1. Introduction

The Gotthard axis has always been an important and direct north-south connection. It passes over or through the Gotthard Massif of the Swiss Alps. The older Gotthard railway tunnel opened in 1882. Today more and more people and goods cross the Alps and the established routes no longer meet the demands of the continually increasing volumes of rail traffic. In 1988, after years of planning, deferments and examination of different alternatives, the New Railway Alpine Transversal (NEAT) including the Lötschberg and Gotthard Axis was developed. The Swiss nation finally accepted the proposal, which provides a high-speed rail link through the Central Alps, by referendum in 1992.

The 57 km long Gotthard Base Tunnel (GBT) is the core of NEAT. The tunnel consists of two parallel single track tubes which are linked by cross-passages every 300 m. Two multifunction stations are located at two locations one-third and two-thirds along the length of the tunnel. These will be utilized for the diversion of trains to the other tube via crossover tunnels and as an emergency station for the evacuation of passengers. The tunnel is divided into five construction sections in order to attain a reasonable construction time and for ventilation purposes. Excavations started from the portals at Erstfeld and Bodio as well as from three intermediate attacks located in Amsteg, Sedrun and Faido. Almost the entire tunnel will be excavated by tunnel boring machines, except the section Sedrun and both multifunction stations which will be constructed by drill & blast.

The construction works began in 1993 with the first blasting of the Piora exploratory gallery in the Faido section. The GBT is scheduled to be opened in 2017 and will be the world’s longest railway tunnel.

This paper deals with the handling and countermeasures taken regarding the main geological risks. Following a brief overview and introduction, the main theme of the paper will be expanded by the examination of two critical geological sections. From the study of these important sections measures to reduce risk to acceptable levels and detailed precautionary plans were developed. This included risk handling procedures and risk response planning for the excavation work. The zones considered are the:

- Piora syncline and the
- Tavetsch sub massif (TSM)
Both are intermediate fault zones located between major geological units. At this time both zones have been successfully excavated confirming the design assumptions.

The history from first geological investigation in the early 90s up to excavation and lining of the main tunnel is described in this article. The evolution of the geological interpretation is explained along with the additional investigation work, the proposed solutions at the different stages, the proposed back-up plans and the assessment of risks.

2. Geological longitudinal profile and alignment of the GBT
2.1. Geological profile

From north to south, the 57 km long Gotthard Base Tunnel passes mostly through crystalline rock. The three crystalline rock sections include the Aar massif to the north, the Gotthard massif and the Pennine gneiss zone to the south. These massifs consist mainly of high strength igneous and metamorphic rock. More than 90% of the total tunnel length consists of these types of rock. The massifs are interrupted by narrow sedimentary zones. The main hazard is the risk of rock burst caused by high overburden, the instability of rock wedges and water inflow.

2.2. Alignment

On the surface the choice of the alignment is affected by geographical aspects (e.g., the access alignment of the high speed rail on the open stretches, location of villages or reservoirs for hydro-power schemes) as well as the positioning and accessibility of intermediate points of attack. Other important criteria influencing the optimal alignment were the different geological conditions (especially the major fault zones), which had to be crossed during the construction of the GBT.

Factors taken into consideration were:

- Alignment through rock conditions favorable for construction wherever possible
- Aligning the tunnel through geological difficult zones at their narrowest points wherever possible (i.e. Piora Syncline and major fault zone in the Gotthard massif)
- Crossing under the fault zone “Piora syncline” at sufficient depth
- Avoiding areas with the highest overburdens
- The optimization of the numbers and positioning of the intermediate points of attack to reduce construction time, reduce construction risks and optimize operational aspects (safety aspects, ventilation, maintenance). This leads to the following additional access points;
  - An intermediate tunneling face at Faido: excavations of exploratory gallery for the Piora syncline and access tunnel for the base tunnel could be started from one construction site. Positioning of this additional adit as far north as possible
  - An intermediate face at Sedrun: possibility of attacking the difficult rock conditions in the Tavetsch sub massif as early as possible and independently from the other points of attack. The shaft allowed investigations and the design of measures at the most challenging geological section, the TSM, without constraining tunnel excavation in the southern direction. The shaft itself was positioned in good rock conditions, which was important for the shaft sinking process
  - An intermediate face at Amsteg: access to reduce construction time
- No endangering of groundwater resources
- In order to allow high speed: flat rail: max. incline 15 ‰ and radii > 5000 m

These considerations led to the S-shaped alignment you can see in Figure 1.
2.3. Continuous monitoring of critical geological sections during the project

For the GBT project an extensive risk management with comprehensive risk analysis and risk response planning was applied by the Alptransit Gotthard AG. An important part was the assessment of geological risks.

In the following paragraphs the geological risks of the Piora syncline (Faido construction section) and the Tavetsch sub massif (Sedrun construction section) are shown. The appropriate investigations and measures to mitigate risks or to reduce the resultant costs are described herewith in more detail.

In the initial planning phase special attention was paid to these most challenging geological sections, both sections were thoroughly investigated. The Piora syncline was an important point in the geology of the GBT since its structure and extent were unclear from the beginning. The expected squeezing rock conditions at the Tavetsch sub massif required special excavation and support measures. The following paragraphs show the investigation and excavation works in these sub-sections in detail.

Based on the aforementioned investigations the range of geological risks was reduced and the accuracy of cost estimation was improved from +/- 25% to +/-10%.

3. Piora syncline
3.1. Investigation and geology

The tunnel excavation had to pass through the Piora syncline at the section Faido with an overburden of about 1800 m. At the beginning the extent of knowledge of the geology was gained from geological mappings, several test bores in the sixties and some seismic campaigns. As a
result the Piora syncline was defined as a Triassic deposit of Dolomite in the Gotthard Massif, which is inserted between Lucomagno Gneiss and Medelser Granite. In the Piora syncline this Dolomite disintegrated into a matrix of fine sand and solid Dolomite blocks in water. It was decided to carry out an extensive exploration in order to ascertain the actual conditions at the base tunnel level of tunnel construction. The key question was: what does the Piora syncline look like at a depth of 1800 m? Will the tunnel headings have to pass the Piora syncline in such a disintegrated matrix and with a water pressure of about 200 bar. Additional investigations were necessary.

From the surface it was difficult to reach the Piora syncline and it was not possible to obtain sufficient undisturbed soil samples from a depth of more than 1500 m. The following aspects had been taken into consideration when deciding the site investigation scheme:

- If the Piora syncline reached the level of the tunnel extensive preparatory works would be necessary. These measures could include drainage, ground improvement by grouting works and excavation of the main tunnel in this section by conventional means using the investigation tunnel as access
- On the other hand there was the risk of a water inrush under high pressure. A possible inrush of more than 1000 l/s would need a natural outflow through a slightly inclined access gallery.

It was decided undertake an investigation, which consisted of, mainly, a 5.5 km long horizontal investigation tunnel, located 350 m above the base tunnel level and – if necessary - a shaft of 350 m depth (Fig. 2). This was constructed from 1993 onward and was stopped just roughly 50 m short of the Piora Basin in March 1996. At that level, the structure and thickness of the basin was examined through exploratory drillings. The drillings revealed a carbonic-sulphate Trias consisting of Dolomites, Rauhwacken, Dolomite-gypsum/anhydrite with differing proportions of sugar-grain Dolomite and high water pressure of up to 130 bar. The extension of the Piora Basin at that level is approximately 230 m.

During these probe drillings the mishandling of a packer lead to an inrush of water and mud of several hundred cubic metres. The first several 100 metres of the access tunnel was filled with mud. Additionally, the TBM was buried. This was the most critical period for the whole Gotthard Base tunnel project. Two years later the Swiss people would have to give green light to the planned financing of the entire Alp Transit project in Switzerland. At that time they had the following question in mind: if it was not possible to handle a boring of 100 metres through this sugar-grain dolomites would it ever be possible to build a tunnel with 10 m diameter in such conditions?
Based on the findings of the first horizontal drillings, several measures were deemed appropriate for further investigation:

- extensive horizontal and inclined bores correlated with seismic measurements to verify the geometry of the basin
- development of a test program to determine the best methods of crossing the Piora Basin at the level of the exploratory tunnel and the methods for excavation of an according tunnel scheme.
- The sinking of a 350 m deep shaft to the level of the base tunnel.

Additionally, investigations and different auxiliary measures would have to be implemented from the shaft bottom. The release of rock mass stresses by material removal and auxiliary measures such as injections, drainage to relieve pore water pressure, ground freezing, jet grouting and all in differing combinations of them were evaluated.

Inclined preventer-protected exploratory bores of over 1000 m length fortunately revealed that at the base tunnel level, the Piora Basin consists of stable dolomite marble or dolomite/anhydrite. No water was found in any of the bores which would indicate the presence of water pressure. A geological model was created to demonstrate the findings of the exploratory bores. This showed the basin to be solid carbonic Trias with occasional lentils of anhydrite or gypsum. Fissures in the rock were filled with gypsum preventing major inflow of water. Geologists interpreted that between the formations at the level of the exploratory drillings which include sugar-grain Dolomite, and the formations at base tunnel level, a gypsum cap had formed through the transformation of anhydrite to gypsum under the presence of water that did not circulate to a lower level due to the bottom of the nearby valleys.

A longitudinal section of the geological model indicates the path of the bores Bs 4.1, Bs 4.2, and Bs 4.3 (Fig. 3) and their results. It demonstrated that a sufficiently wide corridor consisting of stable dolomite marble or dolomite/anhydrite not exposed to high water pressure existed at the elevation of the Gotthard Base Tunnel. A thorough analysis of the exploratory findings related to the crossing of the Piora Basin using the main headings at the level of the base tunnel and integrating the exploratory system into the construction and operation processes of the Gotthard Base Tunnel, led to a decision to end all exploration construction activity.

Figure 3. Inclined probe drills at the Piora investigation scheme
3.2. Tunnel excavation works and support measures

The Piora syncline extends over a distance of about 145 m including the border zone. With the results from the investigation and the data provided by the probe drills additional geotechnical models were developed. The results showed that large deformations would occur but an excavation with open gripper TBM's would be possible. A special, very heavy but flexible support type was designed.

The TBM drives were stopped approximately 50 m before entering the geology of the Piora syncline, to overhaul the TBM and to equip the cutter head with new discs. Long preventer protected core drillings were carried out in the direction of the drives. Preventer protected core drillings up to 250 m could have been performed in ground with high water pressures, however the probability of water inflow was very low. The drilling results were compared with the previous drilling results and investigation findings. The support elements (TH 44 flexible steel arches, shotcrete and mesh) which had to be applied to the entire Piora syncline were adapted accordingly.

Then the TBM drive started: No water inflow occurred. The dolomite was compact and beautifully white. No problems occurred; the deformations never grew above the predicted amounts. The excavation of the Piora syncline was successfully completed in October 2008. The average advance rates were nearly 10 m/day.

4. Tavetsch sub massif
4.1. Investigation and geology

The most difficult section of the entire new tunnel from the viewpoint of geology was expected to be the northern part of the Tavetsch sub massif in the Sedrun section. Located between the Aar-Massif and the Gotthard-Massif, it is one of about 90 different, isolated short fault zones along the 57 km. 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 1100 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 laboratory tests from these drillings and geotechnical models a new heading method for tunnels with an overburden of up to 1000 m was developed. This was full face headings with extensive use of long face anchors. This method had been used successfully in the Italian tunnels for the high speed network – but all these tunnels have been near to the surface.

As it was known that this section of the base tunnel would be the most challenging and it would be a section with very low advance rates it was necessary to build an access system very near by. Already (in 1996) the construction works for this intermediate access with an access gallery and an 800 m deep vertical shaft had been started (Fig. 4).

During the heading works of the main tunnels a core aspect of the new heading method was the necessity of investigation ahead of the tunnel face using both percussion and rotary core probe drillings. The drillings had to be preventer-protected against water inflow and debris under high pressure.
4.2. Tunnel excavation works and support measures

The excavation at the Sedrun construction section started in 2002. The geology encountered in the TSM agreed with the forecast based on the core bore SB 3.2 (Fig. 4). With regard to deformations, the geotechnical behavior of the kakiritic gneisses and slates encountered turned out to match the forecasts. A rapid cessation of deformation (occurring only some 20 to 30 m behind the face) from the perpendicular bedding made the transformation from the yielding to the resistance principle easier. Friability of the rock was extremely high in some areas. In this regard, the influence of the strike of the layers vis-à-vis the tunnel axis was of major significance. In the case of upright layers there was a greater need for supporting the face (shotcrete with net reinforcement, excavation in stages and installation of piles), whereas in the case of horizontal layers, the danger at the edge of the excavation increased.

The cross section of the single tubes was increased from about 80 m² up to more than 130 m². To counteract the expected high rock pressures a full face excavation by drill & blast using a new special support system was developed. The support system in the TSM consisted of shotcrete, net reinforcement and flexible steel mining arches, which were installed by a support placement rig (Fig. 5). After blasting two steel arches were inserted. Each arch consisted of eight segments which were 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 a yielding to a 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 deformation. This technology was already known and used in German coal mines, but it was the first time it was used in this scale in Civil Engineering tunnel construction. Because there had been no previous practical experience gained a few full-scale on-site tests were carried out. The steel arches were loaded until they failed. The tests demonstrated that the selected excavation and support concept was suitable for use in the Tavetsch sub massif. The deformations in squeezing rock occurred at the anticipated average magnitudes of 20 to 80 cm. The deformations in the cross section took place in an asymmetrical manner (Fig. 6). These asymmetrical deformations were treated using additional support elements such as grouted anchors.

It can be concluded that the support system used in the TSM North proved itself to be effective. The average advance rates were approx. 1 m per day. The breakthrough to the North Amsteg construction section was in October 2007 and took place nine month ahead of schedule.
Figure 5. Support placement rig

Figure 6. Installed TH-profiles and occurred asymmetric deformation

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