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DEEP TUNNELLING IN HARDROCK WITH LARGE DIAMETER TBM: WHAT'S UP?

An experience from the
Gotthard Base Tunnel

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by

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Deep tunnelling in hardrock with large diameter TBM: What’s up?  
An experience from the Gotthard Base Tunnel

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**ABSTRACT:** In the driving of underground openings, two main factors are to be borne in mind. First, the existence of failed rock and second, the control of displacements. The general problem devolves into questions of excavation geometry, sequence and support specification while adverse performance of the rock mass in the post-excavation stress field may be caused by either failure of the medium or slip on the weakness planes. During the excavation of the southern section of the Gotthard Base Tunnel, the rock mass response to TBM tunneling activities described unusual magnitudes of displacements in so far as the thrust of the machine couldn’t overcome the shield’s frictional forces. A smooth-blasting technique was implemented so that pressures on it went back to a sustainable magnitude. This paper describes how appropriate design and contractual approach are critical in assuring both efficient geomechanical and economic performance of hardrock tunnelling by large diameter TBM.

1 INTRODUCTION

1.1 *The new Gotthard Base Tunnel Project*

By constructing the New Rail Link through the Alps, Switzerland is integrating itself into the growing European high-speed network. AlpTransit Gotthard Ltd. – a completely state owned subsidiary of Swiss Federal Railways charged with the overall planning and supervision of the construction works of the New Rail Link on the Gotthard axis – is creating a flat rail link for future travel through the Alps.

At the heart of the new transalpine rail route is the world’s longest tunnel – the 57 km Gotthard Base Tunnel – whose highest elevation at 550 meters above sea level is much lower than the highest point of the existing route through the mountains at 1,150 meters, so that gradients will be no steeper accordingly to those of a modern high performance rail link making freight transportation more productive, while passenger traffic benefits from massively shorter journey times.

In 1995, after intensive political, financial and technical studies of several options the Swiss Federal Council approved the plan for the Gotthard Base Tunnel and spoke in favor of a tunnel system with two single-track tunnels. The two rail tunnels are about 40 meters apart and joined approximately every 3,125 meters by connecting galleries. Two double crossovers allow trains to change from one tunnel to the other – which may be necessary to allow maintenance work if an accident occurs. Trains can switch tunnels in the multifunction stations which also house ventilation and technical equipment, safety and signaling systems, as well as two emergency stop stations which are directly linked by separate access tunnels.

Other then the two portals, intermediate headings provide additional accesses to the tunnel from above (shafts) and from the sides (adits), shortening also the construction time and dividing the tunnel into five sections: this paper focuses on the southern section of Bodio.

![Figure 1. Gotthard Base Tunnel. Tunnel systems with shafts and adits.](image-url)
1.2 Site description

The section of Bodio is located in Southern Switzerland (Ticino) at the southern portal of the tunnel. This section is the longest one of the Gotthard Base Tunnel. To allow faster construction of the underground assembly caverns for the TBM, a bypass tunnel was driven out round the site of the portal. From the assembly caverns, two 400 m long – complete driving unit with backup train – open gripper TBM with a diameter of 8.9 m started driving north towards the next section of Faido in 2003: the length of the TBM driven tunnels reaches 13.4 km in the eastern tube respectively 14.1 km in the western tube, the headings facing steadily an uphill gradient of 7‰. The Breakthrough is expected in the “multifunction station” 16 km from portal.

1.3 The event at chainage 13,692 EST W

The sensitivity of large diameter TBM to adverse rock mass conditions has been a major issue since the very beginning of the design and tendering stages of the Gotthard Base Project; in view of the crossing of zones allocated to the poorest excavation classes accordingly to the contract specifications, the owner commissioned TBM with reaming equipment by pull-out cutters fitting the driven diameter up to 30 cm over the standard one. The sensitivity of the TBM was particularly well highlighted by the event occurred in the western tube at ch. 13,692 (2006, March 3rd), where unusual large displacements brought – even without evidence of major failure of the surrounding rock mass – one of the two TBM – the so called West TBM – to be overcome by the frictional forces acting on the short front shield while the second one could pass throughout the same ground unit without getting blocked as well.

This paper presents an attempt to quantify and understand both the records and the limitations in poor ground related to the response of the managing TBM’s operator – as well as the importance of reaming opportunities – by driving through low quality rock masses on the basis of the experience of the above-mentioned event; moreover, the importance of both appropriate design and contractual approach for achieving efficiency in geomechanical and economic performance by TBM tunnelling is showed by the same case study.

2 GEOLOGY AND POTENTIAL MODES OF OPENING BOUNDARY FAILURE

2.1 General geological and geomechanical data

The section of Bodio lies in the hard rock formations of the Penninique gneiss, which are typical of southern Switzerland. The geological longitudinal section shows at the location mentioned in 1.3 a biotite rich gneiss with prominent sub-horizontal weakness planes with relatively low shear strength compared to that of the intact rock; the overburden at the same location slightly exceeds the km mark.

Average geotechnical parameters of intact rock were determined by a large series of triaxial compressive tests carried out by the lab of the Federal Institute of Technology in Zurich on core samples recovered in the near field of the jammed West TBM: Young’s modulus ranging around 10 GPa, uniaxial strength ranging from 5 MPa to 35 MPa. The mechanical properties of the weakness planes of the intact rock were also assumed on the basis of the same lab tests, i.e. cohesion $C' = 1,200 \text{kN/m}^2$ and friction angle $\phi' = 32^\circ$. 

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2.2 Potential modes of rock mass failure

Following the two main factors mentioned in the abstract for designing the rock supports, particular attention has been given to ensure that large, uncontrolled displacements of excavation peripheral rock couldn’t occur in order to satisfy the tunnel duty requirements, such as minimum dimensions required both for excavating equipment as well as for the minimum clearance of the mined section. The first main factor – major boundary failure – could be neglected due to the fact, that around chainage 13,692 no one was reported; nevertheless, the effect of any major discontinuities which will transgress the excavation has been examined by consideration of both the general effect of the structural features on boundary stresses and local stability problems in the vicinity of the discontinuity/boundary intersection. These considerations educed support design adjustments to achieve simultaneous satisfaction of local and general stability conditions for the excavated perimeter near chainage 13,692.

The potential mode of boundary failure is depicted in Figure 4, where the banding (i.e. Ks) running with sub-horizontal banding is showed. Local phenomena of minor parting or slabbing couldn’t be excluded if two or more families of joints (i.e. K1 to Ks) come to intersect each other.

The mapping of the tunnel sets forth the bent of that geological unit to large displacements; this feature has been then confirmed by monitoring the behavior of the rock mass surrounding the tunnel; in fact, the largest displacements were measured between chainage 13,595 and chainage 13,695 (Figures 5 and 6, western tube).

It is important to note that, the possibility to comfort the opening with rock support is not given before the end of the short TBM shield, i.e. at 4 m from the heading, where over 40% of the total displacement has already took place. In other words, the pre-mining stress field came to be disturbed in a quite large extent before any opportunity to control it by rock support were given.

2.3 Rock support

The adverse performance of the opening boundaries in the post-excavation stress field illustrated in the previous chapter were mainly caused by slipping on the pervasive weakness planes while a few sloughing due to induced tensile stress exceeding the strength of the rock occurred.

The opening reinforcement was defined in the attempt to reach as soon as possible a stable equilibrium between the rock mass and rock supports by placing the reinforcement close to the TBM short shield soon after excavation. Heavy rock support consisting of blocked steel sets (TH 29 each meter, all around) combined with a wire mesh and two layers of shotcrete (first layer of 9 cm, second layer of 5 cm, both sprayed on 260°) were installed for a maximum stiffness of the reinforcement.

Although heavy rock supports were installed, evidence of suffering from the disadvantage of a poor stiffness by the blocking points of the steel arches, where overlapping of two neighboring elements often
happened, as well as from failure by sideways buckling were reported.

3 TBM JAM AT CHAINAGE 13,692, WESTERN TUBE

3.1 TBMs working progress

On 2006, March 3rd the western TBM reached chainage 13,692 before getting blocked by the rock mass pressure acting on the short TBM shield; in fact, the machine was no more able to overcome the frictional forces solely with its own thrust. By that time the eastern TBM was progressing at chainage 13,698. The actual distance between the advance headings came to 40 meters (ch. 0 milestones slightly differ each other, of exactly 34,612 m); nevertheless, no mechanical interaction between the openings could be evidenced confirming thus the general rule saying that the zone of influence of one opening lies outside one another’s when the distance between their centers is \( D_{I,II} \geq 6r \) where \( r \) is the opening’s radius (ideal case, hydrostatic stress field).

A fault striking the tunnels with an acute angle and dipping almost vertical was intercepted coming from east and going straight westwards was feared to influence the behavior of the tunnel system in addition, of course, to those to the single tubes. The fault, consisting of a strong weathered, loose material with a thickness of in the m range, hit the two tubes in a distance of about 300 m.

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 have significantly affected the pre-mining stresses field around the western tube so far as the fault location reached the centerline between the two tubes. One can take also reference to Figure 5 again, where the left vertical line points out the chainage – respectively the displacements – by which the fault was located at 3 m away from the tunnel sidewall while the right one do the same for the fault location in the middle distance between the tubes: from this location on, the displacements clearly decrease due to the fact, that the influence of the fault is vanishing.

3.2 TBMs crossing of the zone with large displacements

Both TBMs are equipped with automatic data log instrumentation recording a wide range of operating parameters, mostly of which are directly related to the steering system of the TBM: of particular interest are then the data of the thrust cylinders and that of the shield jacks which supply informations about the advance of the TBM as well as the encountered rock mass pressures. Such data are recorded online by the contractor and delivered to the site engineer in real time.

The site engineer disposes of a code named SISO, which first selects the useful ones and in a second stage processes them; as a result, the whole operation’s track is stored in a data bank and ready for the rendering as graphs or in tables.
By comparing several data coming from the TBM, the stroke’s progression of the jacks moving the upper part of the TBM shield in function of the time delivered the most feasible explanation for the jamming occurred only to the western TBM at chainage 13,692 while the eastern one could successfully manage the similar bad conditions, this with although reported damages of the jacks of the shield ant of the shield itself.

The TBM guidance on the vertical and horizontal planes basically results from the control of two sets of elements: the grippers and the shield. By adjusting them the operator can drive the TBM accordingly to the given alignment as well as reacts in case of troubles, that’s for instance when the ground collapses underneath the gripper or soft rock formations let the cutting head to depart from the horizontal plane.

Seemingly, the western machine entered the difficult zone, characterized by unusual large displacements, with the strokes of the shield jacks being more or less just half way extended (ca. 70 mm out of 150 mm of the total stroke). By the sudden increase of the rock mass pressure – topping 300 bar on the shield jack gauge – the only way left to the operator in order to shift away from such a zone is to lower the upper part of the shield and release then the frictional forces on it. This procedure is usual successful in the short period but not if the extent of the zone is important; in fact, the stop line of the jack is quickly reached. From this point on – if a natural release of the rock mass pressure does not take place – one has to overcome then by other methods.

3.3 Western TBM recovery
Contractor, designer and the site engineer agreed to recover the jammed TBM by taking back the rock pressure to a sustainable magnitude. The implemented technique was based on firing shotholes in short sequences in the upper part of the TBM (smooth blasting). The recovery lasted about 10 days.

4 DISCUSSION

4.1 The importance of the contract
The contract governing the project is a fixed price one, ruled also accordingly to Swiss construction standards such SIA 118 and 198.

The contractor accepted with its tender the risks for stipulated sum or rates nominated in its bid. However, provisions for adjustments have been included; in particular, the risk of a diverting, unexpected geology and delays caused by the owner are compensated to the contractor.

Provisional items, which also are a part of the contract, allow to cover works for which complete details were not known at the time of tendering without creating new ones. Time related costs are covered by separated items offered by the contractor with its bid, so that unexpected variations of order could easily, upon agreement, be integrated in the contract.

That’s to say, the unexpected additional works caused by the recovery of the TBM could be well managed by the existing contract in case of agreement on the liabilities.

4.2 The importance of the TBM data logs
More attention should be paid to the interpretation of the TBM parameters in real time. This should be true at any level of the operation’s management and should be achieved by a more intensive education of the involved technicians.

Contractor and site engineer should take more advantage of the possible fine tuning of the TBM operations, especially in adverse conditions, accordingly to the long learning curve which long lasting, well monitored projects allow.

4.3 What about reaming?
Reaming has been a major issue from the very beginning of this project; in fact, the contract specifications included the opportunity to shift the cutting head of the TBM for 15 cm in radius – on short sections going through the mapped faults for some 200 m in accordance to the contract – for overcoming adverse rock mass conditions requiring a thicker reinforcement and enough comfort for controlled displacements. Accordingly to the literature, no successfully reaming hasn’t yet been carried out in crystalline hard rock.

Actually, any attempt to reaming up to 30 cm in diameter on the section of Bodio failed since the beginning of the operations because of technical problems. Those problems were considered to be insuperable from both the technical and the contractual point of view. As a result, the contractual parties agreed to close any dispute: the owner abandoned the request accepting an equitable technical proposal for replacing
reaming – shift of 10 cm in diameter – along with a fair price adjustment.

5 CONCLUSION

The accident occurred to the western TBM driving the longest section of the Gotthard Base Tunnel would cause delay and extra costs due to the compulsory stop of the operations.

It is not the goal of the authors to argue hereby on the liabilities of the contractual parties.

The goal of the paper is to incentive the discussion on the way to improve TBM operations in deep, long tunnels taking benefits from the experiences learned on the Bodio site and, last but not least, to generally question the ones involved in full face, mechanized tunnelling: still reaming a challenging issue for hardrock TBM manufacturers or is just a designer’s chimera?

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SISO, Site Information SOftware, www.sisonet.ch