Hardrock Technology

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1. Introduction

The construction of approx. 75 kilometres of the longest railway tunnel in the world – the new Gotthardbasetunnel in Switzerland – by Tunnelboringmachines is the result of the successful development of mechanised tunnelling in hardrock. Many tunnel project within very difficult inhomogeneous rock conditions were examined in the past with good economic results. This is the reason why more and more tunnel projects are going to be mined by the safety TBM technique which in the past would have been excavated by the conventional method with all its uncertainties for the personnel. In this context tunnelling in Switzerland can be mentioned as a model.

Fig.1: Hardrock TBM for the longest Railway-Tunnel in the world (double-tube 57 km Gotthardbasetunnel / Switzerland)

The modular design of the mechanised tunnelling does contribute a crucial advantage, because the TBM can be divided into appropriate segments with permissible dimensions according to road traffic regulations, ship transport and the limited space conditions of the assembly cavern.

The various mechanised mining techniques within hardrock are depending on the quality of the rock, which is classified based on international systems. Two of the most well-known classification systems are after Barton and Bieniawski. The final decision for the machine type is always depending on the maintenance of the rock stability and the expected amount of water ingress.
In any case all different kinds of hardrock TBM have to fulfil the high demands on the tools during mining. Thus the focus in hardrock tunnelling is concentrated on tool technology and all related components which are faced to abrasion.

The mining process is based on the overcoming of the compressive and tensile strengths of the rock in order to get rock-chips falling to the bottom. The chips are then picked-up by the openings of the buckets at the gauge area of the cutterhead. Due to the gravity and the rotation of the cutterhead they slide down along the bucket channels to the center of the machine into a funnel (muck-ring) and onto the machine conveyer-belt. From there the muck is transported through the back-ups to muck skips, dumpers or the tunnel conveyer-belt.
Due to the center-free drive unit of the TBM the machine conveyer-belt passes through the open center of the machine which therefore is under atmospheric pressure.

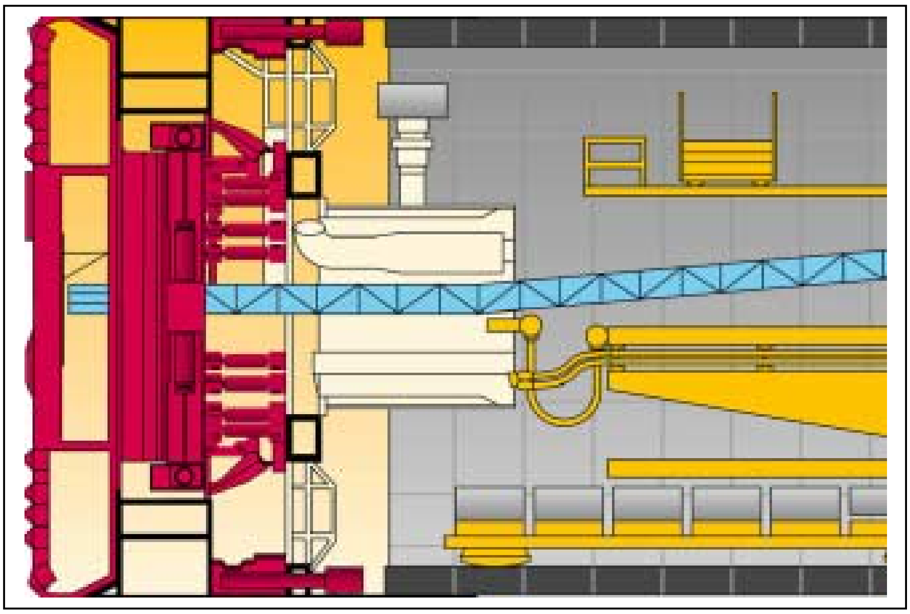

Fig.2: Prinicple of a shielded hardrock TBM

The success of a hardrock project is mainly depending on the mining process, the rock support concept (only for gripper-TBM) and the mucking techniques.

2. Mining techniques

The choice of the mining technique, i.e. the machine type, is mainly depending on the quality of the rock conditions. The stability of the rock in secondary stress state and the amount of water ingress tip the balance to the choice of a gripper-TBM or a shielded TBM.

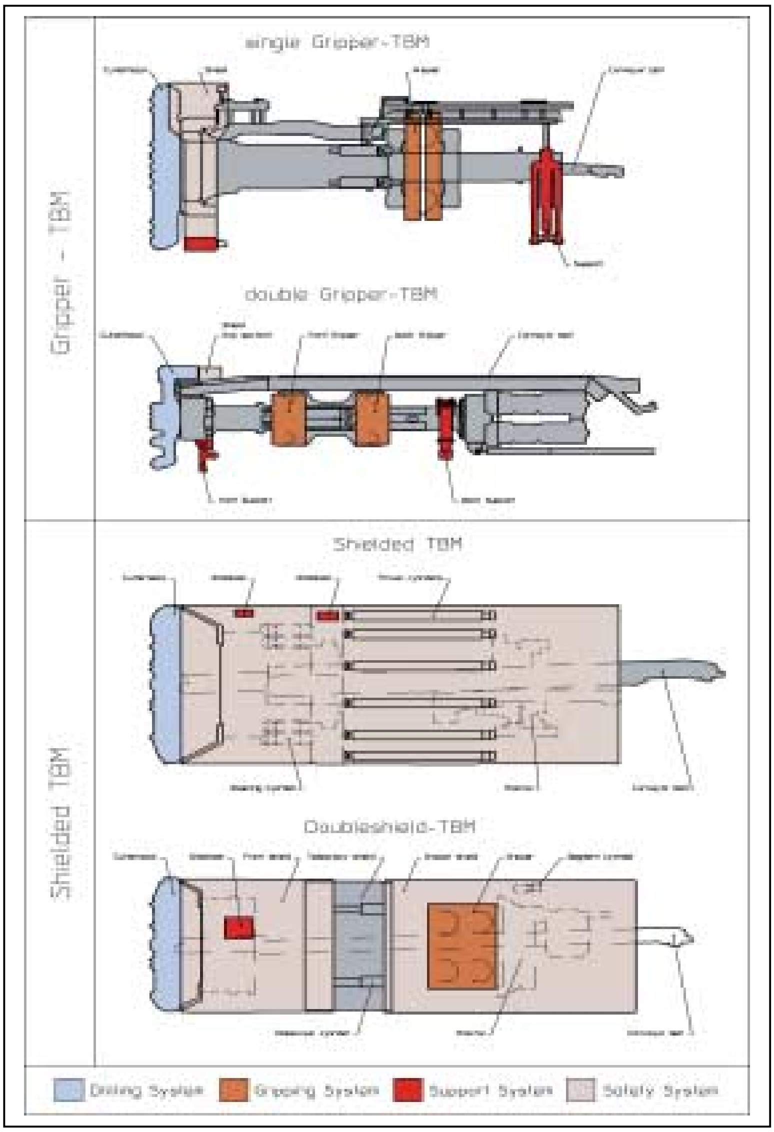

Fig.3: Various types of hardrock TBM

2.1. Gripper-TBM

In stable rock conditions with low water ingress the gripper technique is applied, whereas it has to be distinguished between single and the double-gripper systems. Both techniques are based on the gripper-shoes being tensed up onto the rock surface which offer an abutment to the thrust forces. Thus a certain limit of the rock strength is required for gripping the shoes against the rock surface.
After one stroke the machine stops and the rear support bars of the machine are extended in order to keep the machine supported while retracting the gripper-shoes. Afterwards the cardanic moveable frame with the gripper shoes mounted on is driven forward and tensed up again in order to retracted the support bars for the next mining stroke.

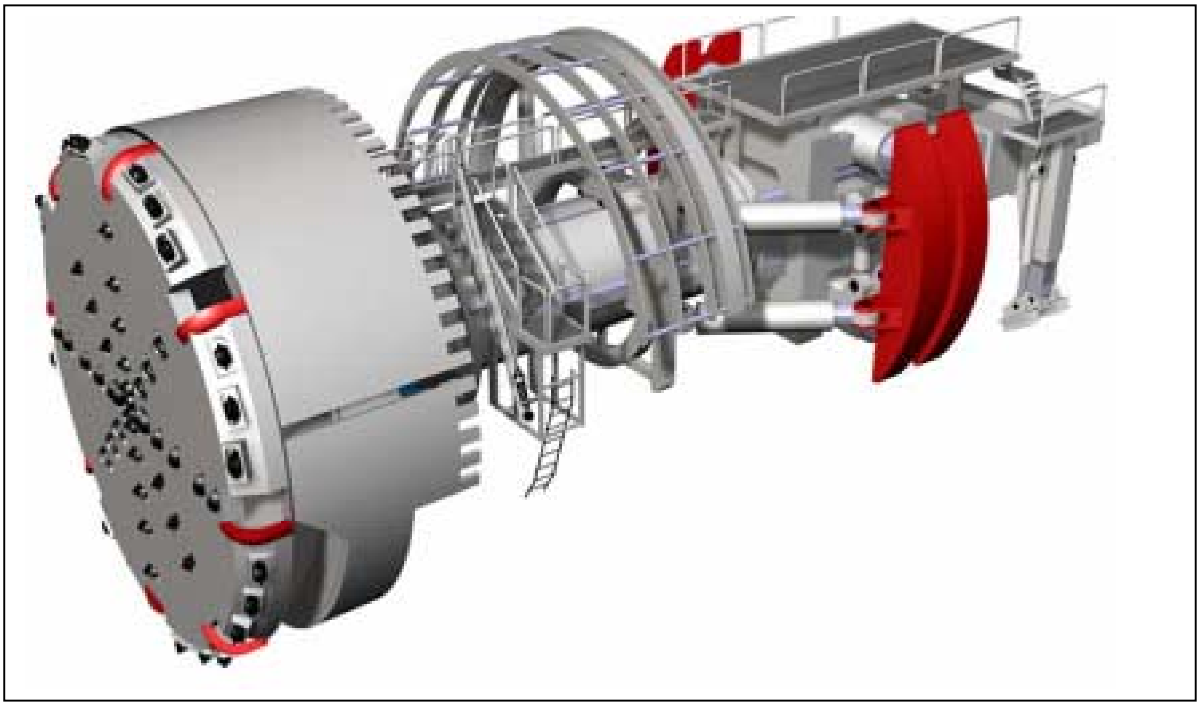

Fig.4: Single gripper-TBM

In contrast to the shielded TBM where the installation of segment lining is independent from rock quality, the performance rate of a gripper-TBM is dependent on the extent of the necessary rock support and of the time required for installation. The installation of the essential rock support devices can be performed immediately behind the front-shield. The devices are anchors, nets, steel installation and shotcrete, which originated from the conventional tunnel construction.

At the single gripper-TBM the drive unit is located at the front part o the TBM at the cutter-head whereas for the double gripper-TBM the drive unit is mounted at the rear part of the gripper shoes.

To guaranty the static determination of the double gripper-TBM the first gripper-area has to be located close to the cutterhead in order to avoid tilting the cutterhead. This would damage the whole system. Thus the free space for rock supporting works is less than compared to the single gripper-TBM.

Another basic difference between the single and the double gripper-TBM is the steering process which can be examined for the single gripper-TBM during mining (s. fig. 5). In the case of the double gripper-TBM the direction of the TBM has to be adjusted before the mining process.

Fig.5: Steering cylinder for a single gripper-TBM

The gripper shoes can be moved hydraulically and can be adapted to the shape of the excavated rock surface. The limit of the maximum gripper forces are determined by the compressive strength of the rock and are in the range of 2-3 times of the forward thrust forces of the machine.

2.2 Single shielded TBM

The shielded TBM is mainly applied in unstable hard-rock conditions with the risk of ground collapse. The shield has the function to support the rock and to protect the

personnel and the technical devices. The lining is made of pre-casted reinforced concrete segments which are put in place by the erectors and temporarily bolted together.
The pushing forces for the machine are maintained axial against the segments. The ring gab between the outer diameter of the segment and the tail skin of the machine plus the conicity of the shield skin has to be grouted continuously with mortar and/or pe-gravel. The geometry of the segments has an influence on the performance rate and the quality of the tunnel.
Due to the atmospheric conditions at the face all thrust cylinders can be retracted at the same time in order to safe time for the ring build.

Fig.6: Shielded TBM (Sörenberg ∅ 4,56 m / Switzerland)

The shielded TBM is suitable especially in glacial water bearing soils because it can be converted into a closed mode Mixshield.

2.3 Double-shield (Telescopic shield)

The double-shield machine (or telescopic shield) uses the techniques of gripper and shielded techniques and thus can be applied in a wide range of geological conditions. The double-shield TBM consists of a front shield with cutterhead, main bearing and drive as well as a gripper-shield with gripper shoes, tail shield and auxiliary thrust cylinders. Both shield parts are connected by a section called telescopic shield where the telescopic thrust cylinders operating as the main thrust cylinders.

The principle is based on the gripping of the machine radial against the tunnel wall, while excavation and segment installation are performed at the same time. cutterhead and front-shield are pushed forward by the telescopic cylinders. The auxiliary thrust cylinders in the tail-shield serve only for the support of the set segments. With reaching the full stroke of the telescopic presses, the tension of the gripper shoes is released and the gripper-shield is pulled forward towards the front shield. The auxiliary thrust cylinders are extended accordingly, in order to maintain the positioning of the last set segment ring. The support during the re-grip procedure of the gripper-shield is accomplished via the vertical support shoes and the shield of the front-shield and the auxiliary thrust cylinders. The bracing of the Gripper in horizontal direction is possible; however, this is generally done in an upward angle of 45˚, in order to push the gripper-shield downward. A more stable tension is accomplished, which enables the admission of vertical forces of the front shield.

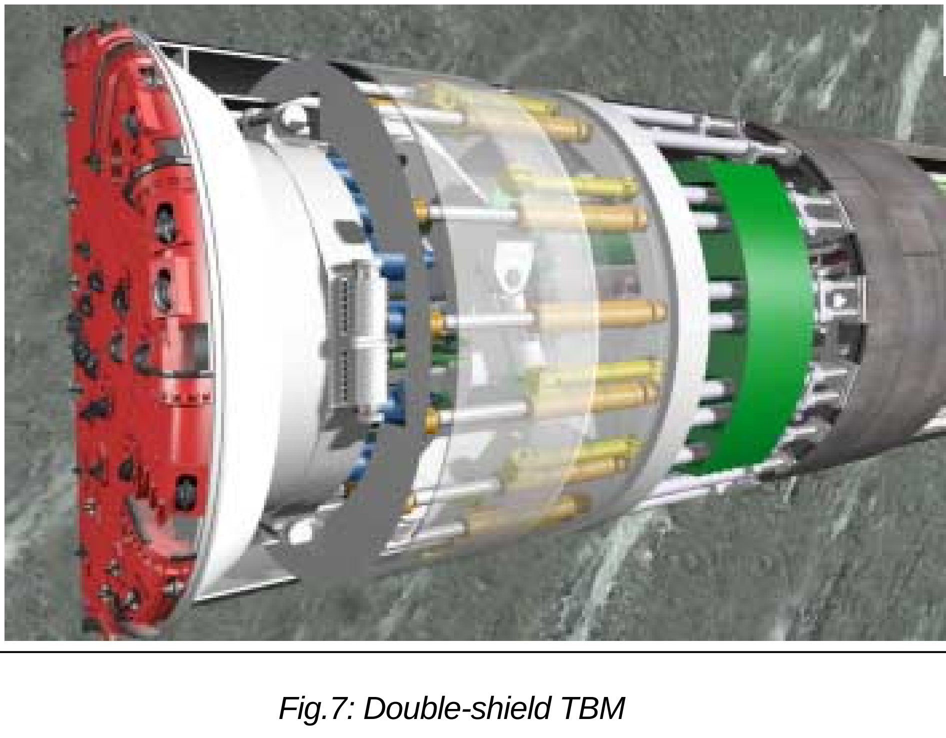

Fig.7: Double-shield TBM

If radial bracing via the gripper system is not possible, the necessary thrust forces can either be applied via the telescopic presses (stationary gripper-shield) or via the auxiliary thrust cylinders. During the tunnelling mode with telescopic cylinder stroke, the auxiliary presses transfer the thrust forces only to the segment lining

The second mode, also referred to as single-shield mode, front and gripper-shield form a rigid unit, the telescopic joint is completely closed and the cylinders are completely retracted. The auxiliary thrust cylinders do not produce the necessary thrust force; therefore, simultaneous tunnelling and building of rings are no longer possible, the performance rate reduces accordingly.

3. The mining process

An important factor regarding the efficiency of the a hard-rock project is the mining process. For crushing the rock different types and sizes of cutter-discs are applied. Depending on the rock type and its strength the distance between the cutter discs mounted at the cutterhead (spacing) is determined. The spacing has an impact on the wear of the tools and the quality of the muck which is important concerning its re-use as aggregates for example.

Standard tools on large TBM today are the 17"-cutter discs with a potential load of 267 kN. Larger cutting tools, as in the past occasionally suggested, proved to be rather unmanageable during cutter changes due to the high weight and bulky physical size. The 17"-cutter disc represents the most favourable compromise between the demand for a larger tool diameter to be able to increase the load and service life on one hand, and still to be able to manage the tool weight during cutter changes on the other hand. Cutting tools, their production and further development, represent a key qualification for the successful TBM operation.

The cutter ring first has to overcome the compressive strength of the rock which results in a crush-zone under the cutter ring. Subsequently cracks occur due to overcoming the tensile strength of the rock from neighbourhood disc tracks and meet each other. Thus a rock-chip is created which falls to the invert. Depending on the rock type and the spacing various chip shapes occur which has an impact on the wear behaviour of the tools. Due to the high temperatures (up to 180°) during mining the cutterhead is equipped with nozzles for cooling water.

Most important machine parameters regarding the mining process are the thrust forces of the cutterhead, the drive torque, the number of revolution of the cutterhead and the resulting penetration.

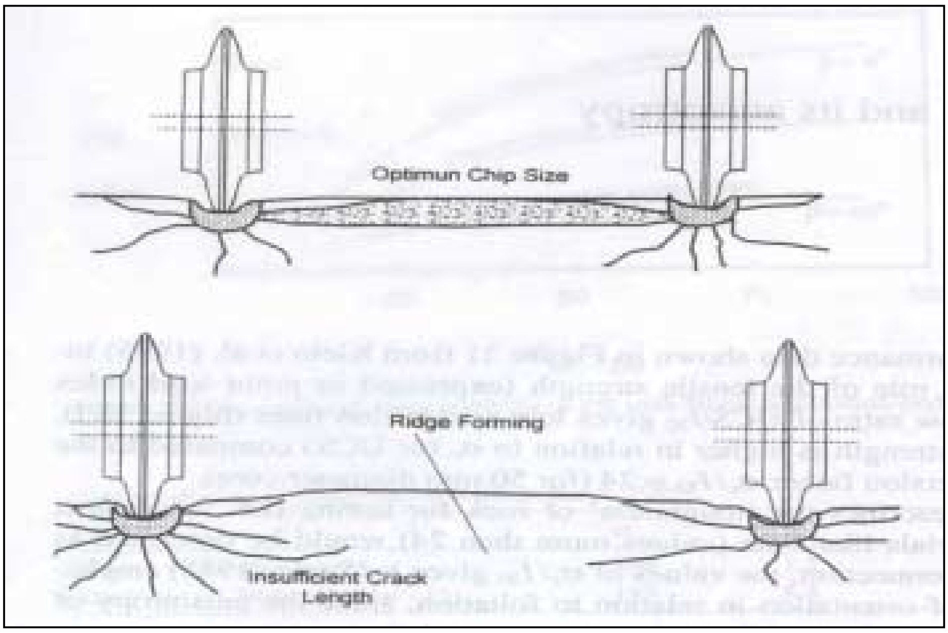

Fig. 8: Chipping process between two disc cutters

In recent past, the weakest member in the chain of the tunnelling technology with large gripper-TBM proved to be the integration of the cutter disks and cutter housings into the steel structure of the cutterhead. The high numbers of revolutions of the cutterhead necessary for the achievement of high net performance rates, and the high contact pressures led due to arising vibrations in both, rigid and flexible cutterhead structured causing cracks in the cutter housings, which occurred on large TBM of different manufacturers. Due to the necessary welding repairs, tunnelling operations had to be frequently interrupted. Cracks occurred at the bearing plates underneath the housing and in the corners of the top side of housing. It is to be assumed, that cracks on the cutterhead top are caused by the total deformation of the cutterhead structure (see fig. 9), while cracks on the bearing strip are developed by the introduction of the cutter load to the cutterhead steel structure.

Tests were carried out with modified housings, in order to compare and evaluate the modifications to the reference housings. Extensive detail improvements finally led to a new bearing housing, which could be substantially optimised, to eliminate crack pattern and crack increase during continuous stress. The new housing is characterised by large rounded shape for decrease of the load peaks and a wider housing for better load distribution. State of the art is the back loading system in order to reduce the required time for maintenance works.

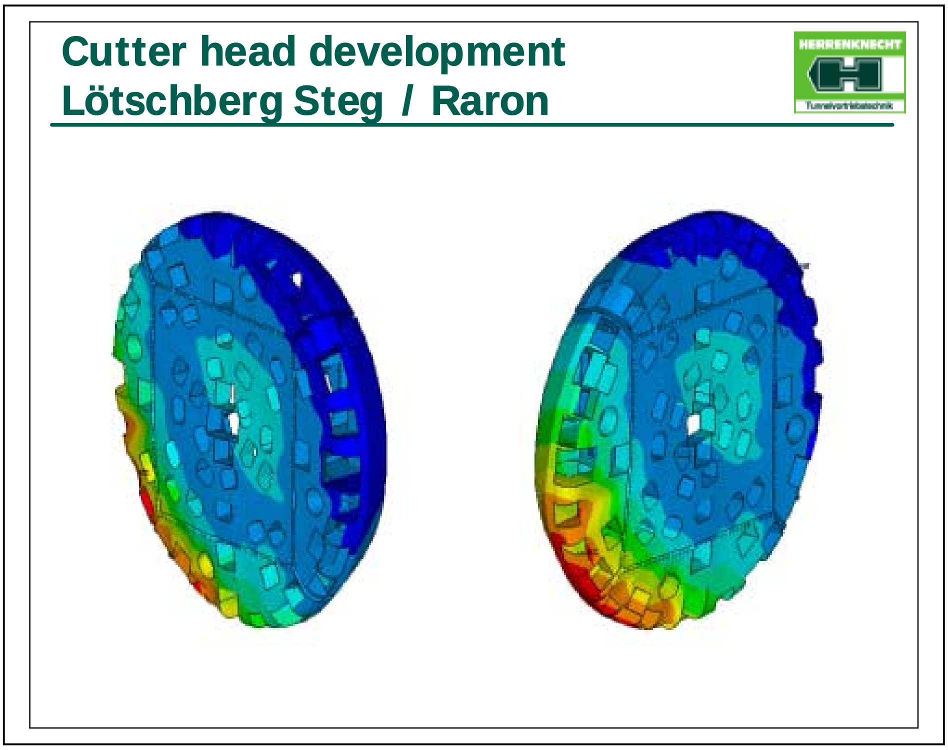

Fig.9: F/E-modelling of the cuttehead

4. Rock support

The rock support concerning the shielded TBM is done systematically by pre-casted concrete segments which are sealed by elastomer gaskets. The ring gab is filled simultaneously while advancing with pe-gravel and/or mortar. The pe-gravel is first blown into the gab and at a certain distance to the shield mortar is pumped into in order to avoid the flowing of the liquid grout around the shield into the working chamber. The quality of the tunnel is very high due to the high degree of automation.

The concept for the rock support for the open gripper-TBM is based on the principle to provide as much security and freedom of movement as possible for the personnel on the machine and with high quality of working conditions and its resulting high quality of the tunnel being built The concept for rocks support within bad rock conditions is the basic factor that influences the success of a project.

The so called L1* working area of a gripper-TBM, located between the cutterhead and gripper area is primarily responsible for security and work space (s. fig. 10).

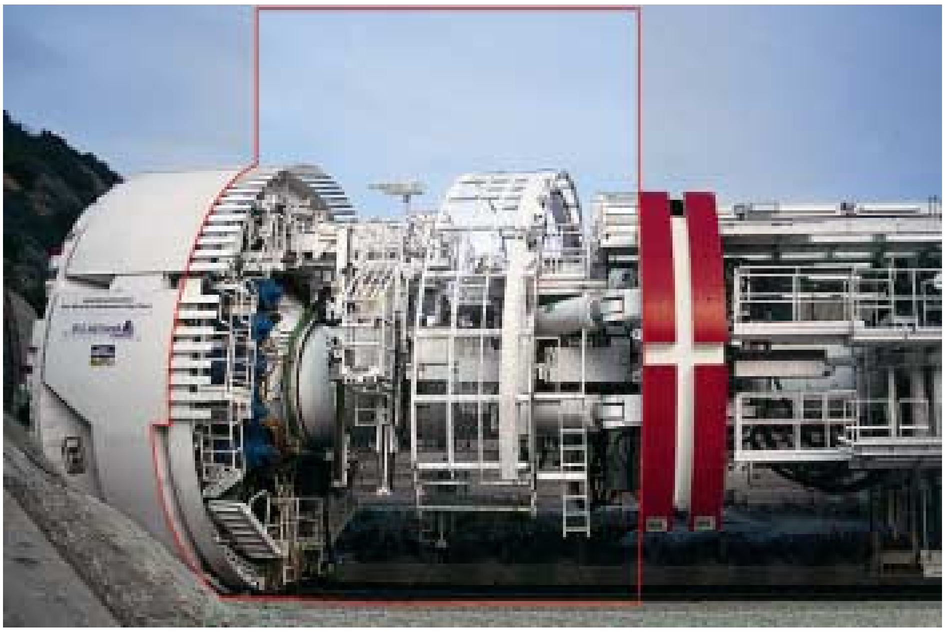

*Fig.10: Rock support area L1**

This area is larger on a single-gripper TBM than on a double-Gripper machine. A new development is the round main frame of the TBM, which replaces the traditionally rectangular shape, in order to obtain an optimal assembly connection for the rock securing devices; i.e. anchor drill equipment and shotcrete manipulators in the L1*-area. The round main frame was flanged to the front cutterhead support area such that the forces are led directly into the support rollers, to protect the main bearing from harmful torque loads.

A present, the standard equipment of the single-gripper TBM is the arrangement of anchor drill equipment behind the front shield of the cutterhead. The roof support is partially mechanised with a wire mesh erector (see fig. 10). The system is horizontally adjustable and therefore allow work to be performed independent from the actual stroke.

This support device is moved towards the rear during anchor drilling and provides the work area. In this rear position the wire mesh erector is equipped. Once it is fully equipped, with the anchor drills removed from the work platform, the erector is moved back into the installation position. Overhead and side wings are pushed against the tunnel walls and roof support is fixed.

Permanently installed probe drill and injection systems (s. fig. 11) are located in the front upper area of the gripper-shoes .

Fig.11: Fixed installed probe/ injection drill device

The longitudinal movement of each stroke reaches between 2 and 4 m. For coverage of the anchor areas, 2 independently operating telescopic anchor rigs can be selected, which cover a 270° arc in the crown. A flange plate is installed on the drilling rig for the assembly of a spraying concrete manipulator, which covers a range of 250° in the circumferential direction. The anchor drilling rigs are brought in and parked downward. In geologically bad zones, where injections are necessary, the rigs can be turned in the forward direction, in order to apply injections into the rock around the front shield.

The high degree of automation of the rock support works increases decisively the quality of the working conditions of the staff which has direct impact on the quality of the tunnel.

5. Jobsite Experience (worldwide application of Herrenknecht Hardrock TBM)

5.1 Sörenbergtunnel / Switzerland

The 5.2 km long Sörenberg-Tunnel forms part of a transit gas line from Holland to Italy. The gas transit tunnel will be excavated with an incline of just under 5 %.

Geological and Hydrological Conditions

The Sörenberg Tunnel runs through heterogeneous rock formations classified as technically unfavourable for tunnel construction. Approx. 65 % of the tunnel runs through clay and marl slate (Sörenberg melange), 25 % in flysch and 10 % in globigerina marl (25 %).

The areas subject to great tectonic strain were viewed as critical. In addition to a rapid loss of strength in the slate, the permeation of water in rocks subject to weathering and related bonding problems can also be expected. Zones with granite enclaves in soft, clay matrix may also arise. In addition, along the entire tunnel route and, in particular in the area of tectonic disruption zones, the appearance of natural gas can be expected.

Tunnelling and machine design

Due to the expected construction ground conditions it was decided to deploy a shield TBM with hard rock cutting head (∅ 4.56 m) and the installation of tunnel lining segments. The following factors influenced this decision:

- simultaneous drilling of hard and soft rock
- managing the transition from soft to hard rock
- conveyance of the material subject to weathering
- good access to the cutting head.

The shield TBM corresponds in its basic design to the customary shield machines in Switzerland. Some special characteristics are described in the following.

The structure of the cutting head has been optimised in respect of the material conveyance canals. The cutting head is equipped with 19 single rollers and 6 double rollers (each 17"). The tools can be replaced from the back.

The 10.5 m long shield casing is equipped with a steering joint which improves the manipulation of curves.

There are two stabilisers in the upper front part of the shield. They support the shield casing during the drilling process. A new aspect is that the shield centre connection is equipped with two stabilisers. These help to prevent displacement of the centre section when the forward part of the shield is being withdrawn.

Pre-drilling equipment in the shield enables pilot drill holes with less than 5° incline to be made through longitudinal slots in the shield casing. The drill mounting is located on an intermediate platform behind the shield.

The entire logistics are tailored for an incline of 5 %, an internal tunnel diameter of 3.80 m and a maximum tunnelling length of 5200 m with target tunnelling performance of 20 rings in 24 hours. Material conveyance takes place via a conveyor belt.

The following measures were taken in respect of the gas problem:

- the machine was equipped with methane gas alarm equipment
- a special ventilation design for the TBM
- automatic power shutoff if the limit value of 1.5 vol.-% CH_4 is exceeded
- telephone and lighting equipment were provided with extra protection and the switch cabinet ventilation adapted to the special requirements.

Course of the project

The machine was assembled at the end of May 2000. Tunnelling commenced in August 2000.

An average tunnelling performance of 142 m per week was achieved. The maximum weekly performance was 226 m (Fig. 6).

Tunnelling was inhibited by the belt lengthening required by the system, the penetration of water at 30-50 l/s and, in part, increased drilling cycles due to greater rock strength.

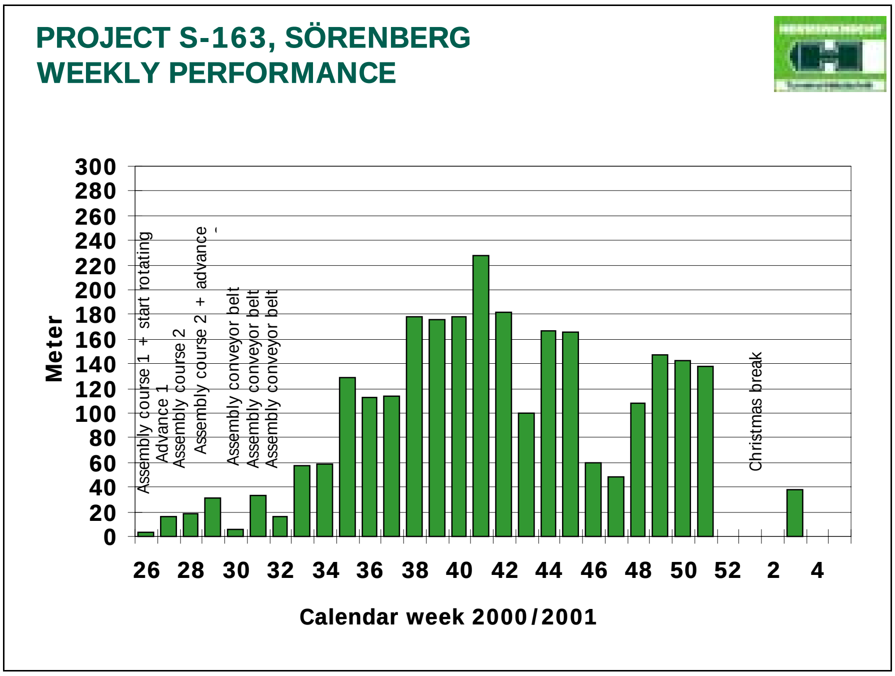

Fig. 12: Tunnelling performance shield TBM S-163, Sörenberg Tunnel, ∅ 4.56 m

5.2 Bözbergtunnel /Switzerland

As an extraordinary example for the re-use of a shielded TBM the machine for the Bözbergtunnel with a diameter of 11,8 m has to be mentioned. This machine was used three times – first at the Bözberg, as a second at the Mugenthaltunnel / Switzerland and then for the diversion tunnel at Flüelen / Switzerland.

The Bötzbertgtunnel is a double tube of the motorway N3 with each 3.700 meters long between Basel and Zürich.

5.3 Murgenthaltunnel /Switzerland

The 4.260 meter long Tunnel was excavated by the refurbished Bözberg-machine which has to pa ss through marl and sandstone. The shield diameter was 11,98m with a length of 8,8 m.

The 40 thrust cylinders generate a total thrust force of 64.000 kN. The cutterhead is equipped with 63 single disc cutters of 17'', 5 double disc cutters, 20 m valve buckets with an opening of 170 mm and 8 buckets at the gauge area. The cutterhead was designed for left and right turming with 14 hdyrodriven motors which generate a power of 3.200 kW.

Fig.13 Schieldeld TBM Bözberg (∅ 11,8 m)

Fig.14: Schielded TBM Murgenthal (∅ 11,9 m)

5.4 Guadarrama / Spain

Fig. 15: Double-shield TBM Guadarrama / Spain, ∅ 9.51 m

A new high speed rail link is currently in Spain under construction. The railway crosses the Sierra de Guadarrama, a mountain range north east of Spain's capitel Madrid. The total tunnel length is 29 km in geology characterised by weathered gneiss and granite. The excavation of the twin tube tunnel begins from both portals simultaneously with four double-shield TBMs.

Two double-shield TBM were manufactured by Herrenknecht AG with an excavation diameter of 9.51 m. The total available thrust is 105,000 kN with a maximum available torque of 20 MNm. The excavation started successfully in October/November 2002.

5.5 La Réunion

The Isle of la Réunion has abundant supplies of water at the west coast and a lack of water supplies at the east coast with a mountain range in-between. A water tunnel is constructed between both coasts to ensure sufficient water supplies.

The excavation diameter is 3.87 m with a double-shield TBM. The geology consists mainly of volcanic rock with varying stability. The TBM weighs about 620 t and has a total length (including backup) of 260 m.

Fig. 16: Double-shield TBM La Réunion ∅ 3.87 m

5.4 Lötschberg Base Tunnel /Switzerland

8,624 m of the Lötschberg Base Tunnel, which has a total length of 34.6 km, will be excavated with an single gripper-TBM. This applies to the construction section Steg/Raron.

Geological and Hydrological Conditions

The tunnel section runs through the rocks of the Aare Massif which consist of gneissic crystals, granite and granodiorite. In accordance with the submission documents, using the Bieniawski RMR classification, the ground for approx. 93 % of the tunnel route was rated as class II: good rock. As a result, an open gripper TBM is being deployed. In the remaining tunnel sections, the ground stabilisation measures can only be introduced behind the TBM in the backup system area (L2). In areas for which a low to medium risk of rock bursts has been projected, however, systematic stabilisation work has to be carried out directly behind the cutting head (L1*).

Tunnelling and machine design

Fig. 17: Single gripper-TBM Raron / Lötschberg ∅ 9.43 m

The cutting head was optimised in respect of the roller bearing housing and cutting head structure. This resulted in the symmetrical, seemingly arbitrarily selected, arrangement of the cutting tools.

The material removal takes place via twelve bucket openings on the cutting head circumference. These are supported by additional cone and rear buckets on the back of the cutting head.

The cutting head drive is powered by 10 water-cooled, frequency regulated electric motors, each with 350 kW capacity.

Fig. 18: Mechanical equipment for excavation stabilisation, gripper-TBM S-167, Lötschberg-Base Tunnel
Anchor drilling and ring erector (left)
Net installation equipment (right)

The installation of support material in the L1* area takes place via a ring erector, two independently manoeuvrable anchor drilling installations and the net installation equipment. Above the machine frame is a high performance drilling device for development drill holes up to 80 m long. In contrast, the installation of the extended rock stabilisation and the floor lining segments takes place in the backup system area. For this purpose, there are two liquid shotcrete facilities with two spray robots installed on the TBM backup system bridge.
The entire backup system runs on rails. The rails are mounted on the floor lining segments. The head of the backup system bridge is supported by a walking mechanism in the area immediately in front of the site where the floor lining segments are installed.

5.5 Gotthard Base Tunnel / Switzerland

The project-specific requirements for the construction of the new Gotthard base tunnel are formulated primarily in the extensive tender documents on behalf of the owner AlpTransit Gotthard AG, which serve the implementing side as base for process engineering as well as financial planning. The preliminary geological investigations for the Gotthard base tunnel began as early as 1963. In a 2 times 57 km long section, it crosses diverging rock formations of the Alps, this means approx. 75 kilometres have to be mined by TBM through predominantly gneiss and granites with several fault zones. The tunnel system consists likewise of two single-lane tubes, which are connected by transverse cross-passages every 300 meters.

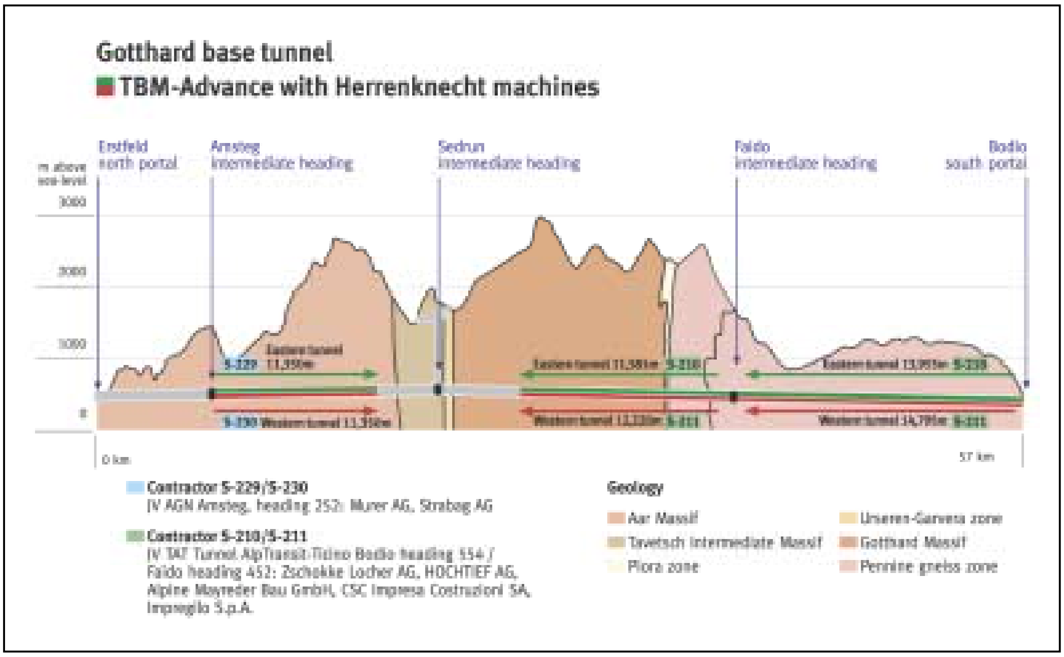

Fig. 19: The longest railway tunnel in the world: Gotthardbastunnel (Switzerland)

At the third locations in Sedrun and Faido, so-called multi-functional places with track changes and emergency stops are configured. The two sections Bodio/Faido were assigned as one contract to the Joint Venture TAT. This had a positive effect on the time expenditure, since it was the same partner for the two different job-sites.

Due to the geological conditions at the South portal at Bodio, a 1.2 km long tunnel section had be excavated around an approximately 800 m long weak rock zone within the Gotthard tunnel, which leads the way to the assembly cavern of the TBM. This entry tunnel as well as the assembly cavern with its limited dimensions and resulting reduced crane capacities placed the highest demands on the TBM manufacturer, who not only developed the TBM design, but also developed the concept for the realisation of transport and the assembly.

Mining of the Gotthardtunnel started in January 2003 and we are optimistic to finish the job in time with a high quality tunnel which then will be another milestone for the mechanised tunnelling