Gotthard Base Tunnel -
core of the new railway line through the Alps

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Abstract

Today, Switzerland is realising its most ambitious transalpine railway project – the so-called AlpTransit Project. It is the key element of Switzerland’s commitment to construct an efficient pan-European high-speed railway network. The project underlines also the political will of the Swiss people and the government to shift the transport of goods from the road to the rail for the purpose of environmental protection and sustainable development.

The key piece of AlpTransit is the 57 km long Gotthard Base Tunnel. After its completion, the Gotthard Base Tunnel will be the longest railway tunnel in the world. Due to its length, the high overburden (up to 2500 m) and the complicated geology, this tunnel is regarded as the most challenging tunnel project ever undertaken in Switzerland’s tunnel history.

The paper reports on the Swiss transport policy and the constructional challenges of the Gotthard Base Tunnel.

1. Swiss Transport Policy

In Europe, more and more people and goods are crossing the Alps. According to a study recently published by the EU Commission, the goods traffic through the Alps in 1998 were accounted to around 90 million tons by road and rail, 30% of the goods were transported through the Swiss Alps.

To guarantee sustainable transport in a long-term vision and to preserve the environment, the Swiss people approved in several votations the policy for the Protection of the Alpine Region from Transit Traffic.

Today, Switzerland is realising its most ambitious transalpine railway project – the so-called AlpTransit Project. The project underlines the political will of the Swiss people and the government to shift the transport of goods from the road to the rail for the purpose of environmental protection and sustainable development. It is also the key element of Switzerland’s commitment to construct an efficient pan-European high-speed railway network. AlpTransit is the mark of quality for the new high-performance railway lines through base tunnels underneath the Gotthard and the Loetschberg mountains. The key piece of AlpTransit is
the 57 km long Gotthard Base Tunnel on the Gotthard axis. Due to its length, the high overburden (up to 2500 m) and the complicated geology, this tunnel is regarded as the most challenging tunnel project ever undertaken in Switzerland’s tunnel history.

2. Project finance and Project Organisation

The key point of Swiss Transport Policy is to shift the goods transport by road in transit through the Swiss Alps on rail for the purpose of sustainable transport development and environmental protection. To promote the combined transport and sustainable development, the Swiss government elaborated a program, which is built up on:

- a heavy vehicle tax, calculated on the maximum permissible weight, kilometers run, emissions and consumption of the vehicle;
- a road transit tax on heavy vehicle traffic through the Alps (tax on Alpine Transit);
- financial aids for construction of two new transalpine railways on the Gotthard axis and the Loetschberg axis for attractive transport service through the Swiss Alps.

Based on the above financing plan, around 30 billion Swiss francs have be raised and invested.

To manage and coordinate the design and construction works for the Gotthard Base Tunnel, special legal units – AlpTransit Gotthard Ltd. and AlpTransit Loetschberg Ltd were established.

2. Planning and Construction of the Gotthard Base Tunnel

The Gotthard Base Tunnel is the key object of the new transalpine railway project.

The Gotthard Base Tunnel is designed as a deep level railway link to allow high-speed passenger trains to travel at speed of 250 km/h and freight trains at speed of 140 km/h through the Alps.

The horizontal alignment of the Gotthard Base Tunnel is curved, having to consider the safety distances to reservoirs above the base tunnel, the height of the overburden as well as the possibility to install intermediate headings. In addition, geological conditions had to be considered in the attempt to avoid difficult geological formations or to traverse such zones at minimal expansion.

Based on intensive investigations with regard to constructional aspects, traffic capacity, facility maintenance, safety, construction and operational costs, as well as comprehensive risk analysis in relation to costs and duration of the construction, the tunnel has been outlined as two parallel single-track tunnels without service tunnel, but with two multifunctional stations and with cross passages at regular intervals. At multifunctional stations, there are lateral and evacuation galleries, crossovers and technical rooms which are provided with fresh air in the case of an emergency and permit immediate escape and evacuation of passengers from the tunnel. Via crossovers, trains can change from one tube to the other.

The 57 km long tunnel required special consideration in regard to an efficient construction and for a sufficient ventilation under traffic. In order to achieve an acceptable over-all construction time, intermediate points of attack were conceived. These intermediate points of attack do not
only fulfill functions as additional points for tunnel heading, but also as ventilation in- and outlets once the tunnel is under traffic.

The intermediate points of attack have been topographically arranged to divide the tunnel into roughly equal long sections and to allow geological difficult sections to be dealt with at an earlier stage of the realisation of the tunnel. The intermediate points of attack are the following:

- Erstfeld: northern portal;
- Amsteg: a 1.2 km long horizontal access tunnel;
- Sedrun: two 800 m deep vertical shafts of approx. 8 m diameter, accessed through a horizontal access tunnel of approximately 1 km length, an additional shaft which extends from the head of the blind shaft to the surface will serve as ventilation during operation. A multifunctional station is situated at the foot of the blind shaft;
- Faido: a 2.7 km long inclined tunnel with a 13% gradient and a height difference of 330 m. A multifunctional station is situated at the end of the inclined tunnel;
- Bodio: southern portal.

Fig. 1 shows the layout of the Gotthard Base Tunnel

![Fig. 1: Layout of the Gotthard Base Tunnel](image)

The base tunnel passes through mostly crystalline rock formations which are intersected by a few narrow sediment zones. One can distinguish between three main igneous formations of crystalline rock: the Aar massif in the northern part, the Gotthard massif in the central part, and the Penninic gneiss in the south.

Between the main crystalline formations, a few narrow sediment zones are embedded which were squeezed between the massifs.

At the Gotthard Base Tunnel the two zones of the Piöra Basin and the Tavetscher Massif have been regarded to be the most difficult zones to drive through. Therefore, it was decided at a very early stage of the project to carry out geological investigations in both zones.
In the Tavetscher Massif investigation drillings were lowered from 1991 to 1998. The exploration works for the Piora Basin saw the construction of an investigation gallery and drillings at its end also. These investigation works started 1993 and were finished 1997.

Fig. 2 illustrates the geological profile.

![Geological Profile](image)

Over major sections of the tunnel, the overburden is extremely high. 35 km of the tunnel have an overburden of more than 1000 m, 20 km more than 1500 m, and 5 km reach more than 2000 m. The maximum overburden amounts up to 2300 m.

In addition to the geomechanical effects of the high overburden, rock temperatures reached up to 45°C. The high rock temperatures together with heat generated by the machinery required air conditioning to be installed during tunnel construction.

Most sections of the tunnel were excavated using Tunnel Boring Machines (TBM). In sections Sedrun where the rock conditions are poor, a conventional drill & blast tunnelling method was applied.

Fig. 3 shows the cross section design for the TBM bored section. The tunnel lining is based on a two-shell support system secured with shotcrete and reinforced with mesh, rockbolts and, if necessary, steel supports and a membrane seal. This membrane will be attached to the vault drainage pipes with a cross-feed to the main drainage at 100m intervals.
4. Material management as part of sustainable development policy

Apart from the measures considered for protection of environment such as noise, water pollution and landscape, special consideration was made to the handling of the excavated materials. The concept adopted for the Gotthard Base Tunnel with respect to the material management of excavated materials represent a very important chapter of Swiss sustainable development policy.

The 57 km long Gotthard Base Tunnel produced totally 24 million tons of excavated materials. Special concern was paid to the deposit of the excavated materials at a very early stage of the planning. The concept adopted is to re-utilize the excavated materials as concrete and shotcrete aggregates and put them back into the tunnel again. In this way, 25% of the excavated materials could be directly adsorbed from the tunnel site.

5. Challenges in Tunnel Construction

During the construction of the Gotthard Base Tunnel several geotechnical challenges were encountered. Beside various occasions when the TBM was trapped in fault zones of different geological nature squeezing conditions and brittle failures in the form of rockbursts are to be mentioned.

In the squeezing rock conditions of the Tavetsch intermediate massif a zone of approx. 1200 m length had to be crossed.

The most difficult section of the entire new tunnel from the viewpoint of geology was expected to be the northern part of the Tavetsch intermediate sub-massif in the Sedrun section. It consists of a steeply inclined, sandwich-like sequence of soft and hard rock. Exploratory drillings in the early nineties indicated extremely difficult rock conditions for about 1,100 m of the tunnel. As well as compact gneiss, there are also intensively overlapping strata of schistose rock and phyllite.
Based on the results of the lab tests from these drillings and geotechnical models a new heading method for tunnels with an overburden of up to 1'000 m was developed. The full-face heading with extensive use of long face anchors. The excavation at the construction section Sedrun started in 2002. With regard to deformations, the geotechnical behavior of the kakiritic gneisses and slates encountered turned out to match the forecast. A rapid cessation of the deformations (occurring only some 20 to 30 m behind the face) from the perpendicular bedding made the transformation from the yielding to resistance principle easier.

The cross section of the single tubes increased from about 80 m$^2$ up to more than 130 m$^2$. To counter the expected high rock pressures a full-face excavation by drill & blast with a new special support system was developed. The used support system in the TZM consisted of shotcrete, net reinforcement and flexible steel mining arches, which were installed by a support placement rig. After excavation two steel arches were inserted. Each arch consisted of eight segments which are joined together by slightly yielding connectors to form two concentric rings. They allowed a certain degree of deformation. The installed steel arches gradually closed under the rock pressure until their maximum support pressure (resistance of the support) was reached and the system transformed from yielding to resistance principle. In the resistance condition one closed steel ring consists of two overlapping TH profiles. They had the capacity to deform up to 80 cm radial deformations. The deformations occurred radially at the anticipated average magnitudes of 20 to 80 cm. The deformations in the cross section took place in a very different and asymmetrical manner. These asymmetrical deformations were reacted by corresponding additional support elements like grouted anchors.

It can be concluded that the support system used in the TZM North proved itself to be effective. The average advance rates were approx. 1 m per day. The breakthrough to the construction section Amsteg in the North was in October 2007 and took place nine month ahead of schedule.

The same yielding principle was also applied to the TBM drives in squeezing rock conditions. Partly the large deformations are welcome because as deformations in the ground increase, the stress around the tunnel decreases and the amount of rock support can be reduced, resulting in a more economic excavation support. Within an open type TBM and its back up, there are only certain areas where the rock support means can be applied. Therefore the rate of advance, the quantity and type of the support measures as well as the occurring deformations are inseparably interrelated and influence each other mutually.

A rigid lining system would have needed very high support capacity and with a shield machine, the permissible deformations would have been too limited. Squeezing rock conditions were encountered for instance in the East and West TBM drives between Faido and Sedrun
The drive of the east tube was first started with a relatively rigid rock support. Already after some meters though, the rock support was damaged (deformed steel arches, shotcrete failure, Figure 4) due to deformation. The TBM had entered a totally unexpected 200 m-long zone of squeezing rock.

This led to an adaptation of the rock support. A heavy but flexible support type, consisting of yielding steel arches with friction clutches, steel anchors and shotcrete with longitudinal convergence slots (with styrofoam inserts), was chosen and successfully applied. This rock support type was assuring an advance rate high enough to prevent blocking of the cutter head.

The west tube TBM was started in October 2007. It was right in December 2007, when first cracks developed in the rigidified shotcrete of the eastern tube on the level of the western TBM, about 600 m behind the face. The subsequent drive led to a failure of the rock support in the eastern as well as the western tube on a length of several hundred meters.

In the eastern tube, not only the vaults were demolished, but also the pre-cast concrete blocks of the invert were heaved and torn. The transport logistics for the eastern advance could be maintained, as the invert was stable. A speed reduction was though necessary for the trains upon the deformed tracks.

In the western tube, the situation was more critical. The back-up installations were in danger of jamming due to the deformation and the invert was demolished.
To assure the trailing of the back-up installation, the shotcrete had to be removed. In these difficult working conditions, the advance rates decreased to a minimum of 1 m/d. The average advance rate slowed down to 3 – 5 m/d, instead of the previous 11 m/d. Minor advance rates also increase the risk of a blocking of the TBM cutter head due to deformations. Maintenance time was thus optimized to maximize the excavation time. In order to explain these processes, extensive numerical calculations and back analyses were done. The calculation results revealed that the geological conditions were worse than originally predicted. In addition, the transition zone between an unfavorable flat rock layer and steeper layers of Lucomagno gneisses (the Chièra syncline) was located in a zone about 500 m further north with a higher overburden. Thus, higher rock pressure had to be borne by a weaker rock than predicted. Due to the difficult geological conditions, the tunnel tubes were interacting, against all expectations. The excavation works in the tubes were influencing one another.

As the damages to the excavation support and the already cast invert had developed beyond an acceptable threshold and since the profile was undersized due to deformation along a considerable distance of the tunnel, a section of approx. 200 m in both tubes was subjected to remedial measures.

As a consequence, a detailed action plan was developed as a guideline for the reprofiling works in the tunnel tubes. Different phases and renovation levels were defined for vault and invert, whereby the major distinction was made between a partial or a total renovation and a reinforced or a non-reinforced lining.

Another specific hazard was rockburst. Rock burst is a brittle failure. The danger of rock burst exists in hard solid rock with a low joint intensity and a high overburden. This hazard scenario is typical for deep tunnels in hard rock. In the Faido section many and large rockbursts were experienced. The rockbursts were classified into 4 categories which allowed to set up conditions that guaranteed the workers' safety. For the entire multifunctional station in Faido set up predictions of expected rock burts together with their intensity were made. This meant that it could be ensured that the necessary support measures were built in. Despite about 1000 smaller rockburts (mostly at the tunnel face) and some 10 larger rockbursts no accidents or injuries due to rock bursts occurred.

### 6. Monitoring and Risk Management

Risk management is the systematic process of handling project risks. It consists in general of risk identification, risk analysis and risk responding.

Risk management is not only a single event but also a continuous process during the entire project. Therefore risk monitoring and control are part of the project life cycle from project initiation to project completion. Risk management covers the handling of project threats and project opportunities. Project threats are risks which can have a negative impact on a project whereas project opportunities are risks which have a positive impact.
A comprehensive risk analysis was carried out to identify all possible risks at the GBT. Threats as well as opportunities including their influence on the project were disclosed. The risk analysis was discussed in detail and the mitigation measures were compiled.

A special risk was identified in the form of above ground dams and reservoirs. Long time before the excavation work started large areas around the dams and the reservoirs were monitored, together with the dams as well. Due to this monitoring concept, it was possible to identify the settlement of the dams because of drainage effects of the tunneling works already at an early stage. This allowed to consolidate the ground with injections and to lower the water drainage considerably. The positive effect was that the tunneling work could be continued without any further problems to the dam structure.