EXCAVATION, USING TBM, OF THE LONGEST RAIL TUNNEL OF THE WORLD
CONCEPTS AND EXPERIENCES

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ABSTRACT

The Gotthard rail base tunnel is the biggest single work of the Swiss transalpine rail system. Due to its extraordinary length, 57 km, it was evident, that the tunnel can only be constructed in a reasonable time applying two main concepts:

- construction starting not only from the portals, but also from several intermediate attacks,
- using mainly TBM headings.

These main guide-lines have been followed by the leading engineer, the J.V. Gotthard base tunnel South (Lombardi Ltd., Amberg Engineering Ltd., Pöyry Infra Ltd.) throughout the development of the project.

Of course there were numerous other conditions contributing to the configuration of this huge project, whose realization is actually about on half way, this in terms of planning and construction time (1996 – 2016), as well as in terms of the state of the works (60% excavated, 20% equipped with final lining, finishing works in bidding phase).

The present paper deals with one of the main topics, which has been determinant for the project development and its successful realization: the adequate design for long TBM drives.

With increasing use of mechanical tunnelling, design of TBM drives are not as much a challenge as far as the geological situation is stable, uniform and well known, and the tunnel has a relatively rational cross profile and a reasonable length. For long and deep tunnels however the TBM drives have to be accurately designed and prepared with solid knowledge.

General remarks on alpine TBM tunnelling

As some other recent alpine tunnels, the Gotthard base tunnel presented in general quite favourable factors for using TBM. They are related to the extended experience made in the past. TBM headings have became quite a long tradition in Switzerland. The country has played a role of avangarde, not what the manufacturing of boring machines is concerned, but for their numerous and successful applications. In fact one can look back as far as the year 1970, when the twin road tunnel under the town of Lucerne has been built by a TBM. This has been the first large diameter mechanical excavation, driven by means of the reaming system. A pilot TBM drive of 3.5 m of diameter has been enlarged in two steps to the final diameter. This system has been successfully applied during the following years for several other road tunnels in Switzerland and in Italy (figure 1).

Some years later, during the construction of the Gotthard road tunnel in the seventies, the inclined ventilation shafts have been as well driven by TBM, first upwards with a pilot of 3 m of diameter, followed by a top down...
6,64 m reaming machine (figure 2). At that time, TBM technology for large diameters in hard rock has not been ready yet: in fact, bidding documents for the main tunnel have been proposed for a TBM solution as well, but no offers have been presented.

The elevated percentage of TBM application in Switzerland can be made clear by the following graphical presentation, which shows the evolution of the different excavation methods during the last decades (figure 3).

The second favourable factor is the generally rather good knowledge of the central alpine underground. There are rail and road tunnels along the Gotthard route, extended systems of water galleries and caverns, beside numerous underground military facilities. Of course the Gotthard basis tunnel, which extends over the major part of the area, is much deeper than the existing works, but the forecast can profit from the advantage, that the main stratification in the central massif is subvertical, oriented from east to west. This information is in general helpful for the forecast, even if it should not be overestimated.

**Project configuration defined by excavation conditions**

The fact that the long basis tunnel does not follow a straight line, but describes a light S, is not only due to meet the most suitable position of the intermediate attacks, but a consequence of the geological situation and its interpretation (figure 4).

Three main factors were decisive:

- The alignment has been set to take advantage of the fairly good rock qualities along the major part and to cross the foreseen difficult formations at their narrowest points, mainly the Piora syncline in the Southern part and the Tavetsch intermediate massif in the centre of the tunnel.
- Avoiding maximum overburden, especially when crossing the Alpine crest.
- Avoiding to pass under one of the existing reservoir concrete dams.
Measured along the main tunnel axis 80% of the total length is driven by TBM (figure 5) whereas referred to the total of the single drives, the TBM proportion is about 2/3 of the total length. Roughly 60 km of it have been excavated already. Some 36 km still have to be done.

The “drill and blast” portions are limited to the sector of Sedrun, where the deep lying tunnel passes through rather tender rock, to the access and preparation works, as well as the complex cavern system of the multifunctional stations.

**TBM for preliminary works**

During the preliminary execution phase, three accessory galleries have been carried out by TBM:

- The Piora exploration gallery, 5.5 km
- The muck conveyor gallery near the South portal, 3.2 km
- The inclined air outlet shaft in Sedrun, 0.45 km

A particularly interesting application has been chosen for the second vertical Sedrun shaft, parallel to the first shaft, lowered in a previous phase by traditional shaft technique. This 800 m deep shaft has been realized by a raise drill pilot bore, followed by a top down reaming machine with an external diameter of 7 m (figure 6).

All these mechanically driven accessory works have been carried out with no major geological difficulty, if one disregards the particular approach phase to the Piora basin, which is described in a following chapter.

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*Figure 5: Construction with several excavation methods.*

*Figure 6: Reaming the shaft of Sedrun.*
Key elements of the heading concept in the South part

Due to the extreme interdependence between the different sectors, the finding of the best concept was a very complex task and required a lot of technical knowledge and experience. The two sectors of Bodio and Faido make up more than half of the total tunnel length. Whereas from the portal of Bodio the running tubes could not be attacked directly in solid rock, but only by a detour around an unstable rock fall deposit, the Faido access consists in an inclined adit of 2.7 km in length. The final solution for the heading concept has been found among a great deal of possible combinations of excavation methods and sequences. The problem was not only to fit the overall work schedule, but there were a lot of other limiting conditions to meet: uncertain results of the project approval procedures, availability, near the site areas, of adequate and approved muck deposit areas, limits to the impact on the natural environment, and last but not least: the effort for an economic design.

With the following steps, one could meet the main scopes of this heading concept in the best way (figure 7):

- Early kick-off of all the preparation works, necessary for the main tubes in Bodio, in particular the detour gallery in good rock, in order to gain time for the main headings.
- Separate headings of the running tubes through the difficult ground of the rock fall deposit for 420 m, where only a reduced advancement rate (1m/working day) was possible.
- High performance TBM headings, starting right after the availability and installation of the machines, for 15 km, and early breakthrough at the base of the previously realized Faido adit.

This concept satisfies the necessity to dispose of the critical connecting facilities between Bodio and Faido as soon as possible, in particular for the following three main scopes:

- Muck disposal; the available volumes in Faido are very limited, whereas the main site is located near Bodio.
- Dewatering; during the whole period precedent to the breakthrough, the inflowing water of the whole Faido system cannot freely exit, but has to be pumped for 300 m in altitude, presenting a not negligible cost factor.
- Security concept; an early connection between the long drives from Bodio with the Faido adit is an essential security element, if one has to face extraordinary events like fires, flooding or all kind of accidents. A complex system with more than one exit can offer better escape routes and easier access in case of an unforeseen event.

Figure 7: Gotthard base tunnel South, key elements of the heading concept.
The bidding documents, which have been submitted separately for each sector, contained two supplementary precautions, in order to be able to guarantee the overall schedule: on one side using a double shield machine for the first, preceding tube from Bodio, relying on a more regular and faster heading speed, on the other side introducing an option for a transportation gallery, driven from the opposite side, from Faide southbound, parallel to the future running tubes. The latter was meant to reduce the risk of a possible standstill of the works in Faide due to the factors already mentioned above.

As the result of the submission of the works, enrolled in the year 2001, a combined solution for both sectors showed to be most convenient, at least what times and cost are concerned. Alternative solutions by means of D&B headings have been offered; but they were more expensive than going by TBM and had brought no advantage in schedule. Therefore the tunnel has been finally carried out by two parallel running, open, short-shielded TBM’s.

The importance of preliminary exploration and probings ahead of the TBM face

Starting from the preliminary studies during the late eighties, up to the final design ten years later, the whole project has been accompanied by numerous geological and hydrological investigation programs. Apart from the local investigation campaigns near the portals and the adit entrances, the two following main geological problem zones drew the major attention. Whereas the initial uncertainty at the Piora basin has been cleared by an extensive exploration system, consisting of a 5.5 km long gallery and a dozen of sophisticated long range drillings, the deepness of the Tavetsch area could only be explored by drillings alone. The related feedback has been used for the reiterated revision of the project layout, the heading methods and the estimated support quantities.

It is evident, that preliminary explorations from the surface are not enough to assure a safe TBM drive with 1000 and more metres of overburden. Because of the limited flexibility to react to unforeseen events at the front, and of the risk related to a possible TBM jam, the headings are systematically escorted by advanced drillings from the face. The figure 8 shows the three typical cases adopted in the Gotthard basis tunnel. The two cases related to TBM drives at the Piora and in Bodio have each its particular scope and its particular application conditions.

![Figure 8: Advanced probings ahead of the front in the different sectors.](image)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Sedrun</th>
<th>Piora</th>
<th>Bodio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel element</td>
<td>running tubes, 4 headings</td>
<td>exploration gallery</td>
<td>running tubes, 2 headings</td>
</tr>
<tr>
<td>Method</td>
<td>Drill &amp; Blast</td>
<td>TBM</td>
<td>TBM</td>
</tr>
<tr>
<td>Cross profile</td>
<td>circular/horse shoe, variable size</td>
<td>Ø 5.00 m</td>
<td>Ø 8.83 m - 9.03 m</td>
</tr>
<tr>
<td>Main scope</td>
<td>controlled approach of instable faults, prevention of uncontrolled water inflow from near-by reservoirs</td>
<td>safe approach, investigation and crossing of undrained dolomite, with 150 bar of water pressure</td>
<td>detection of fractured fault zones, prevention of TBM blockade by loose rock parts</td>
</tr>
<tr>
<td>Schedules</td>
<td>works started in 2004</td>
<td>works finished 1997</td>
<td>works actually ongoing</td>
</tr>
</tbody>
</table>

The critical and most interesting working phase in the Piora has been the approach to the basin, formed by sugar-grained dolomite, mixed with water at a pressure of up to 150 bar. The concept of the approach aimed to avoid an uncontrolled encounter of the TBM with the basin. Among the different prediction methods, several geophysical and occasional radar measurements have been carried out, but the relevant decisions had to be based on bore results. The advanced bores from the TBM have been started long before the supposed limit of the basin and along the final approach drillings, of 80 – 120 m of length, have been carried out step by step, overlapping for 10-20 m (figure 9). Alternatively the TBM has been driven ahead, so that a security rock pillar of at least 20 meters remained. The drilling installation, mounted on the TBM, was equipped with a sophisticated preventer system, fit to retain a water pressure up to 150 bars. In fact, regular hydrogeological tests showed real ground water pressures, just a few meters aside the tunnel wall, between 70 and 100 bars.
The probings ahead of the main TBM headings in Bodio are less complex, but not less important, in view of the heavy excavation equipment and the length of the drive. After a first phase based on tests with seismic explorations, completed with roto-percussion drillings, it was considered advisable to cover the whole length with advanced probings, in order to be prepared for the several forecasted, but locally unknown faults, or groups of faults of modest to medium technical importance. This allowed to renounce to further seismic explorations. The probings have been carried out without preventers and the use of core drillings occurred exceptionally, where the geologist needed more accurate information about the characteristics and the composition of the rock mass.

The probings have been carried out without preventers and the use of core drillings occurred exceptionally, where the geologist needed more accurate information about the characteristics and the composition of the rock mass. The drilling equipment is mounted on the TBM and the bore hole is set in the crown just behind the short finger shield, usually with a 5° slope. The cutter head has a diameter of 76 mm.

According to the operational guidelines, the length of the drillings was decided in consideration of the geological situation; usually it was 80 –100 m, which fits to a normal weekly advancement rate. The drillings were normally carried out during the maintenance shift of the TBM and did not cause any delay for the construction programme. The interpretation of the bore results were done on the behaviour of the drilling resistance, followed by the quantity, the pressure and the turbidity of the inflowing water. Depending on the results, eventual supplementary explorations were carried out and the necessary rock support measures could be decided and prepared without further delay. In the case of flat lying faults, complementary radial bores were driven by means of the normal anchor drilling equipment.

The advanced investigation has been carried out systematically in the advanced tube; in the following tube it was reduced to zones, where the advanced tube has met special geological disturbances.

**Overcoming unforeseen geological events in a long TBM drive**

In spite of the generally favourable geological forecast, with hard rock formations of the Penninique gneiss, the TBM headings encountered two significant areas with brittle and unstable rock conditions. For this type of situations the owner and the project engineer have since the very beginning prepared design procedures and contract specifications. Instead of choosing a larger nominal diameter of the TBM, which would work out in excessive lining thickness for the most part of the whole length, the TBM has been commissioned with peripheric pull-out cutters, in order to locally fit the driven diameter up to 30 cm over the standard one, which is 8.80 m. In that way, local zones with brittle rock could be excavated with a diameter which allows to set heavy steel ribs, while along the normal stretches, the cross section and the thickness of the preliminary support can be reduced to an economic minimum.

The sensitivity of the TBM’s has been brought to evidence during a particular event, when in the Western tube unusual large displacements brought – even without signs of major failure of the rock mass – the machine to be overcome by the frictional forces acting on the short front shield. The event took place at chainage 13‘692 m, far from the tunnel portal and 1.5 km before the breakthrough point with Faido. The neighbouring parallel running TBM, whose heading was just 40 m away from the first one, could pass throughout the same ground formation without getting blocked. A fault was striking the tunnels with an acute angle and dipping almost vertical (figure 10). It consisted of a strong weathered, loose material with a thickness in the meter range.

![Figure 10: TBM progress through the faults.](image-url)
Accordingly to a back analysis carried out by a 2D-model using both a FLAC code and the characteristic curve method, the influence of that fault would significantly affect the pre-mining stress field around the tunnel. The calculated results corresponded rather well with the measured displacements. Locally they reached 20 cm in radius and caused plastic deformations of the steel ribs.

The jammed TBM suffered from unusual large displacements and a significant increase of the rock mass pressure, acting on the shield. The only way let to the operator, in order to get away from the critical zone, would be to lower the upper part of the shield and release then the frictional forces on it. This procedure is usually successful in a short period, but not if the extent of the pressure zone is important. In fact the natural release of the rock mass pressure did not lead to a sustainable magnitude, so that it had to be obtained by another method. The implemented technique was based on firing shot holes in short sequences from the upper part of the TBM (smooth blasting). The recovery operation lasted about 10 days (figure 11).

**The importance of the TBM data logs**

All TBM's at the Gotthard basis tunnel are equipped with automatic data log instrumentation, recording a wide range of operating parameters, most of which are directly related to the steering system of the TBM: of particular interest are the data of the thrust cylinders and the one of the shield jacks which supply information about the progress of the TBM as well as the encountered rock mass pressures. The site engineer disposes of a code named SISO, which first selects the useful ones and in a second stage processes them. Apart from the data collection, more attention should be paid to the interpretation of the monitored parameters in real time. In this way one can take more advantage of the possible fine tuning of the TBM operations, especially in adverse conditions, according to the long learning curve which long lasting well monitored projects allow.

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