on the rear side. Especially the center area becomes a major issue were there is very little or no tool speed or mixing dynamic. For this particular reason, active center cutters including slurry feed and suction lines have been developed for STBMs to provide higher tool speed and dynamics in the center (Fig 4). An increase of the mining speed of up to 30% has been achieved in cohesive soils. At the same the cutterhead torque has been reduced by about 25%.

The basic idea of an independent center wheel has been realized also for the first time now on the 15,2m EPBM for the M30 project in Madrid, Spain (Fig 11). The inner and outer wheel have completely independent drives and can rotate at different speeds and in different directions. Thus the center wheel with a diameter of 7m provides higher tool speed and mixing dynamic in the inner face area of this giant EPBM. An additional effect of partial torque compensation could be also achieved by rotating the inner and outer wheel in different directions.

Figure 11. EPBM for M30 Madrid during shop assembly and in the arrival shaft

Designing the cutterhead for only one working direction would help for optimization of the muck flow but eliminates the possibility of correcting shield roll by changing the direction of rotation. A few unidirectional cutterheads for soft machines have been built but it has to be accepted that in order to counteract the cutterhead torque by skewing the thrust cylinders the torque transfers into the tunnel lining. Since this places additional demands on the tunnel lining the common solution is the use of bi-directional cutterheads.

Boulders

For both EPBM and STBM machines mining through cobbles and boulders is a demanding but nevertheless quite common requirement. The implementation of cutter discs and soft ground tools is common practice under such conditions (Fig 12). The decision to install cutter discs in the center area is based on a risk evaluation or the predicted boulder frequency. The use of center disc cutters would normally leave very little possibilities for center openings allowing optimized muck flow (Fig 10).

Figure 12. East Side CSO Portland, tunnel face (left) and boulder entering the excavation chamber (right)

Based on practical experience from numerous job sites it is proven that large boulders can be excavated by the disc cutters as long as they are properly fixed in the surrounding matrix. Depending on the boulder size the excavation process could be regular chipping as known from hard rock excavation or splitting of the boulder in smaller pieces. For the operation of the machine it is essential to understand that the presence of boulders in the face limits the cutterhead penetration to the maximum value allowed by this rock excavation. Even if the boulder (or rock surface) is only a few percent of the face area it is not possible to mine through a granite boulder with a penetration rate of 15 or 25 mm without destroying the cutterdiscs by extreme impact loads. Situations like this frequently happen in some cases even resulting in significant cutterhead damage caused by “grinding” through the boulders (Fig 13).

Figure 13. Cutterhead damage as consequence of broken cutter disc

The disc cutters for the use in pressurized closed mode operation were originally designed similarly to those intended for hard rock TBMs. For higher face pressures improved seal configurations with higher capacity and low friction have been developed that worked successful up to approximately 4 bar. For higher face pressures the use of pressure compensated disc cutters is recommended.

Very good results were achieved with monobloc designs without using exchangeable cutterrings. These cuttertyps are more expensive but less sensitive to secondary wear or damage. Where ground conditions make it feasible twin cutters can probably also be used because of the reduced risk of failing to rotate in soft ground.

Figure 14. 14” Monobloc cutters as used on East Side CSO Portland

Based on extensive experience with STBMs mining through gravel with cobbles and boulders it appears to be likely that in most cases no boulders bigger than 500 mm in diameter or remaining pieces of them would fall out of the face or enter the excavation chamber. These findings are based on the fact that entering the chamber to recover boulders has no longer been a frequently needed operation after the introduction of jaw crushers with of this grain size capacity.

Due to the fact that there is still no solution for the installation of a stone crusher mechanism in an EPBM, boulder sizes smaller than 500 mm that must be considered as being critical for these machine types. Whereas there is no real difference between STBMs and EPBMs for the excavation with disc cutters in the face the handling after entering the excavation chamber is critical should the screw conveyor size of the EPBM be incapable of tackling such grain sizes. This problem can be solved in very large machines but becomes more and more critical for diameters below 6m. Here, screw conveyor diameters in excess of 800 mm can scarcely be realized.

CONCLUSION

Hand in hand with the great extension of the application range for STBMs and EPBMs in the last decade significant improvements in the design of cutterheads and all kinds of cutter tools have been achieved. Even though some border lines are being passed like EPBM – diameters beyond 15m or hard rock STBMs for face pressures beyond 10 bar, there is still enough left to improve and develop. Some of the key tasks for the near future may be cobbles, boulders or variable ground conditions for EPBMs, high face pressures for STBMs and most important permanent improvement of personnel safety when entering the chamber under pressurized conditions.

THE HALLANDSÅS DUAL MODE TBM

(Rapid Excavation and Tunneling Conference 2009, Las Vegas)

Werner Burger
Herrenknecht AG

Francois Dudouit
Skanska – Vinci JV

ABSTRACT

The Hallandsås project with a long history, first started in 1991, is well known in the tunneling community. In the past it has been stopped twice for technical and environmental reasons. The third attempt started in 2004 using a dual mode rock TBM. The heterogeneous highly fractured and abrasive rock mass as well as large areas of water bearing zones present most difficult subsurface conditions. The tunneling concept is based on the use of watertight segmental lining and a TBM able to operate in open mode, possibilities for extensive pre excavation grouting and high pressure closed mode operation up to 13 bar to cover exceptional conditions.

THE HALLANDSÅS PROJECT

The Hallandsås Railway Tunnel Project is a major infrastructural project presently under construction in southern Sweden. It is part of a large investment aiming to expand and re-build the west coast railway line between Gothenburg and Malmö. Once completed and taken into operation the new twin-track rail link, designed for fast trains, will shorten the travel time between the two cities by two hours. Furthermore, the overall capacity of the rail link will increase from 4 trains/hr to 24 trains/hr.

Two parallel 8.6 km long tunnels are presently being excavated using a 10.6 m dual mode Mix-Shield rock TBM.

The tunnel construction began first in 1991/92 but was suspended in 1997. By this time, 5,5 km of the tunnel, or a third of it’s total length of 18,6 km, had been completed. The tunnels were originally scheduled to open in 1997, but the project has been dogged by problems. The first contractor unsuccessfully used an open gripper TBM which excavated only 18 m of tunnel. After changing to drill and blast method the contractor finally aborted the project leaving only 20% of the total length completed.

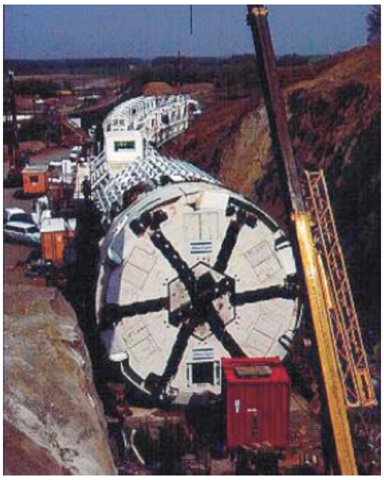


Figure 1: First attempt, gripper TBM “Hallborr” ready to go

When the second attempt started in 1996 using traditional methods water leakage in the tunnel became a major problem. The water leakage limits for the project where exceeded. Alternative sealing methods where evaluated, leading to the testing of Rhoca Gil, a chemical sealing agent. This caused acylamide, a toxic additive, to leak into the tunnel and spread into nearby wells and watercourses. Tunnel workers experienced health problems, and cows in the vicinity became lame. These events caused great alarm and strong reactions, and the National Railway Administration (Banverket) left it up to the Government to decide the future of the tunnel. Between 1998 and 2000, on commission by the Government, the National Railway Administration conducted intensive investigations regarding possible working methods, environmental impact and the costs of continuing the project. A shielded TBM has been recommended for the tunnel construction, but traditional blasting techniques may also be used. In either case the rest of the tunnel is to be lined with concrete. In 2001 the Swedish Parliament and Government gave the go-ahead for the tunnel construction to proceed.

The project started for the third time in 2004 (to excavate the remaining 2 times 5 500 m of tunnel) using a much more advanced technique including a dual mode hard rock Mix-Shield TBM and a watertight segmental lining to control water ingress. The client is the Swedish Railway Administration (Banverket) and the contractor a joint venture between Swedish company Skanska Sverige AB and French company Vinci Construction Grand Projets (Skanska-Vinci HB). The contract is a design and built contract amounting (based on end of 2001 numbers) to almost 430 M€.

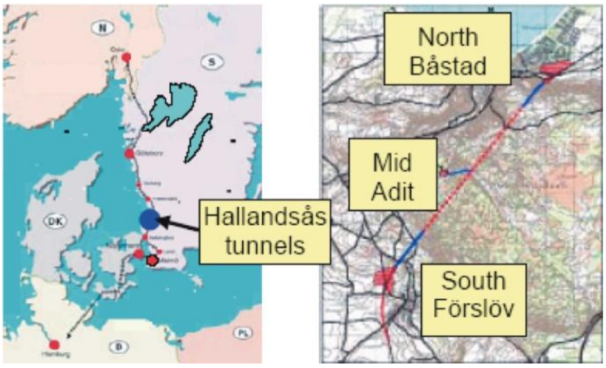


Figure 2: Location of the Hallandsås project

The project is considered to have a high risk profile and three significant circumstances particular to the project are:

- the history, including two unsuccessful previous attempts and a public debate on the legitimacy of the project.
- the very complex geological and hydro geological situation.
- the high environmental demands, including comprehensive chemical evaluation of all chemicals used within the project and tight restrictions on water ingress.

End of December 2008, about one third of the remaining 11 000 m has been excavated by the TBM.

GEOLOGICAL DESCRIPTION

The rock mass in the area consists of precambrian gneiss and amphibolite. The Hallandsås ridge is a horst which is topographically very conspicuous. The horst is a result of major uplifting that occurred approximately 70 Million years ago. The rock mass within the horst is strongly affected by the pronounced jointing and faulting, implying very complex geological conditions. Three major tectonic zones, several hundreds of meters wide, are located along the tunnel alignment.

The uplifting movement especially caused severe fracturing and crushing along each side of the horst, today seen as the Northern and Southern Marginal Zones. These zones have also been subjected to a relatively strong deep-weathering and parts of the rock mass are completely disintegrated into clay. Within the Southern Marginal Zone triassic sediments, mainly siltstones, claystones and unconsolidated sandstones, overlay the weathered basement rock. The tunneling conditions within the Southern Marginal Zone are very difficult as the rock mass partly exhibits raveling or running ground with short stand-up time (less than 1 hour).

Inside the horst another major zone, the Mölleback Zone, is encountered. This zone differs from the marginal zones by being less weathered and therefore extremely permeable.

Pre-investigations comprising different geophysical methods, percussion and core drilling were initially carried out during 1989-1990.

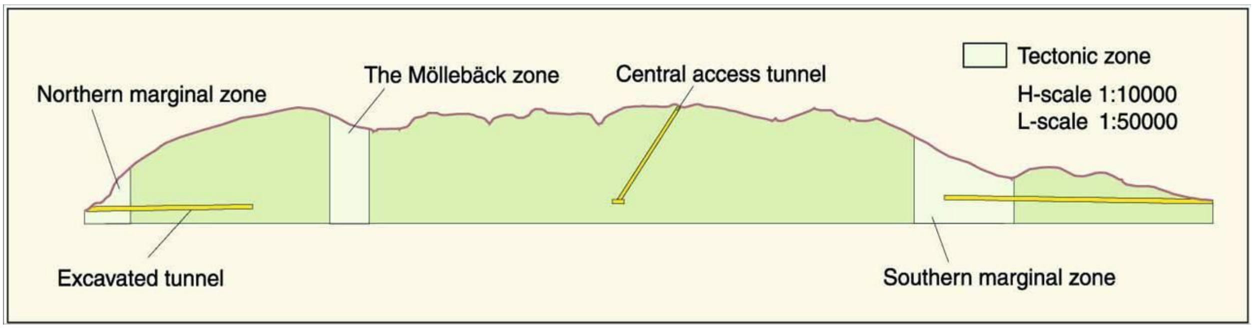


Figure 3: Schematic geological profile of the Hallandsås ridge with in 1997 already excavated tunnel sections

The rock mass consists mainly of gneiss intruded by amphibolite dykes (generally with unknown geometry) and by dolerite dykes, which have been well defined during the site investigations. Unixial compressive strength of the unfractured rock can reach 250 MPa, abrasivity is generally above 4.5 Cerchar, but values up to 5.9 have been measured.

Due to the intense fracturing the horst is completely water saturated and the ground water pressure at the tunnel level reaches 15 bars. In this case the major problems for the tunnel excavation were expected to be related to ingress of water.

ENVIRONMENTAL DEMANDS

Following the two unsuccessful attempts, very strict environmental legal demands, set by the Swedish Environmental Court, were finally applied to the Hallandsås project.

The flow of ground water coming out from all tunnel excavations in the ridge shall, during the construction period, not exceed the following limits:

- over a rolling period of 30 days: 100 l/s
- over a rolling period of 7 days: 300 l/s
- at any time: 400 l/s

The water discharged from the project shall be sufficiently treated in order to comply to the defined quality criteria:

- suspended material: 65 mg/l for discharge in the sea and 30 mg/l for discharge in the surrounding rivers
- concentration of hydrocarbons: 5 mg/l

Any breach of the demands set by the Swedish Environmental Court will result in legal proceedings. In addition, Ph adjustment is required.

Before being brought to the project and used, any chemical product must have its full composition known, which in most cases requires secrecy agreements with the suppliers, and its impact on the environment must be duly assessed. Approval to use a product is granted by the client and by the Swedish authorities. Each product is only approved for a particular application and for a defined quantity. For example a product approved on the South site, cannot be used on the North site, since the recipient is not the same, as long as a new environmental assessment has not been carried out. More than 430 chemical products have been already assessed.

TBM – BASIC CONCEPT DEVELOPMENT

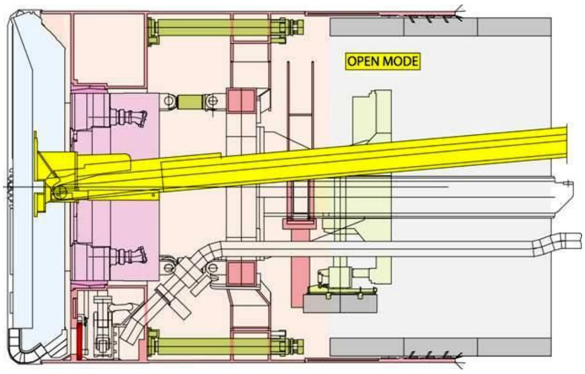
In light of the project history and the high profile project requirements from both the subsurface ground conditions as well as environmental aspects the first conceptual developments started at Herrenknecht in the year 1999/2000 even in a pre tender stage based on the key requirements:

- excavation of a hard and abrasive rock mass
- zones of soft soil and mixed face conditions
- potential of high water inflow along the total length of the tunnel
- static water pressure above 10 bar along the majority of the alignment
- strict environmental (legal) restrictions on water inflow volume
- strict environmental restrictions and approval procedures on materials and methods used

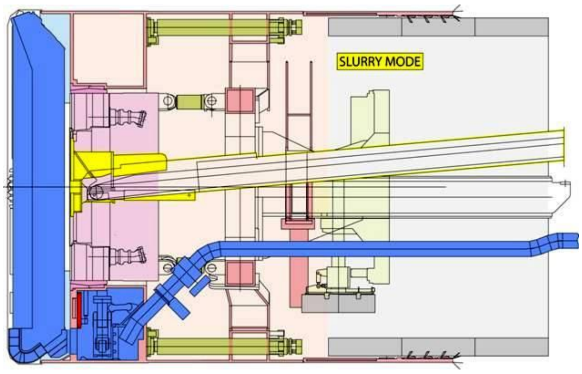
At the time of this first conceptual design stage this set of requirements was asking for a technical solution close to or even beyond the state of the art of TBM design at the time. It became obvious quite soon that if any mechanized solution could be feasible only a shielded machine with watertight segmental lining would be able to address the requirements to their full extend. The TBM itself should be able to operate in open as well as in closed mode to overcome worst case conditions, with anticipated maximum water pressure and ground conditions leaving the slurry method as only feasible closed mode option to be available as a “last resort”.

Being aware that high pressure closed mode excavation under hard rock and mixed face conditions is a most difficult way of operation extensive possibilities for pre excavation grouting from within the machine should be incorporated to support open mode operation. For such a concept of a dual mode hard rock Mix-Shield the available modes of operation could be:

- Open mode with dry primary muck discharge system (TBM conveyor)
- Open mode with (cyclic) pre excavation grouting
- Open mode with (cyclic) pre excavation grouting in closed static conditions
- Closed mode with hydraulic (slurry) muck discharge system under reduced face pressure
- Closed mode under full face pressure and potential for positive face support



Open mode with dry primary muck discharge system (TBM conveyor)



Closed mode with hydraulic muck discharge system (slurry)

Figure 4 and 5: Dual mode Herrenknecht Mix-Shield

After the contract for the Hallandsås tunnel was awarded to the Skanska Vinci JV an intensive twelve month pre design period for the TBM started whilst the project still was waiting for the final rulings of the environmental court. The decision to invest and use the “waiting time” for an intensive design work program involving the owner’s representatives, the contractor and the TBM manufacturer was taken in light of the difficult nature of the project and finally proved to be very positive for the overall concept development process. The state of the art at the time of the pre design for the different aspects of the technical concept were:

- Large diameter rock excavation – the at the time ongoing excavation of the new Alpine tunnels at Lötschberg and Gotthard already provided results and “lessons learned” of cutter and cutterhead developments that had been done previously.
- Pre excavation grouting, inflow water management systems – the developments done for the difficult Arrowhead project in California and their success on site also including 10 bar static seal systems.
- Dual mode Mix-Shields – with the first large diameter dual mode Mix-Shield being employed at the Grauholz project in Switzerland in the early nineties the second generation of that machine type already had finished the Thalwil project in Zürich.

- High pressure operations – having the Westershelde project in the Netherlands finished long term experience for dynamic seal systems as well as process experience for saturation diving in tunneling for pressure ranges 6-8 bar were available.

With the most important mandatory requirement to control the water inflows within the limits set by the Swedish Environmental Court, the following technical means were planned to be used:

- grouting ahead of the TBM, with cementituous grout, rather at the periphery than at the face, in order to reduce the permeability of the rock and consequently the future ground water inflows, in water bearing zones.
- excavation in closed mode with a face pressure up to 8 bars, in order to reduce the water inflows entering the cutterhead chamber. However, maintenance on the cutterhead was planned to still take place under atmospheric conditions. It was estimated originally that 20 % of the tunnel will have to be excavated with the TBM operated in closed (slurry) mode at maximum 8 bar.
- installation of a segmental lining, equipped with gasket and capable to withstand 15 bars of water pressure, within the tail of the TBM.

These technical means should be combined with all the conventional requirements of hard rock tunneling with a TBM.
In addition, in order to handle possible zones of unstable ground (soil like conditions) under a high water pressure, the TBM should be capable to be operated with 13 bars of face pressure including the preparation for the use of saturation diving methods for hyperbaric face access.

TBM – DESIGN CONCEPT

The dual mode Mix-Shield TBM supplied for the Hallandsås project has on board the full size equipment for open mode single shield hard rock TBM excavation as well as for closed mode slurry operation with positive face support up to a maximum dynamic face pressure of 13 bar. Additional equipment and installation for extensive pre excavation grouting from within the machine as well as the handling of high water inflows and water laden muck in open mode operation.

Figure 6 and 7: The S-246 Hallandsås TBM pre assembled in the workshop

Figure 8: Trailing gear in front of the tunnel portal

CUTTERHEAD

At the design stage of the Hallandsås cutterhead five major design arguments were identified each of them causing its own design requirements. Some of these requirements contradicted each other and could only be combined accepting compromises.

Hard and abrasive rock conditions - To address the strength and abrasivity of the rock mass the strongest structural design and cutter housing implementation had to be applied. The design principles and load assumptions had to follow to full extend the baseline and experience developed for the Alpine tunnels. The at the time proven 17” backloading disc cutter technology as used on the alpine projects was applied instead of the at that time still “experimental” 19” systems. Face cutter spacing of 85 mm followed a more conservative approach as the Alpine machines with 90 mm.

Occasionally blocky rock - Expected sections of blocky rock conditions in the vicinity of fault zones were addressed by integrating the full range of improvements and findings from the blocky rock sections at the Lötschberg tunnel, thus anticipating the cutterhead to operate as a rock crusher for limited length of tunnel as already experienced before at Lötschberg.

Figure 9: Wear protection features and details on the original Hallandsås cutterhead

High water inflows in open mode - A new developed type of grids arranged along the muck discharge channels was realized, after real size testing and optimizing during workshop assembly of the TBM. The water management / discharge system layout integrated a flushing circuit with gantry arranged treatment plant for fines handling.

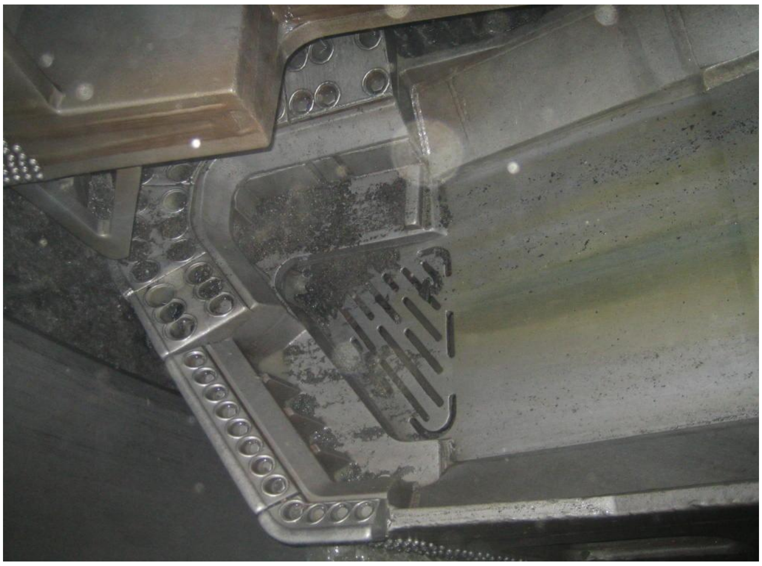


Figure 10: Dewatering grids along muck channel

Dual mode operation (center belt – slurry) - The basic design principle of the dual mode cutterhead is the same as on earlier convertible cutterheads using the structural arms of the cutterhead also as open muck channels to transport the muck to the center arranged belt conveyor in open mode. In closed mode (slurry mode) the open rear structure between the arms allows the muck to pass through the submerged wall opening to the crusher-suction pipe area. The permanent presence of two entirely different mucking versions caused some compromises for cutter arrangement and access compared to a single mode conventional hard rock cutterhead.

Potential soil like ground behavior in closed mode (clogging) - A still acceptable amount and size of center and face openings in the cutterhead front had to be realized to address potential clogging risks that would potentially cause major problems and need for manual intervention in closed mode. The need for increased muck openings leaves fewer degrees of freedom for disc cutter arrangements especially in the center area causing a more “star type” disc cutter arrangement, less favorable for hard and blocky rock conditions.

CUTTERHEAD DRIVE

Due to the anticipated wide range of ground conditions and the potential of high water inflows the decision was taken in favor of a hydraulic cutterhead drive system. The fact of being able to combine the potential of very high torque at low speed (soft and mixed ground conditions) with a typical high revolution hard rock operation took advantage over the 20% better power efficiency of a VF drive. For the same reason of variable ground conditions and to maintain the maximum amount of operational options the installation of a fully articulated cutterhead drive system was decided with the possibility of longitudinal adjustment and angular tilting for eccentric overcut. A heavy three axis roller bearing, drive pinions with independent supports and a fully equipped lube oil circuit is installed as state of the art solution for today’s heavy duty cutterhead drive systems.

Special care and further development was necessary for the bearing seal systems since they have to withstand a maximum dynamic pressure of 13 bar. The cascade seal system design that was first used successfully at the Elbetunnel in Hamburg and the Westersheldetunnel was further developed towards an automatic controlled pressure cascade system. Due to the importance of this system an original size dynamic shop test up to 15 bar pressure was performed to optimize and verify the settings of the automatic control system. In addition an activated system to isolate the main seals from the chamber pressure in standstill mode is installed to release the dynamic seal system from pressure during extended standstill periods for example during pre-excavation grouting periods.

Figure 11: Original size shop test of the main drive seal system

SHIELD STRUCTURE

The multi piece bolted shield structure is designed to withstand a theoretical water pressure of 15 bar and associated ground loads for conditions as described in the geotechnical documents. In addition to the water and ground loads operational loads as well as special load cases following potential worst case scenarios from pre-excavation grouting are considered.

The main shield body is built from six sections with bolted and sealed flanges including submerged wall, pressure bulkhead and erector support frame. A submerged wall gate and all required installation and connection ports for a full size slurry circuit as well as a jaw crusher are foreseen. All required connections and precautions are foreseen for a potential use of saturation diving including a pre chamber for a future transport shuttle connection.

The fixed double shell tailskin is supplied in three sections and welded on site to the shield. A wire brush tail seal is installed in a three chamber configuration (three rows of wire brush and rear row as five layer spring steel plate) and a 360 degree spring steel excluder to the outside. Grout lines and all necessary tail seal mastic and sampling lines are integrated in the dual layer tail plate.

The need for underground assembly of the shield structure also provided size and weight limits to be addressed during an early design stage.

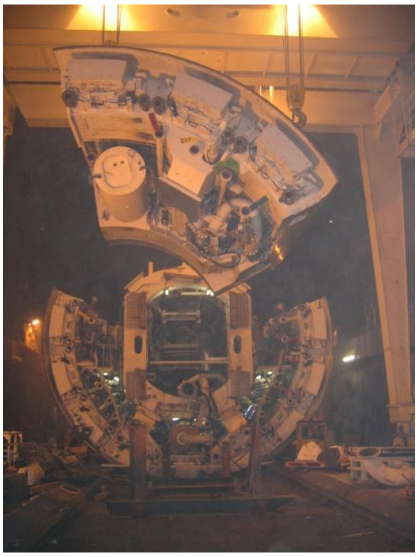


Figure 12: Underground assembly of the shield structure

MUCKING SYSTEM

A full size mucking system for open and closed mode operation is installed. The capacity of the open mode belt conveyor system being 1000 to/h and the closed mode slurry circuit and treatment plant for a nominal flow rate of 1800 m³/h

The open mode belt conveyor system consists of a TBM and gantry conveyor as well as the advancing tailpiece, transfer point and belt extension area for the tunnel conveyor. When changing the mode of operation from open to closed the muck hopper including the TBM conveyor in the cutterhead center can be hydraulically retracted. The front plate of the muck hopper then closes and seals the center opening. Special features are foreseen for the handling of water laden muck. Dewatering areas and drainage basins along the machine and gantry conveyor are installed including a flushing circuit with on board treatment plant for 600 m³/h.

The slurry circuit for closed mode operation has besides the typical slurry shield requirements to address the wide variation of potential face pressures and pressure levels. Also the typical muck grain size distribution from a hard rock excavation process has to be taken into account for its layout.

Figure 13: Water laden muck on gantry conveyor

SEGMENT ERECTION AND BACKFILL

The supply of segments and backfill material is via train into the closed deck trailing gear. Segment handling is with vacuum gripping systems for the segment crane and the erector. A segment feeder with a storage capacity for one complete ring consisting of 8 pieces is installed.

The machine is prepared to use either mortar or pea gravel backfill material or a combination of both. Handling systems and storage capacities for both are installed on the trailing gear. Also equipment as well as material handling and storage facilities for second stage grouting is provided.

PRE EXCAVATION GROUTING

With the pre-excavation grouting being identified as one of the major tools to handle the difficult ground conditions the machine is prepared and equipped with extensive permanent installation for drilling and grouting.

Multiple inclined channels in the shield skin as well as a large number of ports in the bulkhead, submerged wall and corresponding cutterhead openings allow a dense drill pattern around and in front of the tunnel face:

- 30 channels through the shield skin in two different lockout angles of 10° and 13°
- 26 outer face positions
- 7 inner face positions

A total of three permanent installed drill rigs installed are located on a 360° carrier ring behind the erector able to reach the periphery and outer face positions. Two more permanent drills can be installed in the front of the center shield area if required. A temporary drill installation is possible in the shield center and on the erector.

A permanent pre-excavation grout plant and materials storage and handling area is provided on the gantry

Figure 14: Permanent drill installation at the front end of the trailing gear behind the erector

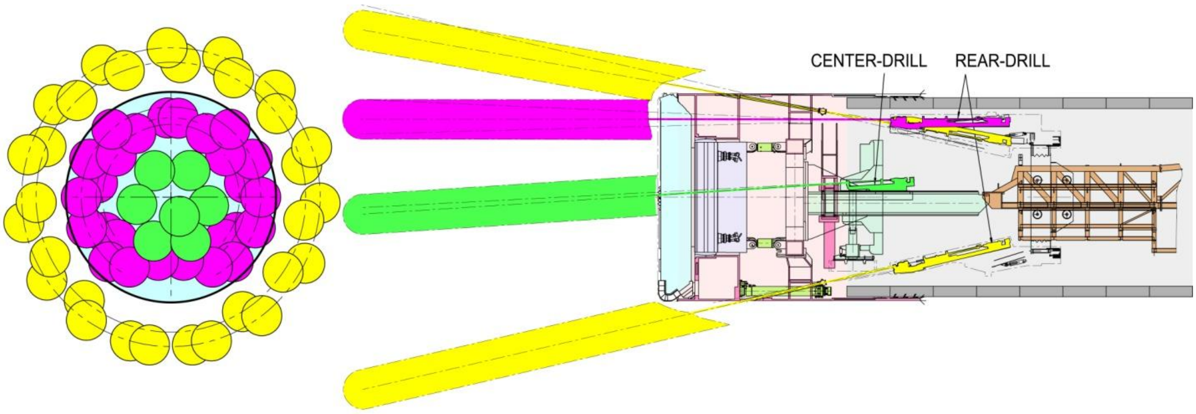


Figure 15: Possible drill pattern ahead of the tunnel face

HYPERBARIC FACE ACCESS

In order to be prepared to inspect the cutterhead in worst case conditions with high water pressure and unstable face the machine is equipped with all necessary basic installation for chamber access in saturation mode. In front of the fact that along the entire tunnel alignment the water table is in the range of 100 – 130 m above the tunnel the machine is prepared for face access with saturation method only. No permanent man lock for decompression within the machine is foreseen as used for applications with a maximum of 3 - 5 bar chamber pressure. Besides piping and connections required for saturation access a permanent pre chamber is installed in the shield to which the transport shuttle can be connected. A transport shuttle is available on site and all means of transport and passage of the shuttle through the gantry to the pre chamber are foreseen and have been tested during workshop commissioning.

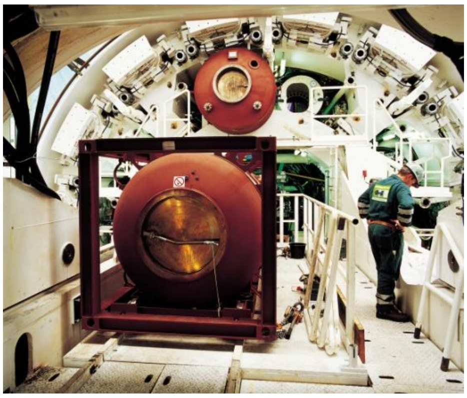


Figure 16: Test for shuttle handling during shop assembly

Machine type	*Mixshield, dual mode*
Manufacturer	*Herrenknecht AG*
Excavation diameter	*10,60 m*
Total length	*250 m*
Total weight	*3100 to*
Total power	*8600 kW*
Cutterhead	*Hard rock, dual mode, articulated*
Cutters	*17”, backloading (19” second cutterhead)*
Power	*4000 kW*
Speed	*0 - 5 rpm, hydraulic drive*
Torque	*20,3 MNm / 26,0 MNm*
Thrust	*22.000 kN (42.000 kN in high pressure mode)*
Shield	*∅10,53 m*
Max. pressure	*15 bar*
Thrust	*139.500 kN (188.500 kN in high pressure mode)*
Mucking system open mode	*1000 to/h (cont. Conveyor in tunnel)*
Mucking system closed mode	*1800 m³/h, rock crusher (STP at portal)*
Segment backfilling system	*Two systems, mortar and pea gravel*
Flushing system	*600 m³/h on-board STP*
Probing / grouting	*3 permanent drills (5 possible)*
Drill pattern	*30 periphery positions, 33 face positions*
Trailing gear	*11 trailers, closed deck, train supply*

Table 1: Technical data Herrenknecht TBM S-246

EXPERIENCED ROCK CONDITIONS AND CONSEQUENCES

After site assembly of the shield and gantries excavation started in November 2005. The shield was assembled in an undergound cavern at the end of the previous drill and blast excavation at the south portal, the gantry was assembled in front of the portal and then transferred through the drill and blast section and connected to the shield.

From the beginning of the excavation with the TBM, in addition to the difficulties associated with handling of the ground water inflows, difficulties associated with the rock mass have been experienced:

- Repetitive block instabilities. Significant overbreaks at the face and amounts of blocks were observed in such conditions
- High variability of the rock mass

The consequences of the blocks instability have been dramatic on the cutterhead and mucking systems, the belt conveyor system in open mode and on the slurry circuit in closed mode. From the start of the excavation until the arrival of the TBM in the underground cavern of the mid-adit, which is an intermediate access excavated in 1995-1996 to allow four additional drill and blast faces, approximately 14% of the then excavated distance of 2540m has been mined in closed mode.

CONSEQUENCES ON THE CUTTERHEAD

In blocky rock conditions (block instabilities at and in front of the face), the blocks falling from the face are of a size and strength that major rock crushing takes place in front of the cutterhead. The rock excavation does not proceed from the controlled cutting action of the disk cutters, but from the rather uncontrolled crushing actions of the entire cutterhead front.

Routine face inspections to record at the face overbreaks and percentage of cutters tracks are performed basically every one or two rings in order to know the percentage of cutters working in a regular cutting mode.

Observation of the damages on the cutterhead and on its tools (cutters and scrapers) has confirmed the disastrous effects of the blocks. The crushing actions are associated with peak loads on the cutters, which can exceed by at least a factor of 5 – 10 times the nominal load of 250 kN and which are variable in direction. In particular, they result in damages on the cutters, on their fixations and housings. The percentage of cutter changes due to normal wear reaches only about 40%, the rest being replaced due to blockage / damage (generally caused by premature failure of the bearing, cracks in the cutter ring, damaged hub). Damages in the fixing elements and housings result in additional difficulties in replacing worn or damaged cutters.

Duration for daily maintenance on the cutterhead increases from 0.75 hour / tunnel meter to 0.9 - 1.65 hour/m, as the boring conditions move to highly blocky conditions.

CONSEQUENCES ON THE BELT CONVEYOR SYSTEMS

The size of the blocks, transported by the mucking system is a consequence of the size and geometry of the openings provided in the cutterhead and of deflectors and grain size limiters installed in these openings. The size of the blocks can be reduced by closing the openings, but additional crushing actions take place and consequently more damages occur on the cutterhead front and its cutting tools and buckets.

Transport of blocks on the belt conveyors system is associated with blockages at transfer points between two belt conveyor units and with belt damage, being repetitively punched or suddenly cut by blocks, trapped in a hopper.

Figure 17: Typical tunnel muck showing crushed blocks from open mode operation

CONSEQUENCES ON THE SLURRY CIRCUIT

In closed mode operation, the blocks, entering through the cutterhead openings, have to pass through the suction grill / jaw crusher combination in front of the discharge pipe inlet. The suction grill limits the grain size allowed to enter the discharge pipe to 150 mm. Larger blocks stay in front of the grill and will be crushed by the jaw crusher to a suitable size.

After less than 50 m of tunnel excavated in closed mode, severe damages to the slurry circuit have been experienced: several elbows and steel pipes being pierced by the repetitive impacts of the blocks. Such observations were even made on the special reinforced components of the slurry circuit installed in the TBM and trailing gear. The destructive actions of the blocks, worsened by the abrasivity of the transported rock materials, were observed also on other components such as slurry pumps, valves, and telescope pipes.

Despite time consuming repairs, maintenance programme on the slurry circuit and replacement of some components by ones with a higher wear resistance (made of steel with 500 HB on the complete thickness), severe difficulties were experienced to maintain the slurry circuit operational. The typical crushed blocks initially angular in front of the suction grill were found at the slurry treatment plant rounded after their transport through the slurry discharge circuit.

Figure 18: Typical tunnel muck from closed mode operation (rounded blocks)

In blocky ground conditions the jaw crusher capacity often became the determining factor for the achievable mining speed. Depending on the severity of the situation significant reduction of the TBM advance speed or even to stop it in order to give the time to the crusher to absorb the blocks were found necessary. In the worst situations the blocks piling up in the chamber were obstructing the submerged wall opening to an extent that a proper hydraulic connection between the cutterhead and air bubble chamber was lost. The effect followed by this was over-pressurisation of the cutterhead chamber.

Due to the unfavourable shape and size of the rock particles the flow in the return line had to be increased from 1800 to 2000 m^3/hr (16 inches diameter pipes) to achieve a higher flow speed and reduce the risk of settlement and blockages in the discharge line.

ACTIONS TAKEN TO ADAPT TO THE ROCK CONDITIONS

The extremely difficult rock conditions and tunnel face behaviour resulted in a number of modifications of operational and mechanical equipment aspects resulting from a necessary re-adjustment of some of the basic projects requirements finally dictated by the in situ ground conditions.

TBM DRIVING CLASSES

In order to find the best compromise between spot progress and damages to the cutterhead, a back analysis exercise was launched very early, involving study of:

- TBM excavation parameters such as cutterhead rotation speed, penetration step of the cutters, average load on the cutters
- Face inspections (geological description, details of the overbreak, percentage of the cutters marks visible at the face)
- Records pertaining to the maintenance on the cutterhead

A strategy regarding selection of the TBM excavation parameters related to the degree of blockiness has then been adopted for the original 17” cutterhead. Three different TBM driving classes have then been defined respectively in the gneiss, amphibolite and dolerite:

TBM Driving Class Ga/Aa/Da:

- *Chips on belt conveyor*
- *More than 80% of the cutter marks visible at the face*

TBM operation parameters:

- *4-5 rpm*
- *200-250 KN/cutter*
- *10 mm/rev*

	*TBM Driving Class Gb:* • *Chips and small blocks (<200mm) on belt conveyor* • *More than 20% of the cutter marks not visible at the face*	*TBM operation parameters:* • *2,5-3,5 rpm* • *200 KN/cutter* • *12 mm/rev*
	*TBM Driving Class Gc/Ac/Dc:* • *blocks on belt conveyor* • *Cuttermarks not visible at the face*	*TBM operation parameters:* • *1-1,5 rpm* • *60 KN/cutter* • *20 mm/rev*

Table 2: Parameter table of the three TBM driving classes

Based on the parameters recorded during the probe drilling exercise (three holes are systematically drilled at the periphery ahead of the face), the geotechnicians are making a prognosis of the TBM driving classes, which is given to the TBM driver. The final selection of the TBM parameters is based on the observation of the blocks on the belt conveyor and on the face inspection results. Due to the high variability of the geology, it is very frequent that several changes of TBM driving classes are necessary during the same day.

CUTTERHEAD MAINTENANCE

The daily maintenance routine on the cutterhead was modified and a higher frequency of inspections was adopted following a defined procedure (segment ring length is 2,2m):

- Ring n: Check of all tools (cutters and bucket lips) and wear measurement. Re-tightening of cutter fixing bolts and change of the worn or damaged tools
- Ring n+1: Re-tightening of the fixing bolts of the cutters changed at ring n
- Ring n+3: Visual check of all tools and change of the worn / damaged ones
- Ring n+4: Re-tightening of the fixing bolts of the cutters changed at ring n+3
- Ring n+5: As ring n.

A follow up of the cutterhead and tool damages has shown that most damage is concentrated to a certain area of the outer face likely to correspond to intense crushing taking place at this location as a consequence of block instabilities in the face.

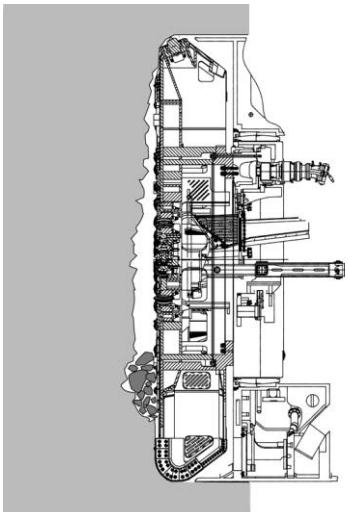


Figure 19: Schematic sketch of rock crushing area in front of the cutterhead

In addition to the daily cutterhead maintenance carried out from inside and behind the cutterhead a approximately 500m interval has been established for heavy cutterhead maintenance including access possibility to the cutterhead front to maintain and replace front wear protection and block deflectors. Whereas comparable heavy maintenance procedures are required every 3000-5000m of tunnel for the Alpine hard rock TBMs the blocky rock conditions in the Hallandsås project require far shorter intervals in order to keep the cutterhead fully operational.

Figure 20: Front wear protection in worn conditions before replacement and repair

SECOND CUTTERHEAD

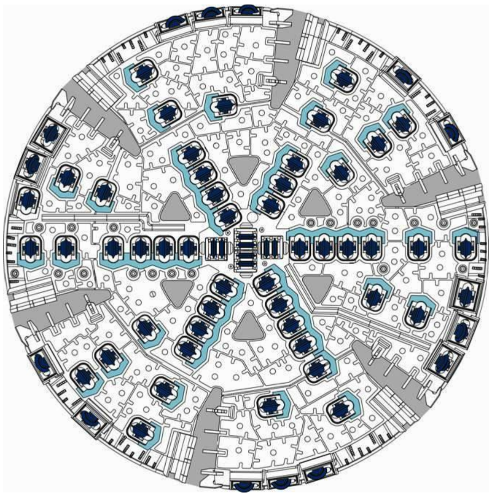
With the view to reduce the impact of the cutterhead maintenance on the production, and aware of the fact that repetitive heavy underground welding operations may finally have a negative effect on the basic structure, decision was taken in autumn 2006 to launch the design for a second cutterhead. Also the access possibility of the mid-adit ahead about halfway of the first tube as well as the chance to do design modifications in order to adapt to the in situ experienced rock conditions and face behaviour were major arguments for the decision.

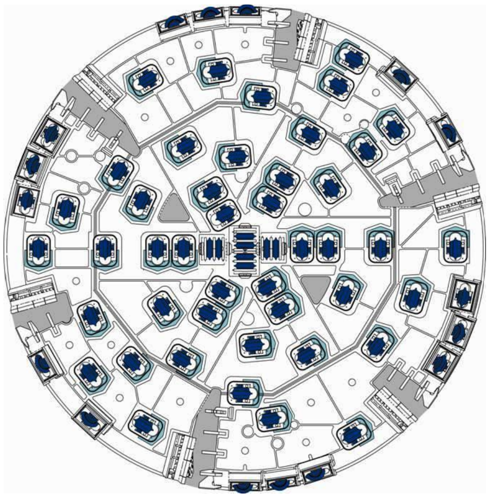
Design of the second cutterhead should take due consideration of the experience gained through the various conditions already encountered along the route of the east tunnel, in particular the blockiness, and all the modifications regarding wear protection and block deflectors / grill bars already done to some extend on the first cutterhead.

Since meanwhile reliable experience in the use of 19 inches cutters for backloading cutterheads existed, a decision was taken to use these heavier cutters for the second cutterhead. In the specific case of the Hallandsås project, the benefit is rather thought to be in the heavier and more rigid structure of the cutters and of their fixation systems for withstanding the crushing impact loads than in the higher performance associated to the increase of the nominal load from 250 to 320 kN. In addition, the larger diameter of the 19 inches cutters permits to move the fixation system 25 mm backwards away from the face and more inside the basic cutterhead structure and therefore better protected.

The risk of clogging of the cutterhead in soil like conditions identified originally on the project has been re-evaluated and some openings on the cutterhead have been removed. This move permitted a better arrangement of the cutters in the face area.

Protections have been designed for easier refurbishment and some new developed backloading crushing tools have been added along the most affected outer face area.





Original cutterhead requirements:	***Adapted requirements for second cutterhead:***
Conventional hard rock type with closed mode possibility	*Closed mode possibility less important but still required*
Hard and abrasive rock conditions	*Increased importance*
Occasional blocky rock	*Blocky rock conditions as part of the regular situation, rock crushing in front of the cutterhead*
High water inflows	*No changes*
Dual mode operation (center belt – slurry)	*Slurry option less important but still required*
Potential soil like ground behavior in closed mode (clogging)	*Less important*

Table 3: Readjustment of cutterhead requirements based on in situ experience

Experience, since the re-start from the mid-adit, shows that the new cutterhead has permitted to reduce significantly the daily cutterhead maintenance. This has in return led to an increase of the daily production, which is in the range of 11.6m/day outside the periods of ground treatment, barriers construction, heavy maintenance on the cutterhead. These periods amount to 55% of the time.

Overall the progress of the TBM is equivalent to the one achieved in the past by five simultaneous drill and blast headings, without considering the fact that the tunnels were unlined at that time.

BELT CONVEYOR SYSTEMS

The following measures have been taken in relation to the belt conveyors system:

- Modification of the geometry of transfer points between two belt conveyors to improve passage of blocks
- Strengthening of impact bars at muck chutes
- Additional personnel to watch transport of blocks at strategic positions to limit the risk of damages and blockages
- Installation of a block separating unit at the entrance of the tunnel in order to protect the outside belt conveyors. Such installation could not be done on the TBM back-up due to geometrical restrictions.

SLURRY CIRCUIT

Due to the severe damages and to the difficulties to maintain the slurry circuit operational in the encountered ground conditions, decision was taken to abandon progressively the use of closed mode to control the ground water inflows and put priority on the use of the alternative excavation in open mode supported by pre excavation grouting.

In addition, the time consuming cutterhead maintenance, experienced on the project, reduces dramatically the benefit of the closed mode as a measure to control the ground water inflows, since cutterhead maintenance is carried out under atmospheric conditions.

Heavy maintenance on the slurry circuit, replacement of components with ones having an even higher wear resistance at strategic positions have been implemented in order to be still in a position to operate the TBM in closed mode for exceptional cases if required

GROUND WATER INFLOW

With the strict limitation of groundwater inflow for the overall project being one of the essential mandatory project requirements, the limitation of inflow quantity in the active heading is of major influence for the total inflow water quantity. Ground water inflows are controlled by mainly the use of two techniques:

- Ground treatment ahead of the face (pre-excavation grouting) to limit the future inflows
- Optimised method of backfilling with frequent construction of water barriers behind the segmental lining

Works relative to control of the water inflows are time consuming. On a monthly basis, between 6 and 66% of the time is spent in such works. Consequently the monthly figure of tunnel excavation is highly depending on the ground water inflow conditions.

In order to permit advance of the TBM through water bearing zones, ground treatment is carried out ahead of the shield. The target is to seal off the rock mass sufficiently to permit progress of the TBM in open mode without violating the maximum limits set by the Swedish Environmental Court ruling.

Ground treatment is triggered by the water inflows measured during the forward probe drilling campaigns, which are systematically performed with the requirement to maintain a minimum of a 10m overlap between subsequent probe holes.

Drilling of grout holes is performed under atmospheric conditions, however depending on the water inflows, particularly the 30-day average value and the risk of grout leakage at the face, grouting is carried out either under atmospheric pressure or under pressurised conditions. To achieve pressurised conditions the muck hopper in the centre is retracted thus isolating and sealing off the excavation chamber from the tunnel. Under such conditions the chamber pressure is increased until the balance with the surrounding ground water pressure has been reached and no more water inflows measured. The typical chamber pressure to achieve a static (balanced) situation is found in the range of 9 – 11 bar. Microfine cement is used as grouting material.

Experience, which has been gained along the first 2500 m of tunnel, shows that better results are obtained by drilling through the face than at the periphery, confirming also experiences from other jobsites as for example the Arrowhead tunnels.

Difficulties have been encountered in backfilling behind the lining due the ground water inflows. Despite the use of PP fibres, anti-washout agent and accelerator, washout of the mortar, as backfilling material, could not be totally prevented. In order to complement the backfilling of the loss resulting from the washout phenomenon, second stage backfilling about 15 m behind the shield has been introduced.

The backfilling method, originally based on mortar, has been modified to introduce the use of the pea-gravel. The lining is backfilled with a controlled quantity of pea-gravel from the invert to the spring line. Mortar is injected in the upper part. Since the water is circulating through the lower pea-gravel matrix, washout of the mortar in the top is avoided. Construction of barriers is required to stop this circulation. Results in terms of movement of the heavy segmental lining behind the shield are very satisfactory using the combined technique pea-gravel and mortar.

Figure 21: TBM arriving at mid-adit in April 2008 with the second cutterhead waiting in front

CONSTRUCTION OF BARRIERS BEHIND THE SEGMENT LINING

Various methods have been tested to build efficient barriers behind the segmental lining, preventing ground water inflows from behind the watertight segmental lining along the shield and into the cutterhead chamber. The usual phases for construction of a barrier are the following ones:

- Installation of special segments equipped with drainage valves in the invert, backfilling being done with pea-gravel behind these segments
- Backfilling with mortar of the following 5 rings in order to create a “rear wall”
- Backfilling with pea-gravel of the following 3 rings
- Excavation without backfilling of the following 4 rings. The design of the segmental lining includes strong dowels between rings which permit to omit backfilling without significant movements between the rings
- Pressurisation of the shield to balance the surrounding ground water pressure and achieve static conditions
- Backfilling of the last four rings with mortar
- Grouting of the pea-gravel matrix contained between the two mortar walls with a microfine cement grout
- De-pressurisation of the shield.

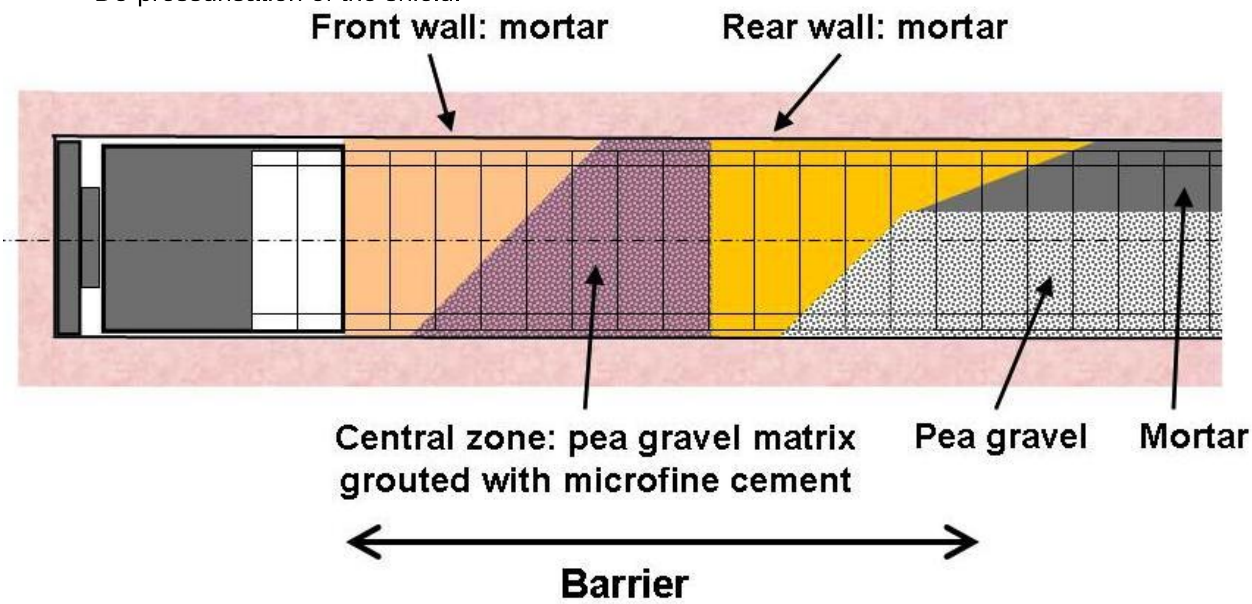


Figure 22: Barrier construction

Results in terms of reduction of the water inflows vary in function of:

- Local geological conditions prevailing around the barrier two mortar walls (in particular characteristics of the rock mass fractures: orientation, opening, infill). It has been observed at various occasions that the ground water was circulating in the rock and parallel to the lining.
- Amount of water inflows and ground water pressure prevailing in the surrounding rock mass
- Overbreaks
- Length of the barrier
- Ability to balance strictly the ground water pressure

The two tools “pre-excavation grouting ” and “barrier construction” are combined in order to control the water inflow within the given limits. Pre-excavation grouting is used to limit the increase of water inflow when mining through a water bearing zone. Barriers are used to reduce significantly the inflow from behind after passage of that zone.

Ground treatment and barrier construction is time consuming. The objective remains to limit them in time and consequently to maximize the available mining time of the TBM.

INFLOW WATER FLUSHING SYSTEM

The already installed inflow water management system with a flushing circuit including an on-board treatment plant has been upgraded and modified for several details to be able to handle short term high inflow volumes in order to support the tendency for as much as possible open mode operation.

The flushing circuit has been extended to pass as well through the invert of the air bubble chamber to evacuate water and fines direct from behind the cutterhead, involving as well the slurry circuit and above ground treatment plant also in open mode if required. An additional dewatering section along the gantry conveyor has been installed with a flat belt section, 7 m long and a large flushing basin below.

This upgrades and system adjustments enable the machine now to technically maintain open mode operation with water inflows from the face as high as 240 l/sec.

Figure 23: Lined tunnel

CONCLUSION

The Hallandsås Tunnel Project with its history of more than 15 years in total now presents one of the most demanding tunneling projects currently underway. At the end of 2008 more than 3600m of difficult waterbearing rock have been excavated by a dual mode hard rock Mix-Shield followed by a clean and dry final tunnel product. No further environmental issues have occurred and public acceptance could be re-established to a large degree.

Appropriate technical solutions able to deal with the conditions may not have been available on the market at the time of its first start. The lessons learned for the tunneling industry from the third attempt of the project are definitely that difficult projects need a close and focused partnership and collaboration of all involved parties, the owner, the contractor and the TBM supplier to succeed.

The TBM has successfully excavated more than 1000m since the restart at the mid-adit with all the system adjustments and modifications in place. It is still a long and hard road to go to the end, but there are true reasons to be optimistic.

In August 2010 the TBM finished the first tube. The machine was dismantled and transferred to the south portal for reassembly. The excavation of the second tube started in March 2011, mid-April the TBM had already excavated 300m of the second tunnel. The modifications and adaptations of the excavation system that have been done during the first drive proved to be a great success in such difficult conditions and only minor further optimization was required for the second drive.