Experiences with TBM drives in the Gotthard Base Tunnel, Bodio section

Erfahrungen bei der TBM-Vortriebe im Gotthard-Basistunnel Teilabschnitt Bodio

A. Ferrari & S. Pedrazzini, Engineering Joint-Venture Gotthard Base Tunnel South, Lombardi SA Engineering Limited, CH

ABSTRACT

The Bodio section is the southernmost and, being 16 km in length, the longest of the five sections of the Gotthard Base Tunnel (57 km: the world’s longest tunnel). Most of the parallel twin tunnels have been mined using two open hard rock TBMs. During the drives through the Leventina Gneiss (massive gneiss alternating with highly fractured rock), the different ground conditions resulted in variable structural engineering effects. Furthermore, both TBMs unexpectedly met two fault zones of several hundred metres in length. These zones, due to both brittle and squeezing characteristics of the rock mass, were a particular challenge to man and machine and were successfully mastered thanks to appropriate technical solutions. This paper gives an overview of some of the technical experiences made during mining and lining works.

ZUSAMMENFASSUNG

1. INTRODUCTION
With a length of around 57.1 km, the Gotthard Base Tunnel is the longest tunnel in the world. It consists of two single track tunnel tubes, that are interconnected approximately every 325 m by transverse tunnels. Furthermore, at the one third and two third points along the tunnel, there are two multi-functional stations with track changes, emergency stations, technical equipment rooms and ventilation systems. In order to optimise the total construction time, the Gotthard Base Tunnel was divided into five sections.

The Bodio section, at around 15.9 km, connects the South Portal with the Faido multi-functional station. The two tunnel tubes and 51 cross-passages of this section were excavated between the years 2000 and 2006. After cut-and-cover and loose ground sections of approximately 400 m each in length, 1.7 km in the eastern tunnel tube and 0.8 km in the western tunnel tube were excavated by drill and blast technique. Next, the remaining section as far as the boundary with the Faido section was driven by the main contractor using two open gripper TBMs.

This article deals exclusively with the part of the Bodio section driven by TBM (13.5 km eastern tube and 14.1 km western tube) and the experiences gathered from this in just under four years of tunnelling.

2. GEOLOGICAL PROGNOSIS AND FINDINGS
In the geological prognosis, the TBM tunnels of the Bodio section were supposed to belong entirely to the Leventina gneiss of the Penninic zone. The joints of the rock mass consisted of a sub-horizontal rock cleavage and sub-vertically running fissures. The maximum overburden is approximately 1’000 m. The existence of long fault zones with relevance to construction work and especially with strong squeezing behaviour was not to be expected. According to the geological prognosis, exclusively short individual vertical fault zones perpendicular to the tunnel axis up to a few metres in length were to be expected.

During mining, variable geological conditions were observed. Mostly, the TBM encountered compact gneiss with few fissures. However, to a certain extent some zones with heavily fissured rock had to be passed. Furthermore, in both tunnel headings two unexpected, extended fault zone areas with significant construction implications were encountered: after a few hundred metres from the TBM start (Tm 2’705) and the other about 1.5 km before the intersection with the Faido section (Tm 13’460).
The first, sub-horizontal fault zone consisted of a layer of kakirites, cataclasites and heavily fissured rock (Fig 1).

Fig 1: Three-dimensional view of "Tm 2’705" fault zone

The second area of fault zones was characterised, on the one hand, by two cataclastic/kakiritic fault zones sub-vertical and nearly parallel to the tunnel axis (Fig 2) and, on the other hand – outside the fault zones – by the existence of slaty, mica-rich gneisses (as opposed to the previous porphyric gneisses).

Fig 2: Ground plan of fault zone area from Tm 13’460

3. HAZARD SCENARIOS AND TEMPORARY SUPPORT

On the basis of the geological prognosis, initially in the construction project and later in the call for tenders, the hazard scenarios vital for tunnel driving were specified and over and above this, the necessary rock support defined.

For the TBM driving of the Bodio section, the main hazard scenarios to be expected were small rock slides, the crumbling of blocks of fractured rock of varying sizes and rock layers falls caused
by stressing. In the construction project, a number of types of temporary support with different safety measures were planned. Furthermore, criteria were defined for the assignment of suitable type of support to the various hazardous scenarios and geological conditions (distance and orientation of the joints, transection degree, etc.). During execution, the rock support measures to be used, as well as any adaptations and the optimisation of the allocation of support measures on the basis of local conditions was specified amicably on a day-to-day basis between local site management, site geologists and the contractor.

In general terms, in the areas outside the fault zones, the combined use of 3.0 to 4.0 m long swellex rockbolts, welded mesh, UNP partial arches (roof caps) and a layer of shotcrete (usually 5 cm thick) applied in machine section L2 proved its worth (Fig 3). In zones with heavily fissured rock or in fault zones, excavation was, as a rule, made safe using closed TH steel arches, welded mesh and the application of shotcrete already in machine section L1.

Fig 3: Temporary rock support in L1 section, consisting of swellex rockbolts, welded mesh and UNP partial arches

4. CONTINUOUS FURTHER DEVELOPMENT OF THE PRELIMINARY EXPLORATION CONCEPT

Although, according to the geological prognosis, fault zones of great relevance to construction were not expected, given the length of the section to be driven and the residual hazards for driving the Bodio section by TBM, a preliminary exploration concept was developed and implemented. As a
result of new knowledge and experiences gathered, during TBM advancing the preliminary exploration concept had to be adapted on a day-to-day basis.

In the initial phase, firstly the effectiveness of seismic exploration to accompany the tunnelling work was tested. However, the use of this advance exploration method proved to be unsuitable here and was therefore stopped after the first 1’000 metres driven by TBM.

Taking into account the unforeseen encountering of a brittle, sub-horizontally positioned fault zone in the eastern heading (chapter 5), as a result advance exploration was successfully taken care of by systematic, radial percussion drill, as well as percussion drill ahead of tunnelling in a longitudinal direction. The percussion drill in the direction of tunnelling were systematically made, irrespective of the geological prognosis, in the tunnel heading pressing on ahead with a length of 80 m and an overlapping of 10 m. The radial, 16 m long percussion drill were made at regular intervals in the L1 section to look for any lateral or overhead fault zones. As a rule, advance exploration work was done during maintenance shifts.

5. COPING WITH FAULT ZONE "TM 2’705”

5.1 Experiences during TBM drives

After around 200 m from the start, the TBM encountered an unexpected, flat fault zone in the eastern heading with a brittle behaviour of the rock mass. This accompanied tunnelling to around 400 m, and primarily in the roof area. The same fault zone was also struck by the TBM in the western heading at about 100 m and when driving two cross-passages. The main hazard scenario during tunnelling was the frequent crumbling of material similar to loose ground immediately above the cutterhead shield. A number of cavities of very varying dimensions arose, and primarily in the crown area (Fig 4). In extreme cases, these extended practically across the entire tunnel width and reached heights of up to 6.0 m above the tunnel roof.
The temporary support was installed entirely in the L1* zone and this consisted of TH29 closed steel arches made of hardened and tempered steel every 1.0 m, welded mesh and approx. 15 cm of shotcrete. Existing cavities were completely filled during tunnelling in the machine area (L1) and back-up area (L2) with shotcrete and to some extent with cast-in-place concrete.

The boring diameter was widened from 8.80 to 8.89 m by increasing the calibre of the outer disc-cutters. In order to prevent geometric conflicts in the area of future arch drainage channels, special TH29 steel arches with a reduced height were used in the area of the arch feet. The thickness of the lining is a min. of 25 cm (Fig 5).
Given the geological difficulties and as a result of the fact that the tunnelling teams had not settled into a routine during the starting phase of TBM tunnelling, when passing through the entire "Tm 2’705" fault zone, an average advancing rate of approx. 2.5 m/working day was achieved.

### 5.2 Dimensioning of lining

The lining of the single track tubes and cross-passages with a minimum thickness of 25 cm were reinforced in the area of this fault zone for structural reasons. However, the invert remained non-reinforced as usual. Furthermore, due to fire prevention reasons, 2.0 kg/m³ monofilament polypropylene fibres were added to the cast-in-place arch concrete of the single track tunnel tubes.

Reinforcement was gauged according to unfavourable stressing resulting from all possible combinations of loading conditions, loosening pressure, self-weight, temperature fluctuations, etc. What is meant by loosening pressure in such a brittle fault zone is the self-weight of the discontinuum, which could become loose from the rock formation and therefore put the lining under stress. On the basis of a detailed analysis of the geological conditions encountered, various
geometries of such pieces of broken rock with different heights, positions and extensions were investigated.

6. DRIVING THROUGH FAULT ZONES WITH BRITTLE AND SQUEEZING BEHAVIOUR FROM TM 13’460

6.1 Experiences during TBM drives

Another fault zone area was encountered from approx. Tm 13’460 by both TBMs in the Bodio section. Two brittle fault zones that had not been forecast were driven through firstly from the eastern heading (at approx. Tm 13’460 and Tm 14’340) and later from the western heading (at approx. Tm 13’745 and Tm 14’425). These fault zones swept from east to west at an angle of 5° to 10° in relation to the tunnel axes and dropped at an angle of approx. 65°. They consisted mainly of cataclasites with kakiritic intermediate layers and then border areas of heavily fissured rock, as a rule with a variable thickness of between 3.0 and 5.0 m. These fault zones crossed the tunnel profiles on account of the acute angle to the tunnel axes by several decametres. In these sections, the main hazard scenario was (just like fault zone "Tm 2’705") the crumbling of material directly behind the cutterhead.

In addition, when penetrating areas consisting of slaty gneiss before and after the brittle fault zones (where the fault zones were located at the side of the tunnel profile), high pressures were recorded on the TBM cutterhead shield. Also plastic deformation of the installed TH29 steel arches was established, spalling of the shotcrete and deformation of the welded mesh observed, as well as convergences of the temporary support being measured over several hundred metres (Fig 6).

The phenomena observed pointed to the existence of squeezing characteristics in the rock mass: as a result of overstressing of the rock mass in the area surrounding the cavity, incidences of plastic deformation occur and the rock mass indicates a tendency to close up the cavity again.
These occurrences in the western tube between Tm 13’595 and Tm 13’692 – where the sub-vertical brittle fault zone was located between the two tunnel tubes, and was getting progressively closer to the eastern side of the western tube – were particularly distinct and led on March 3rd 2006 to the jamming of the TBM at Tm 13’629 because of excessive pressures on the TBM cutterhead shield and the resulting insurmountable friction. It was only possible to resume tunnelling at that point about 10 days later, by creating a roof lining above the cutterhead shield (Fig 7).
The temporary support installed for both fault zones with brittle and squeezing behaviour was analogous to that used in the "Tm 2'705" fault zone (tempered TH29 steel arches every 1.0 m, welded mesh and 14-18 cm of shotcrete). Again here, the effective boring diameter was 8.89 m. Because of the danger of shotcrete spalling, in certain areas an additional layer of welded mesh was installed to guarantee health and safety at work.

In general terms, from Tm 13’460 for more than 1 km, the geological conditions in both tunnel tubes and their effects on construction work were highly variable. Areas in "good rock" alternated with sub-vertical, sliding, brittle fault zones and with extended zones with squeezing behaviour of the rock mass. The boundaries between the individual sections were often not clearly recognisable, but characterised by intersections, so that it was extremely difficult to clearly distinguish between zones with squeezing tendencies and those with brittle characteristics.

Aside from the standstill of the western TBM due to jamming, this area could be tunnelled with daily progress of between 7 and 15 m. Advancing rate of this type is remarkable if compared with the average performances achieved with fault zone "Tm 2’705". Contributing above all to this improvement were the experiences gained by the tunnelling teams during more than 10 km of tunnel driving and the upgrade of the TBM zone L1* undertaken after driving through the first fault zone to optimise the execution of the closed steel arches.

6.2 Dimensioning of lining

Verification of the structural safety and the serviceability of the lining for the fault zone areas from Tm 13’460 could be achieved using a reinforced lining with a min. thickness of 25 cm and an non-reinforced invert. To estimate the effective rock pressure due to squeezing on the lining, a finite difference (FD) model was used for back analysis whilst taking into consideration the instances of deformation observed and rock supports installed.

Part of the total deformation that occurred could be recorded by transverse convergence measurements at spots, which were staggered in the critical areas every 5 to 15 m. However, the measurements could only be taken once the support had been installed and the reference sections could only be measured at approx. 7 to 8 m behind the heading face. The results of the measurements showed asymmetrical transverse deformation and unequal deformation along the tunnel path, which completely stabilise before the integration of the final invert in the back-up area (80 to 100 m behind the heading face). The absolute values of the maximum convergences measured were approx. 10 cm. To be added to these are the deformations between the heading face and the reference measurement, which could not be recorded using measurement techniques, but which could be estimated at 4 to 7 cm.
The model takes into account the influence of the fault zone between the tunnels, the anisotropic rock characteristics due to its schistosity, as well as the mutual influences of both tunnel tubes (Fig 8).

Fig 8: FD model used for the back analysis

The results of large numbers of tri-axial compressions trials were used as a starting point for the determination of mechanical rock properties to be used for the model. These had been carried out on drilling cores that had been collected during the standstill of the TBM. The tri-axial compressions trials underlined the influence, on the rock resistance, of the schistosity direction compared with that of the stress. The model was then calibrated using a parametric study on the basis of the deformations observed. In this way, rock mass characteristic lines at various points in the profile (roof, side-strips, invert) could be determined (Fig 9), which then, together with the resistance of the temporary support, made it possible to estimate the rock pressures acting on the lining (characteristic line method).
As the resistance of the deformed temporary support actually effective was very difficult to quantify at the time, limit considerations were made and various loading hypotheses for the lining derived from them.

The rock pressures on the lining determined in this way are asymmetrical, which is rather unusual for very deep tunnels. This asymmetry is a direct result of two special circumstances: the 65° sloping fault zone to the side of the tunnel profile (with various strength and rigidity properties compared with the adjacent rocks) and the anisotropic strength properties of the rock resulting from sub-horizontal schistosity.

7. REPROFILING WORKS

The substantial deformations that affected the support in the fault zones generated underbreaks up to a max. 15-20 cm in radius so that approx. 950 m (both tunnel tubes) had to be reprofiled, since such deformations do not allow to construct the final lining of the scheduled minimum thickness.

Reprofiling works are not rare in tunnel construction. In the Bodio section the final invert (already finished with all the water drainage ducts), the limited length of the excavation stages because of the geological conditions present and the logistics caused by the great distance from the tunnel portal of the sections to be reprofiled made additional, restrictive outline conditions essential for there completion.
The reprofiling work was carried out as follows with an extra installation in each tunnel tube in the area of the rear construction site for the final tunnel lining: Demolition of the deformed support, additional excavation and then renewed installation of the necessary temporary support (as several more months elapsed until the installation of the final lining). The reprofiling thickness strongly varied according to the deformations, the existing support and the new support work that was required.

As, due to reprofiling work, the existing balance between rock mass and rock support was disturbed, it was essential along the entire section to be reprofiled to re-establish immediate closure of the ring with the new temporary support after reprofiling, in order to prevent further convergences and unacceptable lifting of the existing, final invert. Instances of the invert lifting were observed all the time during the carrying out of the reprofiling work. To keep these within a permissible range, along long sections the existing invert blocks were anchored down in anticipation with heavy rockbolts (Fig 10). The reprofiling work was effected between November 2006 and December 2007 with an average performance of 2.5 m/working day.

Fig 10: Temporary support after reprofiling with provisional invert anchors
8. CONCLUSIONS AND PERSPECTIVES

On the basis of experiences gained in the Bodio section of the Gotthard Base Tunnel, it can be established that in the case of long tunnelling sections with a high overburden, in spite of a careful, in-depth geological/geotechnical prognosis based on all existing exploration results, unexpected fault zones cannot be ruled out. It is therefore crucial that even in the case of tunnelling, where the prognosis is favourable, that scenarios for possible extraordinary events are worked out and prepared for. Such preventive measures, as well as the ongoing adaptation of the preliminary exploration concept to suit rock mass conditions actually encountered can improve flexibility in the case of disturbed tunnelling with open TBMs. Furthermore, the following fundamentals are of significance when tunnelling with TBMs in squeezing rock: Striving for high tunnelling performance, minimisation of downtime, minimisation of cutterhead shield length and enlargement of the annular gap between excavation border and shield jacket (overdrilling).

BIBLIOGRAPHY

[5] Schneider, Alex: Sicherheit gegen Niederbruch im Untertagbau, 2002