Gotthard base tunnel, Switzerland – the world's longest railway tunnel

Renzo Simoni DSc Civil Engineering
AlpTransit Gotthard AG, Lucerne, Switzerland

When it opens in 2016 the 57 km long Gotthard base tunnel under the Swiss Alps will be the world's longest. Together with the 15 km Ceneri base tunnel to the south, which will open 3 years later, it will provide a virtually flat railway across Switzerland. The tunnels aim to reduce significantly the amount of environmentally damaging lorry traffic crossing the country between Germany and Italy as well as cut north–south passenger train journeys by 1.5 h. This paper reports on the background to the £7 billion project, describes the design and construction of the twin-bore tunnel and its sophisticated railway systems, and summarises lessons learned from over 10 years of tunnelling in hard rock up to 2.5 km underground.

1. Introduction

With construction of the Gotthard rail link, Switzerland is creating transport history. The two base tunnels under the Gotthard pass and Monte Ceneri – hundreds of metres lower than existing Alpine tunnels – are not only a pioneering engineering achievement, they also symbolise the materialisation of a nation's will. As long ago as 1992, Switzerland's voters authorised the new rail links through the Alps under the Gotthard pass and Lötschberg to the west (AlpTransit Gotthard AG, 2002, 2011). In a further referendum in 1998, they endorsed the public transport finance fund to secure financing of these major Swiss railway projects.

The Gotthard base tunnel, at 57 km the world's longest railway tunnel, will go into operation in 2016. In 2019, the virtually flat route through the Alps – rising no more than 550 m above sea level – is scheduled to be completed with the Ceneri base tunnel to the south (Figure 1). This will restore the competitiveness of rail transport over road transport, and passenger traffic will benefit from substantial time savings.

Switzerland broke new ground with regard to organisation and supervision of the Gotthard and Ceneri tunnels. Whereas during the feasibility study phase, project leadership was with the Federal Office of Transport (FOT), at the beginning of the works preparation phase responsibility transferred to Swiss Federal Railways (SBB). In a further step, in 1998 AlpTransit Gotthard Ltd was established as a wholly owned subsidiary of SBB to design and construct the two 'Gotthard axis' tunnels.

The most important and direct contact partner for AlpTransit Gotthard Ltd is the FOT as supervisory body. The federal parliament, as ultimate political overseer, is regularly informed on progress. SBB AG is technically the strategic and operational supervisor of AlpTransit Gotthard Ltd but refrains from exercising undue influence. SBB as the ultimate operator will receive a

Figure 1. The new nearly flat route through the Alps runs from Altdorf to Lugano

Figure 2. Organisation model of new rail link through the Alps Gotthard axis

fully operational turnkey railway system which can be integrated into its existing network. To attain this goal, close collaboration is necessary during design and construction.

The organisational model (see Figure 2), which is being used by the federal government for the first time, has generated significant interdisciplinary knowledge and experience. The following features have made it a success

- direct and simple management and control by the client (FOT)
- transparency through direct parliamentary oversight and control

Construction of the tunnel required highly diverse rocks to be traversed, ranging from hard, massive granites to gneisses and soft, sometimes flaky rocks

- clear boundaries between the roles of client, constructor and operator
- efficient project execution thanks to a lean organisation with short communication paths and simple decision processes.

2. Tunnel design and construction

The Gotthard base tunnel runs from Erstfeld in the canton of Uri to Bodio in the canton of Ticino. Construction of the tunnel required highly diverse rocks to be traversed, ranging from hard, massive granites, through gneisses with varying degrees of foliation, to soft and sometimes flaky rocks.

The tunnel was designed with two single-track bores, which are linked to each other every 325 m (AlpTransit Gotthard AG, 2010, 2011). Situated at the one-third points in Sedrun and Faido are multi-function stations, which contain emergency stopping points and other installations (Figure 3).

For 250 km/h line speed, SBB specified structure gauge EBV 4 (corner height 4.2 m). The bores were excavated at 9.2 m

Figure 3. The tunnel system under the Gotthard pass

diameter and the completed internal tunnel diameters are around 7.7 m.

An important goal when planning the tunnel was to optimise total construction time to minimise costs. The tunnel was therefore divided into five sections, which for some of the time were constructed simultaneously: Erstfeld, Amsteg, Sedrun, Faïdo and Bodio.

Around 80% of the tunnel was excavated with tunnel boring machines (Erstfeld, Amsteg, Faïdo and Bodio) and 20% by drilling and blasting. The average daily advance rate for tunnel boring machines was around 12 m, while for blasting in favourable rock it was 4 m and in unfavourable rock 1 m.

2.1 Erstfeld

The Erstfeld section is 7.8 km long and the first 600 m were constructed by the cut-and-cover method. Branch-offs in the tunnel ensure that a future extension of the tunnel to Brunnen, in the canton of Schwyz, is possible without interruption of operations. At Erstfeld the tunnel passes under parts of the village at a relatively shallow depth (7–8 m). For reasons of noise and vibration prevention, only driving by tunnel boring machine was possible.

Since contractor ARGE AGN (a joint venture of Strabag and Züblin Murer) was also awarded the contract in Amsteg, after a brief overhaul one of the tunnel boring machines from Amsteg was deployed again at Erstfeld. Driving began in December 2007 and was completed in September 2009, 6 months earlier than planned.

2.2 Amsteg

Before driving work could begin on the approximately 11 km long Amsteg section, a 1.8 km long access adit had to be constructed. A 1.8 km long cable tunnel was also created, which leads directly into the underground centre of the Amsteg power station.

The two tunnel boring machines started out from Amsteg in October 2003 and January 2004 respectively. Breakthrough of the east bore took place in October 2007. In the west bore in June 2005, water ingress washed loose material into the cutter head and blocked it. In parallel with 2800 m of injection bores, a reverse drive was cut from the east tunnel. In mid-November 2005, the miners succeeded in releasing the cutting head and, in mid-December 2005, the tunnel boring machine could resume driving. Despite the temporarily blocked cutter head, breakthrough to Sedrun took place 6 months ahead of schedule at the end of November 2009.

Since then, contractor ARGE AGN has removed its plant and equipment and the site has been largely recultivated (Figure 4).

2.3 Sedrun

The 8.5 km long Sedrun section is only accessible through a 1.5 km long access adit and two 800 m deep supply and hoisting shafts. This situation presented a special challenge to construction

The Sedrun section is only accessible through a 1.5 km long access adit and two 800 m deep supply and hoisting shafts, presenting special challenges

Figure 4. The installation site at Amsteg (a) during and (b) after the main works

operations and logistics, since enormous quantities of materials had to be transported through the two shafts. The lift system also served to transport around 150 miners per shift.

In addition to the difficult logistical situation, the rock conditions in this section presented a major challenge. The geologists forecast extremely difficult rock conditions, which would only allow drill and blast. From the bottom of the shaft at Sedrun, the four drives proceeded simultaneously 2.1 km northwards and 6.5 km southwards. The excavation work also included creation of one of the two multi-function stations.

To the north, the constructionally difficult Tavetsch Intermediate Massif and Clavaniev Zone had to be penetrated. To absorb the large squeezing movements of the rock, deformable steel rings were installed (Figure 5). Thanks to the construction method that was used, the excavation work was completed 6 months ahead of schedule in autumn of 2007.

When driving to the south, rock conditions turned out to be more difficult than forecast. Numerous fault zones were more extensive than expected. Here, too, deformable steel rings were used in some cases. Final breakthrough of the east bore took place in October 2010, followed by the west bore in March 2011.

Construction work in the Sedrun section is now complete. The large storage halls and numerous container buildings on the site have been removed and part of the site will be turned into a wetland.

Figure 5. Installation of deformable steel arches was required to resist the massive rock pressures

2.4 Faido

The Faido section is approximately 15 km long. In this section, too, one of the two multi-function stations was constructed in addition to the tunnel bores. Before work on the tunnel bores could begin, a 2.7 km long access adit was excavated. The adit, as well as the multi-function station, was cut by drilling and blasting.

The Faido and Bodio sections were both awarded to the Consorzio TAT (a joint venture of Alpine Mayreder Bau, CSC Impresa Costruzioni, Hochtief and Implenla and Impregilo) because of the close logistical links and an advantageously priced tender. As a result, only two tunnel boring machines were used for the entire distance from Bodio to the boundary of the Sedrun section.

Work in the Faido section was challenging: difficult geological conditions had to be overcome at a rock depth of up to 2500 m. In the area where the multi-function station was originally planned, the steel beams that were installed could not withstand the pressure from the rock. Extensive repairs to this area were necessary. In the southbound drive, unexpected earth tremors occurred. The unfavourable geological conditions caused a delay in the construction schedule.

The northward drive also presented a major challenge. In the areas of heavily squeezing rock, extra-strong supports were used. Despite these measures, in January 2008 in the west bore, the back-up train of the tunnel boring machine became trapped. Various items of equipment had to be removed or relocated, in some places shotcrete had to be chipped off laboriously by hand and steel rings had to be partly removed.

The tunnellers crossed the Piora Zone in only 14 days. However, in the Medels granite that followed, the tunnel boring

The Faido section was particularly challenging: the steel beams could not withstand the pressure from the rock, causing the back-up train of the tunnel boring machine to become trapped

machines suffered heavy wear, and intensive overhauls lasting several weeks were needed. At the beginning of March 2010 in the west bore, a rock fall caused driving to be interrupted for several months.

In October 2010, the first final breakthrough was celebrated between Faido and Sedrun in the east bore (Figure 6). In March 2011, the last final breakthrough of the Gotthard base tunnel took place in the west bore. In September 2013, all of the underground built structures were handed over and in January 2014 the construction site was closed and removed.

2.5 Bodio

The Bodio section is approximately 15 km long. Before the tunnel boring machine could start its work, various preparations had to be made. A 3.1 km long spoil tunnel was constructed for environmental disposal of the excavated rock.

The first 800 m of the tunnel passes under the area of the Ganna di Bodio landslip. A total of 420 m of this section was driven by the so-called crown method. The remaining 380 m was constructed as a cut-and-cover tunnel. At the same time, a 1.2 km long bypass tunnel made it possible to blast both assembly caverns for the tunnel boring machines and the first few metres of the main bores.

Figure 6. On 15 October 2010, the miners from Faido and Sedrun celebrated the final breakthrough of the Gotthard base tunnel

Although the geological forecasts indicated that the section would be constructionally favourable, soon after the tunnel boring machines started out they encountered an unexpected fault zone. In March 2006, a further unexpected fault zone caused the tunnel boring machine in the west bore to become jammed. Only after the cutter head had been roofed over, which took 10 days, could driving work continue. The high rock pressure caused deformations in the excavation support, which made extensive reprofiling work necessary.

In the autumn of 2006, breakthrough to Faido took place in both bores.

2.6 Overground sections

The northern approach to the tunnel comprises a 5 km long overground track south of Altdorf railway station in the canton of Uri along with all of the necessary structures. At the southern end, there is a 7.5 km long overground section extending from the south portal to Biasca.

Both overground sections were handed over to the railway systems contractor in September 2013.

3. Spoil processing

Building the Gotthard base tunnel involved excavating 28.2 Mt of rock from 152 km of tunnel bores. Managing this huge volume of excavated material presented an enormous challenge, which could only be mastered with innovative technologies and sophisticated logistics and organisation.

The main goal of spoil processing was maximum recycling of the excavated rock with minimum environmental burden. Spoil management should also not become a performance-determining factor. Around 33% of the excavated rock was suitable for use as aggregate for concrete and shotcrete within the tunnel. Unsuitable material was used for embankments, landfilling and site restoration, as well as further projects such as the creation of bathing and nature-reserve islands in Lake Lucerne.

Removal of the excavated rock, and the supply of aggregate for concrete and shotcrete production, had to be assured at all times. The excavated rock was classified according to its suitability for recycling while it was still at the tunnel face. Where excavated material was transported in the tunnel by conveyor belt, it was mechanically crushed before being loaded onto the conveyor. Where the material was transported by mucking trains, it was preliminarily fragmented after the wagons were emptied. Suitable

Experience on the Gotthard base tunnel demonstrates that spoil-management systems must be generously dimensioned, since forecasts of quantities and recyclability of excavated materials are highly uncertain

material was processed for recycling in the gravel-making plants on the surface sites.

The experience gained on the Gotthard base tunnel demonstrates that all spoil-management systems must be generously dimensioned, since the forecasts of the quantities and recyclability of the excavated material are subject to great uncertainty. The forecasts depend heavily on the rock conditions that are encountered and can fluctuate enormously and extremely rapidly. If spoil processing is not to become a limiting factor, the systems must be dimensioned for peak rather than average values.

4. Progress and methods

The original construction schedule of 2002, when the main contracts were signed, shows that the opening date has been delayed by 2 years. This is attributable to a project-related delay in the start of construction in all sections and further major deviations in the Erstfeld, Sedrun and Faido sections.

In the Erstfeld section, difficulties in the planning-approval and contract-award processes caused a major difference between the planned and actual start of work. In the Sedrun section, relocation of the lot boundary extended the length of the southward drive by 4 km and thereby increased the construction time for this section. In the Faido section, the delay relative to the original construction

schedule resulted mainly from the difficulties in driving the multi-function station.

The choice of driving method determined the advance rate. AlpTransit Gotthard Ltd only stipulated the driving method in those cases where compelling reasons, such as problems with vibrations or rock conditions, allowed only the tunnel boring machine method or only drill and blast. In all other cases, the choice of driving method was left to the contractors. In retrospect, it can be said that this principle proved its worth and the selected driving methods were the right ones.

Even in unfavourable conditions, the tunnel boring machines attained good average daily advance rates, which matched the drilling-and-blasting advance rates. The high flexibility of drilling and blasting proved valuable in the geologically difficult sections and allowed rapid adaptation of the excavated cross-section and the supporting means that were employed. Excavation of the multi-function station at Faido would have been impossible without drilling and blasting.

5. Tunnel infrastructure systems

The mechanical and electromechanical equipment in the tunnels provide a life-saving environment as well as ensuring the permanent functionality of structures. Most of the tunnel infra-

Figure 7. Installing a track-crossover door, weighing approximately 20 t, in the multi-function station at Sedrun

structure systems are installed in the cross-passages and two multi-function stations, with the remainder being in the tunnel bores and portal areas.

In each of the multi-function stations at Sedrun and Faido there are two track crossovers, which allow trains to change over from one bore into the other. The track crossovers are fitted with large doors, which in normal and emergency operation are closed and serve to separate the two tunnel bores aerodynamically (Figure 7). During maintenance work, the track-crossover doors can be opened to allow trains to pass.

The emergency stop stations at Sedrun and Faido are also closed with doors. If a burning train arrives, the doors can be remotely opened from the control centre. The ventilation system blows fresh air into the stations through the side passages and the open doors. 'Bubbles' of fresh air then form in front of the doors.

In all operating modes, fresh air is blown into the multi-function stations through shaft 1 at Sedrun. Various cables and water pipelines also pass through this shaft. So that the shaft as well as the systems that are installed in it can be inspected, and minor maintenance and repair work carried out, a hoisting system has been installed. All technical rooms in the auxiliary structures, such as the railway systems buildings at Amsteg, must be air-conditioned and are therefore equipped with cooling and ventilation systems.

The 176 cross-passages in the tunnel form protected spaces to accommodate the railway systems and, in case of an incident, also serve as evacuation routes into the unaffected bore. Before the railway systems were installed, the cross-passages were fitted with various tunnel infrastructure systems.

The doors of the cross-passages must fulfil various functions: in normal operation they close off the cross-passages from the railway bores, in case of an incident they serve as evacuation doors and during the rescue phase they must prevent the fire from spreading to the other tunnel bore (Figure 8). The construction of the doors is correspondingly robust. In addition, the doors can be opened manually and with little effort.

Ventilation of the cross-passages ensures that in normal operation the temperature does not rise above 35°C. In case of fire, the ventilation prevents the cross-passages from overheating for 90 min, so that the installed systems and electrical enclosures remain functional.

Figure 8. In normal operation, the cross-passage doors close off the railway bores; in case of an incident, they serve as evacuation doors

At Bodio, the rock water emerges with a mean temperature of 27°C. It therefore needs to be cooled in ponds, towers and a 350 m long canal before being discharged into the Ticino river

In normal operation the Gotthard base tunnel is not actively ventilated, since sufficient air is sucked in by the piston effect of the trains. The operational ventilation performs the task of creating the necessary tunnel climate for maintenance work and, in case of an incident, preventing smoke from spreading from the affected bore into the adjacent bore.

In addition to the two ventilation centres in the shaft head at Sedrun and at the portal of the access adit in Faido, the operational ventilation also includes six jet fans close to the portals in each of the bores, making a total of 24 fans. In addition, the entire ventilation system is designed with 100% redundancy.

With regard to drainage, the constantly accumulating rock water is fed into a main drainage pipeline. From there, it drains to the surface where it is collected. At Erstfeld, the mean temperature of the rock water is only 13°C, so no cooling is necessary and the water can be drained directly into rivers. At Bodio, the rock water emerges with a mean temperature of 27°C and therefore flows first into cooling ponds or cooling towers. From there it flows by way of a 350 m long cooling canal into the Ticino river.

Drainage from the two multi-function stations, the two shafts at Sedrun, the access and cable adits and the railway track flows through a separate drain to the portals, where it is channelled into retention basins. If this tunnel water fulfils the relevant quality criteria, it is drained into the water purification plants, otherwise it is removed for treatment by road tankers.

For the fault-free operation of all systems, the tunnel must be supplied with sufficient industrial water. The ventilation and cooling systems in the technical rooms require water cooling with a constant flow of 5 l/s. In addition, in each bore of the two multi-function stations at Sedrun and Faido, there is a water-siphon point for pressurised filling of the Swiss Federal Railways fire-fighting and rescue train. The industrial water supply is obtained from the naturally occurring rock water and – if necessary – from water from the surrounding power stations and local potable water supply.

7. Railway systems

Installation of the railway systems in the Gotthard base tunnel is a complex and challenging task. Good coordination between the tunnel structure and the railway systems, as well as a flexible installation plan, are crucial. Access for installation is restricted, since the only practical access points are the portals. The long transportation distances and limited space call for sophisticated

logistics. Since tired vehicles cannot turn inside the tunnel, virtually the entire railway infrastructure is being installed by rail. The first step was therefore to install the railway track, with other activities following on afterwards.

The trackbed laid in the Gotthard base tunnel is ballastless, which has significant advantages over a ballasted trackbed. Its lower height and increased positional stability reduce maintenance outlay and provide a smoother ride. Around 220 m of track were installed per day by a concreting train (Figure 9).

The mixed passenger and goods traffic through the tunnel will make heavy demands on the traction power supply and catenary systems. For example, the maximum speed of 250 km/h for passenger trains calls for an overhead conductor that is as light as possible, whereas the high currents that are needed for heavy goods trains require a large conductor cross-section. The optimal solution is provided by a conventional catenary conductor system.

All 16.7 Hz railways in Switzerland obtain their energy from a central high-voltage network, which is mainly operated at 132 kV. For the Gotthard base tunnel, a total of five substations have been newly built or enlarged. The 50 Hz power supply in the Gotthard base tunnel must fulfil extremely high requirements regarding safety and availability. The power is therefore supplied from three largely independent high-voltage networks north and south of the Alps. Power is fed in at five points, at each of which two diesel generators ensure an uninterrupted power supply.

The railway systems are very highly automated. An extremely reliable system for information transmission is therefore needed. An important role is played by the fixed-line communication, which links the various components of the railway systems in the tunnel to an integrated whole. Mobile communication systems are used for operational purposes, and passengers travelling through the tunnel will have access to the mobile telephone network of public providers.

Safety systems include the European train control system level 2 electronic cab signalling system, which is standardised throughout Europe. This and other safety systems will control and monitor the movements of the train, combining signals, free-track reporting systems and points movements. The track control system links the safety systems to the other systems as well as the overarching control and operation centre. All operations on the

Figure 9. Around 220 m of ballastless track were concreted per day with the concrete train

Gotthard axis between Arth-Goldau and the Italian border will be controlled from the Pollegio control centre.

8. Commissioning

In mid-December 2013, commissioning of the Gotthard base tunnel began with the first pilot runs. An approximately 13 km long pilot section in the west bore between the south portal at Bodio and the multi-function station at Faido was completely fitted out with the necessary tunnel infrastructure and railway systems and trains successfully ran at up to 220 km/h. Completed in June 2014, the pilot operation phase confirmed that the entire tunnel system met the specified requirements.

From October 2015, the full length of the tunnel will be opened for test operation at speeds of up to 280 km/h, prior to full opening to traffic in December 2016.

9. Ceneri base tunnel

Only with completion of the 15.4 km long Ceneri base tunnel in late 2019 will the seamless flat route through the Alps become reality. Like the Gotthard base tunnel, the Ceneri base tunnel also consists of two single-track bores which are linked together every 325 m by cross-passages. Because of its shorter length, no track crossovers or multi-functional stations are needed. The Ceneri base tunnel is being excavated entirely by drilling and blasting, the maximum depth of overlying rock is 900 m.

When planning the construction work for the Ceneri base tunnel, special attention had to be given to its closeness to the surface at some points, the densely populated areas adjacent to the portals and the crossings under and over major traffic routes. For these reasons, the greater part of the tunnel bores is being excavated from Sigririno, which is located at approximately the mid-point of the tunnel. From here, driving is proceeding towards the portals in both directions. Driving also took place inwards from the two portals.

AlpTransit Gotthard Ltd awarded the main contract to the Consorzio Condotte Cossi consortium in June 2009. Blasting started in 2010 and excavation should be complete by 2015.

References

- AlpTransit Gotthard AG (2002) *Gotthard Base Tunnel – The World's Longest Railway Tunnel: The Future Begins*. Stämpfli Verlag, Berne, Switzerland (in German and Italian only).
- AlpTransit Gotthard AG (2010) *Gotthard Base Tunnel – The World's Longest Railway Tunnel: The Construction of the Century Takes Shape*. Stämpfli Verlag, Berne, Switzerland (in German and Italian only).
- AlpTransit Gotthard AG (2011) *AlpTransit Gotthard – New Traffic Route Through the Heart of Switzerland*. AlpTransit Gotthard Ltd, Lucerne, Switzerland. See http://www.alptransit.ch/fileadmin/dateien/shop/broschueren/atg_broschuere_e_2012_lq.pdf (accessed 04/08/2014).

What do you think?

If you would like to comment on this paper, please email up to 200 words to the editor at journals@ice.org.uk.

If you would like to write a paper of 2000 to 3500 words about your own experience in this or any related area of civil engineering, the editor will be happy to provide any help or advice you need.