

# THE GOTTHARD BASE TUNNEL PROJECT IN SWITZERLAND – CONSTRUCTION OF THE WORLD'S LONGEST RAILWAY TUNNEL

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## ABSTRACT

The Gotthard Base Tunnel with its length of 57km will be the longest rail tunnel in the world when construction finishes in 2017. It is part of the New Rail Link through the Alps (NRLA) which will help to cope with the increasing transalpine freight traffic. The project consists of five lots, two of which are constructed by the Consortium TAT, a joint venture of leading companies from Switzerland, Germany, Italy and Austria. Two 9,4m diameter TBM's are used to excavate the running tunnels while drill and blast methods were used to create the multifunctional station in the Faido lot.

## INTRODUCTION

Like any other country in central Europe, Switzerland has to deal with increasing traffic, most of which is created by trucks passing from Germany to Italy and back. Today this traffic is handled by various highways and the 130-years-old Gotthard railroad which all have come to their limits. Currently more than 150 trains per day pass the Gotthard route. Forecasts predict a rise from 20 million tons per year to more than 40 million tons in the next 20 years.

To resolve the oncoming problems the Swiss government proposed to the Swiss electorate the establishment of a special fund to finance four major projects to improve and expand the existing railway network:

- AlpTransit, including the new base tunnels of Lötschberg and Gotthard
- Rail 2000, a project for modernizing the existing railway system
- Connection to the European high-speed network
- Noise reduction on the existing lines and rolling stock

The Swiss electorate accepted the proposal in 1998, providing a 30 billion CHF (20 billion € or 40 billion NZ\$) fund to be invested over the following 20 years to realize one of the biggest infrastructure projects in Europe ever.



Fig.1 New Railway Lines in Switzerland [1]

The fund is financed by three major components:

- Tax on oil products (approx. 25%)
- Rise of one tenth of a percent of Value Added Tax (approx. 10%)
- Heavy-vehicle tax for trucks passing Switzerland on highways (approx. 65%)

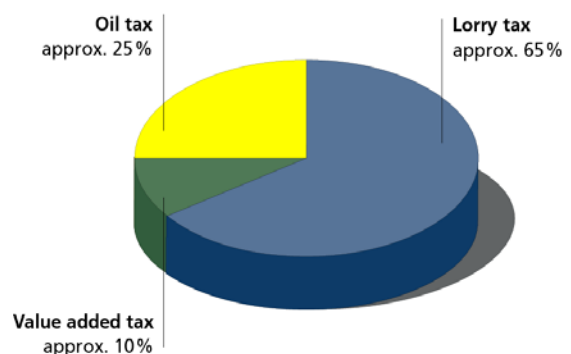


Fig.2 Funding of NRLA [1]

Almost half of the money is spent on the New Rail Link through the Alps (NRLA) comprising the Gotthard and Lötschberg routes to create a flat railway through the Alpine ridge at a maximum elevation of 550m above sea level.

Freight trains, even longer and heavier than today, will be able to travel at a speed of 160km/h, increasing the capacity of transalpine freight to 50 million tons per year.

Passenger trains will travel at 200 to 250km/h cutting travelling times from Zurich to Milan by more than one hour.

Together with the modernization of the existing railway network the Swiss Railway will then be able to cope with the oncoming challenges.

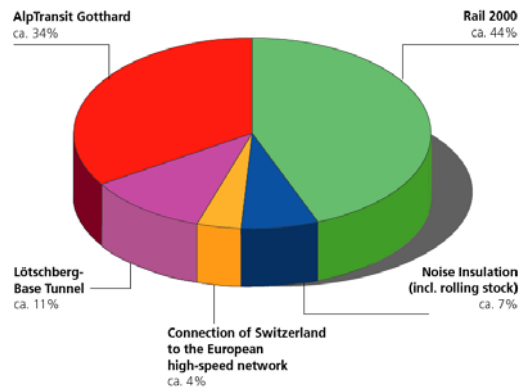


Fig.3 Use of financial resources [1]

With completion of Rail 2000 in 2005 and inauguration of the Lötshberg Base Tunnel in 2007, the first two steps have been made. But the system will only be fully operating with completion of the key project, the 57km-long Gotthard Base Tunnel.

## THE PROJECT

In the AlpTransit Gotthard (ATG) project the Gotthard Base Tunnel is the main object on the new high-speed railway line between Zurich and Lugano, which also comprises the construction of the Zimmerberg and the Ceneri Base tunnels, both approximately 15km long. While the Ceneri project is now under way, the Zimmerberg Base Tunnel has been postponed due to financial reasons.

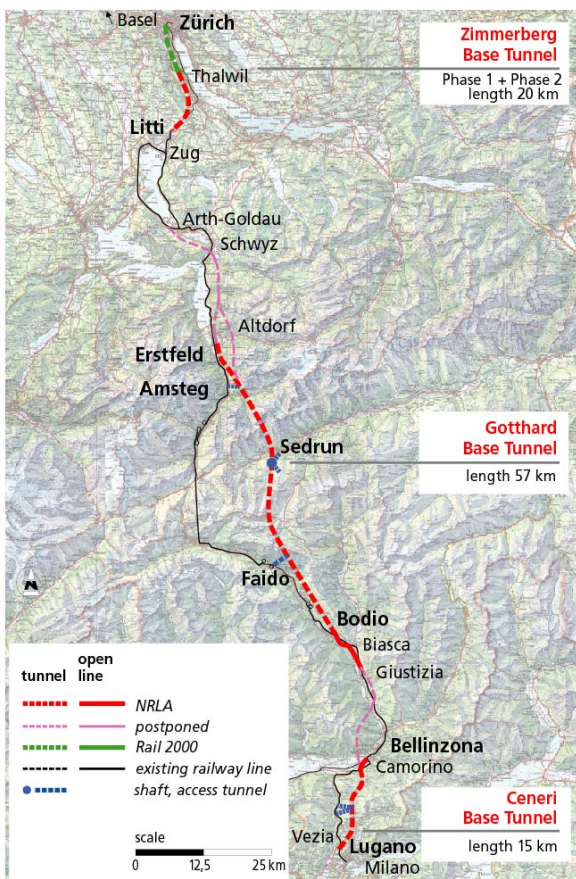


Fig. 4 Layout of flat rail link Zurich – Lugano [1]

Figure 4 shows the layout of the flat rail link, as well as the existing 130-years-old railway line including several loop tunnels to reach the 16km-long summit tunnel at 1150m above sea level (Fig.5).

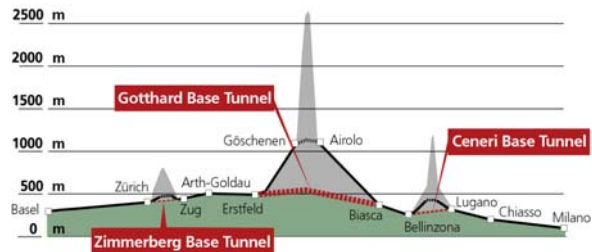


Fig. 5 Base Tunnel System [1]

The Gotthard Base Tunnel consists of two parallel single track tubes 40m apart connected every 300m by cross passages. It also includes two multifunctional stations at the third-points with double crossovers and emergency stop stations to evacuate passengers in case of an incident. Additional ventilation systems within these stations allow for active extraction of any fumes or smoke from the affected tunnel, and safe evacuation of the travellers.

To save construction time the tunnel was divided into 5 lots two of which are situated near the portals at Erstfeld in the north and Bodio in the south. The three intermediate lots at Amsteg, Sedrun and Faido use access tunnels and shafts to reach the base tunnel level.

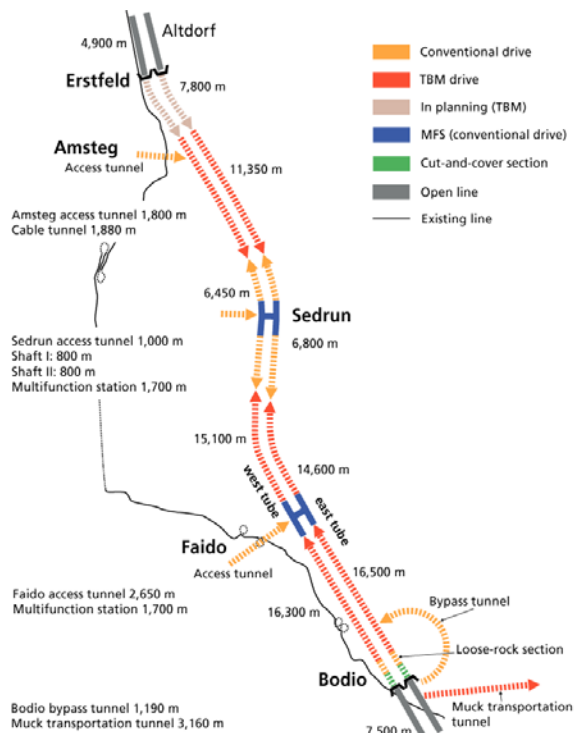


Fig. 6 Division of lots and access tunnels [1]

Construction of the access tunnels and shafts started 1996 and finished in 2001. In that same year contracts were let for 4 of the main lots, and construction started on the running tunnels and multifunctional stations in 2002.

The **Erstfeld** lot is approximately 8km long and consists of a short section in open cut construction, followed by excavation of the running tunnels by tunnel boring machines (TBM's) with a diameter of 9,5m.

This lot is now under way after being blocked for almost two years by a dispute over tender procedure by the two main bidders. The contract was finally awarded to the same joint venture that had previously constructed the **Amsteg** lot.

This lot is accessed via a 1,8km long inclined tunnel which served for transportation and installation of two TBM's of 9,5m diameter, which excavated the 11km long stretch toward the centre lot of Sedrun.

Excavation works finished in 2007, and the two TBM's are now used to excavate the above mentioned Erstfeld lot. In Amsteg works on the inner lining are well under way using 5 formwork sets of 12m to cast a length of 60m every day.

The neighbouring **Sedrun** lot has the most difficult access route to deal with. The first part of it is a 1km long access tunnel from the small town of Sedrun, a well known skiing resort in the region at 1300m above sea level. At the dead end of the tunnel two 800m deep shafts reach down to the base tunnel level creating a great logistic challenge to the construction companies.

Due also to the difficult access but mainly for geological reasons TBM's could not be used in this section, so the running tunnels and the multifunctional station at the bottom of the shafts are excavated by drill-and-blast methods.

Today the multifunctional station is completely excavated, together with the running tunnels to the north where breakthrough with the Amsteg lot took place in 2007. Still under way is excavation of the southbound tunnels through difficult geological formations, such as squeezing or highly weathered rock.

Exceeding water ingress of more than the allowed 3l/s called for time-costly injections to protect the precious water reservoirs at the surface.

Breakthrough with the Faido lot is expected between 2010 and 2011, depending on the still unknown rock conditions of the sections yet to be excavated.

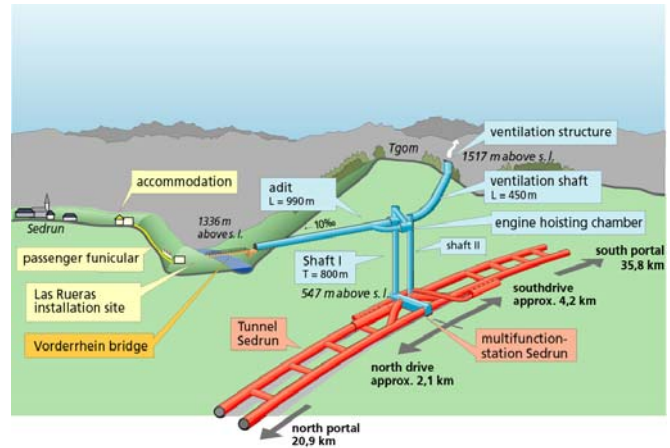


Fig. 7 Layout of Sedrun Tunnel Section [1]

Detailed reports on the current state of the works on the two southern lots of Faido and Bodio will be given in the following chapters.

### JOINT VENTURE TAT

The Joint Venture TAT, or **Tunnel Alptransit Ticino**, was formed in 2000 as a bidding consortium for the two southern lots of Bodio and Faido which were to be tendered separately, but had an option to be combined after awarding the second lot at Faido.

In 2001 the joint venture, formed by construction companies

- Implenia of Switzerland
- Hochtief of Germany
- Alpine Bau of Austria
- Impregilo of Italy and
- CSC of Switzerland

was awarded the Bodio lot at a sum of 800 million CHF (550mio € or 1,1billion NZ \$). Shortly after, also the second lot of Faido was awarded to TAT at 700 million CHF (450mio € or 0,9 million NZ \$), thus creating a combined lot of 1,5billion CHF.

Key aspect of the combined lot was the re-use of the two Bodio TBM's for the Faido lot. In total the joint venture is now in charge for construction of 60km of running tunnels, 52km of which by TBM's, plus excavation of the multifunctional station at Faido, and 100 cross passages using drill-and-blast methods.

Until breakthrough from Bodio to Faido in 2006, both sites were operated separately. At peak production in 2005 the joint venture employed nearly 1'000 workers and 100 persons in staff.



## LOT 554 BODIO

### 1. Scope of Works

The Bodio lot with 16,5km is the longest section of the Gotthard Base Tunnel. It is operated from the north portal site near the small village of Pollegio and comprises the following main sections:

- main installation site including offices, accommodation for workers, material handling facilities, rotary tip, concrete batching plant and workshops
- station and tracks for rolling stock
- 3km transport tunnel to material deposit in a neighbouring valley (excavated prior to main contract)
- 1km bypass tunnel to reach TBM installation caverns (excavated prior to main contract)
- 2 x 300m of open cut construction of running tunnels including portal structures (prior to main contract)
- 2 x 300m of loose rock excavation (prior to main contract)
- 2 x 1,5km of drill-and-blast excavation including two caverns for TBM installation (prior to main contract)
- 2 x 14km of TBM drives
- 2 x 16km of inner lining, walkways and cable ducts
- excavation and inner lining of 51 cross passages

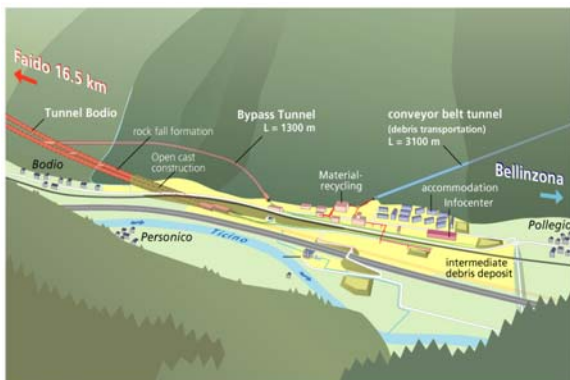


Fig. 8 Bodio site installations [1]

The typical cross section for the TBM driven tunnels is shown in Fig. 9. The diameter of the excavated tunnel is 8,8m for the Bodio section, while in the Faido section it is enlarged to 9,4m. Works on the TBM comprise primary support measures such as rock bolts, wire mesh, shotcrete and steel ribs where necessary.

The in-situ invert concrete slab is also cast on the TBM in 10m lengths, including main drainage and waste water pipes, while the sealing and drainage system, as well as the inner concrete lining, is placed on separate installations following the TBM's with a distance of 3 to 4km.

Also on site are two separate contractors for material recycling and wastewater treatment.

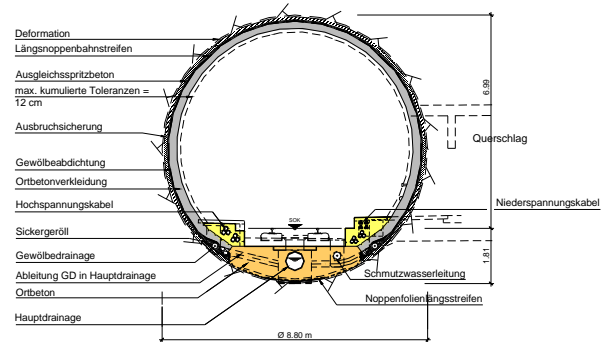


Fig. 9 Cross Section of TBM Driven Tunnel

### 2. Site Installations

Already from the beginning of the site installation in 2001 the Bodio site was foreseen to accommodate all necessary installations to serve not only the Bodio operations, but also, after breakthrough, the TBM drives from Faido to Sedrun.

Due to the fact that the cross passages had to be excavated and the inner lining to be installed while the TBM drives were still under way, conveyor belt solutions to transport the excavated material were soon to be rejected in favour of muck trains, which called for a **multi-car rotary tip** near the material recycling plant. Muck trains consist of 2 locomotives of 35tons to pull 10 cars of 24m<sup>3</sup> loading capacity, enough to hold material from 2 metres of advance. The chosen rotary tip is able to empty 5 cars at a time without disconnecting them from the locomotives and the other 5 cars. The unloading procedure for one train takes about 20 minutes. The excavated rock is rated for each train by a geologist into A-Material, suitable to produce concrete aggregates, or B-Material, to be delivered to the deposit via the transport tunnel.

Both materials are handed over from the rotary tip to the recycling contractor by conveyor belts. The rock is then crushed and screened to produce the needed aggregates, which are given back to the main contractor to produce concrete.

In 2001 the concrete production contract was awarded to the joint venture of Holcim-Sika. The contract includes production of 1 million cubic meters of in-situ concrete for the inner lining and 250'000m<sup>3</sup> of sprayed concrete (shotcrete) for primary rock support and inner lining of caverns, crossovers, rescue and ventilation tunnels [2].

Holcim-Sika established a **batching plant** with two 3m<sup>3</sup> mixers that load into 4 buckets which can travel along the whole length of a concrete train

filling up the mixer cars without moving the train. A train usually consists of 4 to 5 concrete mixer cars of 12m<sup>3</sup> plus a 35ton locomotive.

The batching plant has a capacity of 120m<sup>3</sup>/hour. With two tracks underneath the plant, two trains can be filled simultaneously within an hour, including lifting and placing of the covers with an automatically operating crane device. To date the plant has produced more than 900'000m<sup>3</sup> of concrete and shotcrete, the maximum output for one day has been 1'200m<sup>3</sup>.



Pic. 1 Batching Plant Bodio

More information on concrete production and transport is available in the paper 'Concrete for the World's Longest Tunnel – Requirements, Production and Transport of Concrete and Shotcrete for the Gotthard Base Tunnel'.

Near the batching plant the **washing hall** is situated where, as the name says, all mixer cars are washed after leaving the tunnel and before being refilled or parked in the station area.

Two **workshops** have been established, one for the maintenance and repair of the rolling stock, and one for any other equipment. Next to them a **magazine** has been built for distribution of spare parts, especially for the TBM's and rolling stock, as well as tools and all necessary consumables.

Also near is the diesel **gas station**, designed for parallel filling of both locomotives on either side of a muck train.

During the time the Bodio site operated separately, the **container village** provided accommodation for approx. 500 workers, including a **canteen** and a **change house**. Today most of the containers have been moved to Faido, since the personnel has easier and faster access to the tunnel.

Left behind are the loco drivers and the personnel operating the **material handling areas**, where the trains are loaded with the necessary equipment

and materials for the various working sites inside the tunnels.

### 3. Logistics

The transport to and from the tunnel working areas is handled by rail. Two tracks of 900mm are installed in both running tunnels, connected by electronically controlled switches every 1'000m to allow for trains passing work sites inside the tunnel at all times.

All switches inside and outside the tunnels are controlled by the 'guide office', where all train movements are coordinated. It is a combination of an airport tower and a train station control. Before moving a train anywhere every loco driver has to call the guide office and give his current position and destination. The guide office then operates the switches, creating a so-called 'street' to the destination, and giving green lights to all switches on the way. Train operators are never allowed to pass red light switches.

The total length of tracks installed inside and outside the tunnels has exceeded the 100km mark this year, and will be as long as 150km at the end of the excavation. More than 250 switches are in operation with another 100 waiting to be installed.

While the guide office's electronic heart is controlled by a professional subcontractor for rail systems, train traffic controllers from TAT are deciding the priorities of trains for moving in and out of the tunnel, as well as for using the various installations, such as batching plant and rotary tip.

In total there are 7 sites to be served inside the tunnel, each of which has a range of specially designed trains formed by the rolling stock consisting of 55 locomotives and 350 cars:

- 2 TBM drives using:
  - o 8 muck trains
  - o 3 shotcrete trains
  - o 2 material trains
  - o 2 in-situ concrete trains
- cross passage excavation:
  - o 1 muck train
  - o 1 shotcrete/material train
- cross passage inner lining:
  - o 1 in-situ concrete train
- 2 inner lining formwork systems for TBM sections:
  - o 4 in-situ concrete trains
  - o 4 material trains
  - o 1 injection train for backfill grouting

- 1 inner lining formwork system for drill-and-blast sections:
  - o 1 in-situ concrete trains
  - o 1 material train

Additionally there are 15 other compositions operating, such as personnel trains, track inspection trains, crane trains, rescue trains etc.

Logistics will become even more challenging in 2008, when the western tunnel section between Bodio and Faido is handed over to the technical equipment contractor for installation and test runs. All traffic now distributed over two tunnels will then be concentrated in one tube to serve the Faido to Sedrun operations, making it one of the busiest track sections in all of Switzerland

The guide office not only controls the train traffic, but also supervises the sophisticated ventilation system, temperatures and pressures of the cooling water circuit and the batch-controlled entry system for personnel.

Finally the train traffic controllers also dispatch the more than 150 loco drivers that operate the various trains over a 24/7 basis.

#### 4. TBM Drives

During the bid evaluating and TBM design process in 2001, a bypass tunnel was driven around the rockfall formation near the portal area to be able to start the TBM drives in stable rock conditions. The drill-and-blast operations went on until the main contract was awarded and TBM delivery dates were fixed. Two caverns were broken out and cranes installed to enable the assembly within the mountain.



Pic. 2 TBM Assembly inside Cavern

The TBM contract was awarded to company Herrenknecht of Germany for delivery and assembly of two 8,8m diameter open hard rock gripper TBM's for the 14km long section from Bodio to Faido in rock formations called Leventina Gneis.

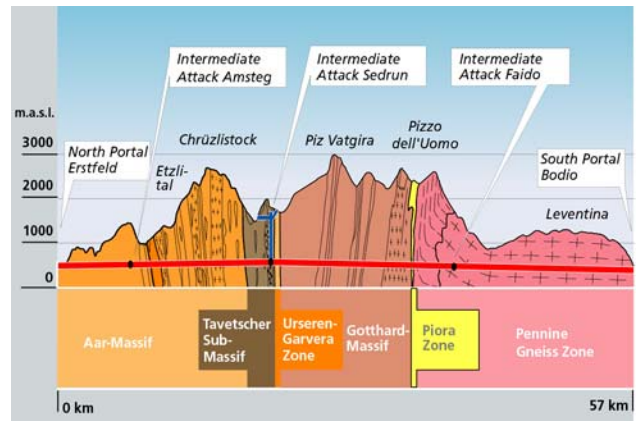


Fig. 10 Geological Profile

The main features of the TBM were defined as follows:

- cutterhead of 8,8m diameter equipped with 17" disc cutters + 2 hydraulic overcutters to enlarge the excavated diameter to 9,1m
- backloading system for disc cutter changes
- 8 bucket openings to transport the excavated material to the conveyor belt inside the cutterhead
- minimum thrust force of 25'000kN or 2'500tons
- minimum gripper force of 70'000kN or 7'000tons
- minimum torque of 6'000kNm
- cutterhead rotating at 6rpm
- dust shield to be designed for rock pressures of 300kn/m<sup>2</sup>

These requirements led to construction of a cutterhead with 58 17" disc cutters with a spacing of 90mm plus two hydraulic overcutters. Ten engines of 350kW were installed, with a total installed power of 3,5MW.



Pic. 3 TBM Cutterhead

The rock support installations are divided into two sections, the so-called L1 zone approximately 5 to 10 m behind the cutter head, and the L2 zone 40 to 60m back.



The L1 zone contains two drill rigs for rock bolting, a ring beam erector, a wire mesh erector and a shotcrete nozzle.

The L2 zone is designed to install additional anchors with two drill rigs, and to apply shotcrete on a large scale.

During the second half of 2002, both TBM's were installed inside the caverns using the bypass tunnel as transport access. In total, the TBM's including the trailers are 420m long, due to the invert concrete casting area that calls for a 90m span bridge directly behind the L2 zone, and to the muck loading area in the back with a length of approximately 150m. The trailers had to be assembled one by one behind the TBM inside the drill-and-blast area without any help of caverns.

On November 7<sup>th</sup>, 2002, the eastern TBM officially started excavation, and went fully operational in February 2003. The western TBM followed in March 2003. Both TBM's started out with a 4/3-shift system working 24 hours, 7 days a week on 8-hour-shifts. There was no maintenance shift planned, the necessary mechanics were included in the shifts with a strength of 23 workers including loco drivers.

Both drives were supposed to encounter good to very good rock conditions, and the machines were therefore equipped with a minimum of rock support installations in favour of high speed rock bolt and wire mesh installation, with application of shotcrete only foreseen in the L2 zone.

Soon enough, in April 2003, the eastern TBM entered a zone of highly fractured and weathered rock, which called for extensive rock support measures in the L1 zone, and bringing the drive almost to a halt. The TBM crew managed to pass the fault zone within the next 5 months with daily advance rates of 2 – 6m, but it was clearly visible that the L1 zone was not suitably equipped should the existing rock conditions prevail. Maintenance time became vital due to extensive use of shotcrete in the L1 zone, thus damaging all mechanical and hydraulic equipment including the engines and the drill rigs.

The first countermeasure was implemented in summer 2004, changing the shift system to a 3/2-rhythm with two 9-hour operational shifts and a maintenance shift of 6 hours. As a first installation the wire mesh erector, which turned out to be too bulky, was dumped overboard.

After on-site brainstorming and extern consulting it was decided to re-design the whole L1 zone during the winter break of 2004/2005. Company ROWA of Switzerland was awarded the design, manufacture and installation of the L1 modifications including:

- new, less vibrating centre platform to allow for moving installations longitudinally
- new shotcrete robot to cover 270° and to enable large overbreaks to be filled quickly and safely
- new, self-propelled ring beam transporter which serves also to move the shotcrete robot longitudinally
- new movable working platforms on either side of the centre platform to allow for easy access to all working areas

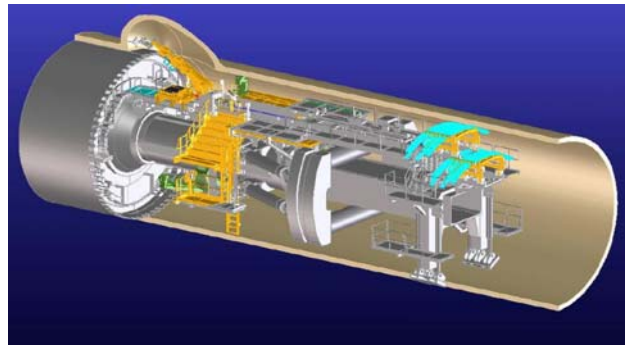


Fig. 11 New Design of L1 Zone

With the above mentioned improvements, leaving only the invert in the L1 zone to be sprayed by hand, daily advance rates could be increased to 12 to 15m per day.

When the TBM's neared Faido in 2006, rock conditions changed when, unforeseen, the drives entered the Lucomagno gneiss section, which was predicted only north of the drill-and-blast section of Faido, but had already there caused multiple problems during excavation of the multifunctional station.

The Lucomagno gneiss is known to be more ductile, and therefore usually causes higher convergences around the circumference of the tunnel. In March 2006, the western TBM got stuck and, despite all efforts, could not be moved any further. The use of the overcutters had long been given up after the first trials in 2003, in fact they had been dismantled in the 2004/2005 rebuild.

The only solution was to excavate around the upper half of the shield by hand to free the top shield. Within ten days, the crew of the TBM was able to free the shield and commence the excavation. It was then decided to try and keep the TBM moving at all times by driving slowly or in short intervals while installing the rock support. With theses measures, the drives could be managed until the breakthrough into the multifunctional station in Faido.



Pic. 4 Hand Mining over Top Shield

While freeing the top shield, an inspection of the invert shield uncovered major damages to the steel structure that had to be repaired immediately before restart. On inspection, the same damage was discovered on the eastern TBM, causing a stop of that machine for repairs.

Obviously the damages occurred while trying to overcome the excessive rock pressures, and friction caused thereby, by applying the maximum thrust force on the machine frame, and so pushing it virtually over the invert shield. Repairs on the eastern machine took another 10 days.

The above mentioned difficulties led to the delayed arrival in Faïdo by more than one year. Daily advance rates overall averaged 12m and 13m respectively for the western and eastern TBM, with peak performances of 38m/day, 190m/week and 620m/month. During 2005, both TBM's advanced more than 4'700m each with a total of 9'457m.

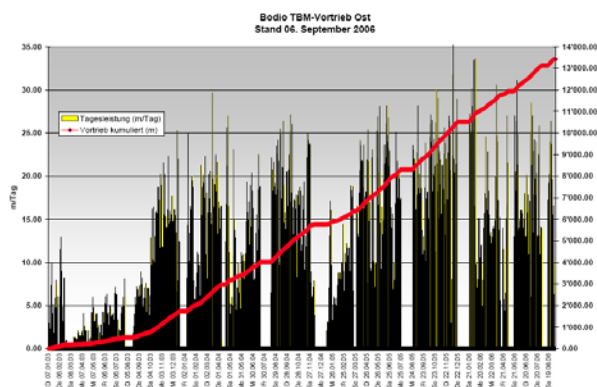


Fig. 12 Daily Advance Rates Eastern TBM

On September 6<sup>th</sup>, 2006, the eastern TBM finally reached the multifunctional station at Faïdo after three and a half years and 13'427m of boring. Seven weeks later, on October 26<sup>th</sup>, 2006, the western TBM crossed the finish line after having excavated 14'083m of tunnel.



Pic. 6 Breakthrough of Eastern TBM

Both TBM's were then partly dismantled and prepared for the next section from Faïdo to Sedrun.

## 5. Inner Lining

Contract conditions and the allowed construction time called for installation of the inner lining parallel to the TBM drives. The joint venture decided to do all preparatory work such as

- re-profiling if necessary
- collection of water inflow
- fine shotcrete application as base for waterproof sealing
- cleaning of invert and drainage channels
- installation of drainage system
- installation of water sealing membranes
- installation of reinforcement if necessary

as well as the casting and curing of the concrete and cosmetic works on the same carriage.

In addition, the carriage had to be designed to let trains to and from the TBM's pass underneath, and to take off, lead through and refit all utility lines from the TBM drives such as

- cooling water pipes
- 24kV electricity cable
- low voltage cable including all tunnel lights
- telecommunication cables etc.

In the end, more than 30 portal cars were joined together to form the so-called 'worm', an installation of 650m length carrying all necessary equipment on the upper deck, leaving one track open for passing trains, while the other served as parking track for material and concrete trains.





Pic. 7 The 'Worm'

To prevent water seepage into the tunnel, a watertight sealing is applied over 270° of the tunnel prior to concrete casting. The water is led to a drainage system consisting of drainage pipes on both sides of the invert slab, and from there every 100m via shafts to the main drainage pipe already placed inside the invert concrete.

To prepare for the installation of the watertight sealing, a 3cm layer of fine grained sprayed concrete is applied where the shotcrete from the TBM drives doesn't meet the quality standards, such as wave form and roughness.

Before the drainage pipes on both sides are installed, the invert and drainage channels are cleaned by a giant vacuum cleaner that removes all dust, mud, garbage and shotcrete rebound.

The watertight membrane is placed semi-automatically by two robots that press the 4m wide lengths onto the previously installed Enkadrain fleece using Velcro joints. The single lengths are then welded together at the joints. The works have been subcontracted to a joint venture of Sika Construction and Tecton.

The concrete inner lining itself serves mainly to reduce air friction for high-speed trains, and is not specially designed to carry any loads from the surrounding rock. The standard thickness of the shell is 25cm, with the concrete usually not reinforced. Only in fault zones and at intersections with cross passages, reinforcement using steel bars is installed, and the thickness of the shell may be enlarged to 30cm. Standard strength of the in-situ concrete is 40N/mm<sup>2</sup>, with a minimum of 30N/mm<sup>2</sup>. Same strengths apply also to the sprayed concrete.

Two shutters of 12m length allow for placing 24m of inner lining per day, which, considering the 9days on/5days off shift rhythm, leads to a monthly production of 500 to 550m per tunnel. The concrete is transported to the worms by trains,

each holding 48m<sup>3</sup> of concrete in 4 mixer cars. On the upper deck of the worm itself, two BP1800 concrete pumps are installed, one of which serves as a spare unit. When the train arrives, the operating pump including a short conveyor belt is lowered onto a flat bed car travelling in front of the first mixer. While the concreting process proceeds, the mixer cars are connected to the electric system of the worm and pushed together one by one to enable the concrete to flow through all the cars to the front mixer.

One shutter usually is filled with 100 to 120m<sup>3</sup> of concrete, which takes approximately 3,5 to 4hours. After 8 hours a set of two blocks is concreted, one front block with two stop ends, and, 24m further back, the trailing block that fills up the remaining 12m gaps.

After 6hours de-moulding starts and leaves enough time to move the worm and put the shutters into place for the next two blocks. Working time is 24 hours in 3 shifts, the total number of workers is 51.

Active concrete curing lasts for 3 days, and the last step is cosmetics on the joints and backfill grouting of the top void.

The key to success for this installation is to be able to finish 24m of every working process within 24hours, in order not to have any critical path except the concrete works itself.

From September 2004 to February 2007, the worms had worked their way almost to within sight of Faido, when they had to be stopped due to the above mentioned phenomena of squeezing rock and invert uplift. The extent of the re-profiling works called for separate installations to completely tear down and reconstruct the primary lining from the TBM's, because the extensive convergences didn't leave enough space for the inner lining.

These works almost took one year to complete, since not only the primary support was to be re-installed, but also the uplifted invert slabs had to be demolished and reconstructed. Both works didn't allow for any trains passing the area, so all traffic was concentrated to just one tunnel, which also had an impact on operations in Faido.

Finally in February 2008, the worms could recommence their work, and on June 24<sup>th</sup>, the last two blocks in each tunnel were cast followed by a short celebration to honour the moment.



Pic. 8 Inner Lining completed

Parallel to the worm works, a separate, much smaller 12m long shutter system was used to cast the inner lining of the drill-and-blast-areas, which had a different cross-section than the TBM profile, so the worms could not be used. This shutter also concreted the two assembly caverns which were then backfilled with gravel from the recycling plant. The so-called 'wurmino' (or 'small worm') finished on the same day as the worms, completing the inner lining works of the Bodio to Faido section.

Since July 2008, the western tube is closed to train traffic, and preparatory work is under way to enable the pipe-laying and concrete works for the walkways, which started in early September. They are scheduled to last 5 months, producing 150m of walkway on either side per day.

## 6. Cross Passages

The cross passages are situated every 300m connecting the two running tunnels. They are approximately 30m long with a cross section of 26m<sup>2</sup>. They are excavated as soon as possible behind the two TBM's, mainly because of two reasons:

- to keep escape routes from either TBM as short as possible
- to enable the tunnel ventilation system to work as properly as possible

The ventilation of the running tunnels works as a loop system, using the eastern tunnel as fresh air tunnel and the western tube as waste air tunnel. The fresh air is blown into the open cross section of the east tunnel until it reaches the third from last open cross passage behind the TBM's. Here, the air is taken up by a ventilation car in each tunnel, and transported via 2,2m diameter flexible ducts to both TBM's, the western TBM being served by a bypass via the cross passage.

The two last open cross passages behind the TBM's extract the used air, polluted from the eastern TBM and the cross passage excavation works, from the east tunnel, using ventilators that blow it into the western tube. Together with the polluted air of the western TBM, it flows, unfortunately through the western worm, to the west portal. Air inflow is kept as high as 150m<sup>3</sup>/s to achieve a minimum air speed of 0,5m/s in all sections of the tunnels.

To let the system work satisfactory, all cross passages have to be properly closed, nevertheless allowing passage via doors in case of emergencies. All doors are therefore electronically controlled and supervised by the guide office. Strangely enough, the doors near the worm west tend to be open a little more often than others.

The cross passages are excavated from the eastern tube by drill-and-blast methods using a drilling jumbo, a small wet shotcrete machine, a loader and a basket, all small size to be able to park them inside the running tunnel to let trains pass. The carriage for the installations, such as compressors, transformers, coolers, rescue containers, workshop etc. is 100m long and of the same design as the worm portal cars. One track serves as parking and loading area for the 5-car muck train, the other for passing trains to and from the eastern TBM. The excavated rock is loaded onto a conveyor belt that can be lowered hydraulically to track level, then dumped into the muck train. One train takes the rock from 2m of excavation, which is the usual round length except for the entrance area. For blasting, a special blast protection car is pulled in front of the cross passage to prevent damage from staff, installations and utility lines which are usually placed over the entrance of the passage.

Rock support measures range from simple rock bolting and wire mesh for head protection to heavy ring beam installation in fault zones. Depending on the extent of rock support, excavation of a cross passage takes two to three weeks, including casting of the invert concrete and installation of the preliminary wall to prevent free airflow. 3 shifts are working 8 hours around the clock during weekdays.

From September 2003 to June 2007, the crew excavated 46 cross passages, while the first 5 cross passages had already been excavated by the drill-and-blast contractor prior to the TBM drives.

Meanwhile, the team has started excavating the first of another 40 cross passages on the TBM section from Faido to Sedrun.

The installation of the water sealing membrane and the casting of the inner lining is done by the worm crews closely behind their installations. A small shutter of 10m length concretes the passage in 3 sections, while the intersection with the running tunnels is already cast with bolted-on shutters on the worm.



Pic. 9 Cross Passage Shutter

Today 50 of 51 cross passages in the Bodio section are lined with concrete.

## LOT 452 FAIDO

### 1. Scope of Works

The Faido lot with 15,1km is the second longest section of the Gotthard Base Tunnel. It is operated from a narrow installation area in the village of Polmengo, and comprises the following main sections:

- installation area including offices, accommodation for workers, concrete batching plant and workshops
- material deposit areas
- 3km exploration tunnel to verify rock conditions in the Piora Basin (excavated prior to main contract)
- 2,7km, 12% decline access tunnel to reach Base Tunnel level (excavated prior to main contract)

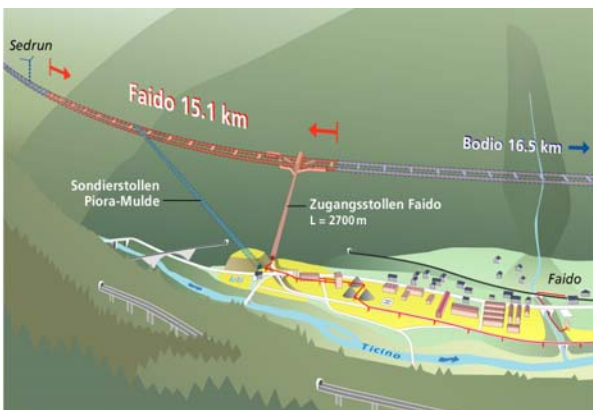


Fig. 13 Faido site installations [1]

Underground works for the multifunctional station (MFS) included:

- central cavern at the bottom of the access tunnel
- 2 x 2,2km of drill-and-blast excavation of running tunnels including two crossover caverns and four TBM disassembly and reassembly caverns
- 2 x 1km of rescue tunnels including 2 x 6 connecting passages to the running tunnels
- 2 x 500m of ventilation tunnels including 2 x 7 connecting shafts to the running tunnels
- several logistic caverns used during construction phase
- inner lining, walkways and cable ducts for the whole MFS
- excavation and inner lining of 2 regular and 4 logistic cross passages

As in Bodio two separate contractors for material recycling and wastewater treatment are on site.

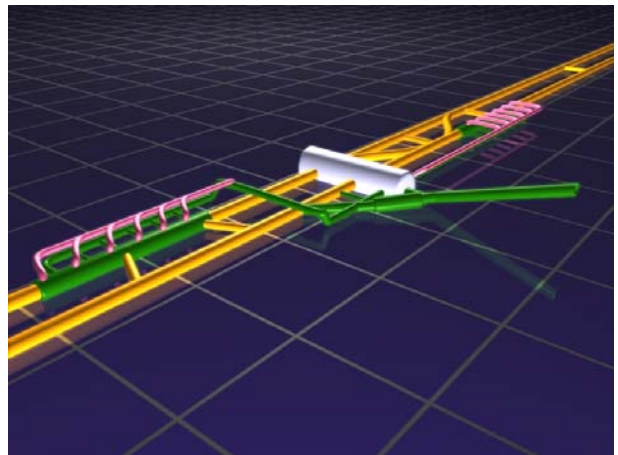


Fig. 14 3D-Layout of MFS

The cross sections for the MFS range from cross passage dimensions of 26m<sup>2</sup>, running tunnel dimensions of 70m<sup>2</sup>, to the huge cross sections of the central and crossover caverns with more than 200m<sup>2</sup>. All excavations except the TBM drives north of the MFS are performed with drill-and-blast techniques. In total 680'000m<sup>3</sup> of rock mass had to be excavated [3].

After arrival in Faido, the TBM's were transported to the northern end of the MFS to start their 12km long journeys towards the Sedrun lot.

The in-situ invert concrete slab inside the MFS, including main drainage and waste water pipes, was cast by the separated TBM trailer construction during the refurbishment of the main TBM body.

The inner lining will be a combination of in-situ cast concrete for the running tunnels, cross passages, central cavern and ventilations shafts, and sprayed concrete lining for all other tunnels and caverns.



## 2. Site Installations

After being awarded both lots, it was a logical consequence that the two TBM's from Bodio would also excavate the Faido lot, instead of purchasing two additional machines. That also decided that all main installations for the Faido TBM drives would remain in Bodio, and the narrow installation area at Faido would mainly be used for the drill-and-blast excavation of the MFS.

Some site installations in Faido could be taken over from the contractor that had previously excavated the access tunnel. Although the Holcim-Sika subcontract for concrete production was also valid for Faido, the **batching plant** including a 1,5m<sup>3</sup> mixer to load onto mixer trucks was taken over from the pre-contractor.

Due to the geological conditions encountered in the MFS and the following bigger quantities of shotcrete, the capacity was later increased. Until the end of drill-and-blast operations, the plant produced approximately 180'000m<sup>3</sup> mainly of shotcrete. The concrete was transported by mixer trucks to the different working sites inside the MFS.

Today the plant is closed down, only to be re-opened to produce concrete and shotcrete for the last phase of the inner lining of the MFS, after both tunnels from Bodio are closed.

The aggregates were to be recycled from the excavated rock by a separate contractor. Since the handover grain size was limited to 150mm, a crusher was installed at the bottom of the access tunnel. All material was then loaded onto a conveyor belt and transported to the recycling plant.

A washing area near the batching plant made sure that the trucks would be cleaned before re-loading or parking.

A **workshop** was established for the maintenance and repair of the machines used in the MFS. Next to them a **magazine** was built for distribution of spare parts, especially for the operating machinery, as well as tools and all necessary consumables.

The **container village** provides accommodation for approx. 500 workers, including a **canteen** and a **change house**. Today, the traditional miners have been replaced by TBM and concrete personnel, but there are still some 350 people living in the Faido camp during their shift times.

## 3. Logistics

The transport to and from the tunnel working areas was handled via the access tunnel with a decline of 12%, which made it difficult for heavy machines to reach the workshop at the surface. The problem was overcome, when the first logistic cavern was broken out and an underground workshop could be established.

Situated at the entrance to the access tunnel is a small version of the guide office at Bodio, mainly to control vehicles and personnel entering or exiting the tunnel, and to supervise the ventilation system and the cooling water circuit

Beginning with 3 headings from inside the central cavern, the number of headings grew steadily to finally 7 working sites, all due to unfavourable rock conditions.

At peak times the following heavy machinery was operating on site:

- 7 rocket boomers
- 5 excavators
- 5 shotcrete mobiles
- 9 dumpers
- 9 loaders
- 6 mixer trucks

Today, almost all of the equipment has left the site, with only shotcrete mobiles left for the later spraying of the inner lining.

During 2007, after excavation works had ended, the utility lines to serve the TBM's and worms were installed inside the access tunnel and the central cavern. Apart from the utilities, all transport of materials to and from the various installations will be furnished by Bodio logistics.

## 4. Excavation of the Multifunctional Station

Excavation started in the central cavern on March 6<sup>th</sup> 2002, followed shortly after by the excavations of the running tunnels to the north and south. The predicted geology was Leventina gneiss, with the border to the more ductile Lucomagno gneiss further north inside the planned TBM section. It soon turned out that the contact between these two geological formations ran right through the central cavern and the two crossovers, planned adjacent to it in the north and south. Being aware that the huge cross sections of the crossover caverns could not be realised in these conditions, the client re-designed the MFS by moving the complete crossover section approximately 600m to the south into better geological rock of the Leventina gneiss, thus extending the MFS by one third of its original length.

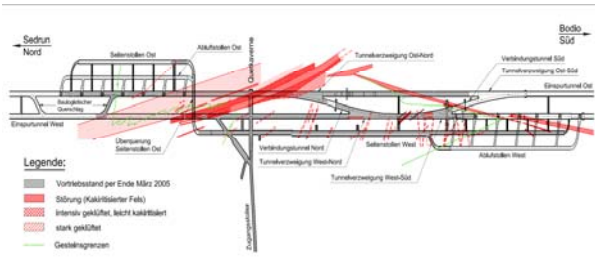


Fig. 15 Fault Zones inside MFS

Meanwhile, national safety regulations also called for an emergency ventilation system, including ventilation tunnels and shafts to connect with the running tunnels (see fig. 14 'pink' sections).

It was clear by then that the excavation of the MFS would take almost one year longer than planned, although attack points were increased from the original three headings to seven headings at peak times.

While the southbound headings made good progress, all excavation near or inside the multiple contact zones between the two geological formations was far from easy. The miners had to deal with radial convergences of 1m and more, which led to destruction of the primary lining, although massive steel ribs were placed and extensive anchoring carried out.

After almost complete destruction of some section of tunnel, paired with massive rock bursts causing 'mini' earthquakes up to 2,4 on the Richter scale, a new method of rock support had to be implemented to cope with the inevitable movement of the rock formation.



Pic. 10 Destruction of 'rigid' Rock Support

This new method was based on a flexible support system to the moving rock mass giving way to a certain extend, before building up resistance to establish a stable condition. Moving joints were built into the shotcrete shell, and flexible ring beams installed into an enlarged cross section which 'closed' down to the designed section

without being damaged. These so-called 'sliding joints' were later filled up with shotcrete should they not have closed completely.



Pic. 11 Re-profiling using 'flexible' Rock Support

The new method was implemented successfully, and today the whole multifunctional station of Faido is excavated, and well within stable conditions. With the last blasting of a ventilation shaft in April 2007, excavation works ended just in time to be able to transport the TBM's to their designated starting point in the assembly caverns at the north end of the MFS.

## 5. Re-Building and Revision of the TBM's

The contract conditions for Faido had originally foreseen the enlargement of the TBM's from 8,8m in Bodio to 9,3m in Faido, paying respect to the different geological conditions causing bigger convergences, and the need for stronger and therefore thicker rock support. The TBM's were supposed to be able to realize a diameter of 9,6m, using the same kind of overcutters as in Bodio. Learning from the experience of the first trials, it was decided to go without them, and instead design the cutterhead for 9,4m, with the possibility of shifting the gage cutters to achieve a diameter of 9,5m. The last 10cm to 9,6m would be achieved by limiting the driving accuracy to 5cm instead of the usual 10cm of allowed deviation.

Therefore, on arrival in Faido, the TBM's main bodies, basically the first 20m, were separated from the trailer construction and stripped off their diameter relevant parts, such as cutterhead, dust shield and grippers. They were then transported on special 22-axle-trucks along the 2,2km of the MFS to the assembly caverns, where the new parts had already been stored in the right assembly order. In addition to the above mentioned parts, also new main bearings were installed, while the gear boxes remained the same.

Meanwhile, the trailer constructions were separated to create space for 3 more trailers, since the bigger diameter would demand longer muck and concrete trains. When this operation was finished, the now 30m longer trailer construction was modified to move on its own along the whole length of the MFS with the purpose of casting the invert concrete slab along the way. Six months later, the trailer constructions reached the newly equipped TBM main bodies, having concreted 3 slabs or 30m of invert almost every day.

Connection of TBM main body and trailer construction took another three weeks, before, on July 7<sup>th</sup> 2007, just 10 months after arrival, the eastern TBM set off again for its 12km drive to Sedrun. The western TBM followed on October 12<sup>th</sup> 2007.

## **6. TBM Drives**

Soon after TBM restart, along came again the bad news for the TBM crews. The horizontal layers of the Lucomagno gneiss proved to be as difficult as in the MFS, causing large scale convergences already within the dust shield area. Multiple times, the eastern TBM was in danger of getting squeezed in, with the rock pressures slowly destroying the rock support in the rear areas. Additional hydraulic cylinders were installed, originally to measure the existing rock pressures, but they also helped keeping the machine steerable by pressing against the top shield.

Rock conditions called for heavy rock support measures, and the flexible system was soon invented on the TBM's as well, keeping ring beams and shotcrete shell from being destroyed completely. But the time consuming support measures kept the TBM from moving at a constant pace which was vital for her survival

Nevertheless, the eastern TBM could survive without any bigger damage, and in April 2008 finally reached the expected fold where the horizontal layers turned to vertical, and conditions became a lot better. Monthly advance rates increased from 180m to more than 500m, and even the 30m/day-barrier has been broken twice now.

No such good news for the western TBM, though. Knowing about the difficulties of the eastern TBM, her sister started out already using the flexible method, and using stronger ring beams to keep the dust shield from being squeezed in.

Since the running tunnels are 40m apart, it was common belief that there would be no reciprocal influence. After a couple of hundred meters, it was clear that this assumption was wrong, at least for the horizontal layered Lucomagno gneiss. Driving

through the same formations, the western TBM had to withstand higher pressures than her counterpart, although the stronger ring beams and the additionally installed hydraulic cylinders kept her from getting stuck at the dust shield.

The problem turned out to be the trailer construction, where convergences of more than 50cm occurred on the top section, while invert heave was more than 70cm. All this was discovered after the 2-week Christmas break of 2007/2008. When returning to work, the crews found the rock support along the first 80m behind the cutterhead almost completely destroyed, with ring beams bent or torn, and the shotcrete shell badly damaged.

At this point, it was obvious that the trailer construction at its narrowest parts would not pass this area, nor could the concrete invert slab be cast. Since most of the destroyed areas could not be reached easily, a temporary support using short anchors and dry rock shot was installed by hand in very narrow spaces. In the worst areas, ring beams had to be cut to allow the trailers to pass.

In front of the casting area for the base slab, excavation operations started to lower the heaving invert, first anchoring the ring beams on the sides before cutting them. Luckily, the rock could be loaded by a small excavator without being blasted. The excavation was about 1m deep, and was anchored heavily immediately after by a small drill rig. The invert slab was then concreted without any further heave occurring. At the same time it was decided to anchor the invert right behind the dust shield to prevent further heave.

Although the invert could now be cast, the cutting of the ring beams led to further convergences in the top section. The trailers had to be modified, and installations to be moved to pass underneath the 'collapsing roof'. Though knowing that the movements would finally come to rest, it was a race against time for the western TBM. Due to the intensive re-profiling operations in the back, the TBM could only achieve advance rates of 2 to 4m per day.

Today, the TBM west has passed the worst areas, and works at a steady pace of 8 to 10m per day, approaching the vertical layers of the Lucomagno gneiss.

Although the eastern TBM got through the difficult section more easily, her work is still in danger of destruction by the drive of the western TBM, which causes convergences and invert heave in the already finished east tube. Here, bending of ring beams and destruction of the shotcrete shell occurred in sections that the eastern TBM had long since passed. Additionally, the invert heave in



some sections was more 30cm, causing not only the necessity to demolish and reconstruct these uplifted slabs at a later stage, but also a remarkable disruption of train traffic. Train speeds had to be limited to 5km/h, while the trains usually travel at speeds of 25 to 30km/h.

The worst section in both tunnels with a combined length of approximately 500m will have to be reconstructed. With the inner lining works approaching, these works will have to be carried out while the TBM's are still running, necessitating the construction of diagonal logistic cross passages enabling trains to pass the re-profiling works.

### **FUTURE CHALLENGES**

Looking into the near future, the eastern TBM will soon be reaching the Piora syncline, once thought of as the key to success or failure of the whole Gotthard project. On the surface, the Piora syncline consists of sugar dolomite, which, in contact with water, acts like cube sugar flowing uncontrolled especially under high water pressure.

To find out if this material would also be present on base tunnel level, an exploration tunnel approximately 300m higher than the base tunnel was bored starting in 1993. When it approached the Piora syncline, temperatures in the tunnel dropped significantly giving first indications of cold water flowing nearby. Preventer-protected horizontal test bores showed that on exploration tunnel level, the sugar dolomite was still present, with water pressures up to 150bar. But when test bores were carried out to the base tunnel level, they showed solid rock without any water pressure. Nevertheless, the TBM's won't pass this section without precaution. They will be stopped 100m in front of the affected zone, and a 300m long preventer-protected core drilling will be bored to explore the exact extent of the zone, which is predicted to be approximately 120m wide. The result will determine not only any additional measures to be taken, but also the remaining construction time of the project. The core drilling from the eastern TBM is due to be executed in September 2008.

Should the Piora syncline appear as predicted, breakthrough of both TBM's, and therefore completion of all excavation work on the whole project, is expected at the end of 2010.

The worms which have now reached the multifunctional station, are currently being refurbished before lining the regular running tunnel cross sections in the MFS while passing through it. It will be vital to keep them as close as possible behind the TBM's due to high penalties that come into effect, if the inner lining is not finished four

months after breakthrough of the second TBM at Sedrun.

The inner lining of the MFS will start in spring of 2009, and is planned to be finished in 2012. The works will be executed mostly parallel to the TBM drives and inner lining operations of the running tunnels, thus giving an extra challenge for logistics concerning coordination of transport, materials and manpower.

Another challenge will be the cooling and venting of all working sites underground. Rock temperatures are expected to rise to 55°C, with heat produced by the installations and train traffic adding to the problem. Coolers will not only be installed on the installations, but also in the tunnels, to keep a steady work temperature of 28°C at all times. 66 air coolers will be installed with a total required power of 22MW. To operate both coolers and ventilation, 300m<sup>3</sup>/second of fresh air and 800m<sup>3</sup>/hour of water are pumped underground. The reliability of these installations will be a key factor for the success of the joint venture.

### **SUMMARY**

When going into operation in 2017, the Gotthard Base Tunnel will be the longest railway tunnel in the world. Yet there are many milestones to be reached, challenges to be met, and problems to be solved before the first train passes. Some of the rock conditions of the yet to be excavated sections are still unknown, while logistic operations as well as handling of high temperatures are reaching new dimensions, bringing the responsible staff and the underground workforce to its limits.

As always, the key to success is teamwork. The two 'operational' departments, TBM drives and inner lining, have to rely on the so-called 'service' departments, technical office, logistic and mechanical department, to be able to reach the high-set goals. Good relations to the client, the supervisor and the project engineer are vital to keep the project on track.

And not to forget the holy Barbara, the saint of all miners, who always has her place at the entrance of the tunnel, protecting the workers from all evil, and giving them the spirit to finally reach the ultimate goal of all tunnelers: Breakthrough and light on the far side of the tunnel!

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