Proceedings of the World Tunnel Congress 2017 – Surface challenges – Underground solutions. Bergen, Norway.

The Challenge of Proving the Feasibility of a TBM drive in Weak Rocks at the Bossler Tunnel in Germany.

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ABSTRACT: The 8.8 km long Bossler tunnel is a twin-tube railway tunnel near Stuttgart. A TBM drive was initially considered impossible in the centre section of the tunnel due to weak rock. Using the benefits of an intermediate access tunnel constructed in advance to the critical sections of the tunnel, a value engineering approach was developed which allowed a reassessment of the ground parameters through in-situ testing, large-scale monitoring and back-analysis. For this purpose a 50m deep shaft was also built. The additional investigations showed that the rocks have about twice the stiffness and a higher strength than originally estimated from the drill cores. With the new parameters the feasibility of the TBM drive was confirmed. In the meanwhile the TBM has passed the critical section in one tube successfully.

1 INTRODUCTION

In the region of Stuttgart two large projects are currently under construction: Stuttgart 21, the re-arrangement and upgrade of the transit railway connections in the region of Stuttgart itself, including a new connection to the airport, will cost about 6.5 Billion Euros. Further, the approximately 60km long new railway line Wendlingen – Ulm (Figure 1), which comprises 5 tunnels and ca. 40 bridges and will cost about 3.3 Billion Euros. About 50% of the section will be in tunnels. This section will be in operation by late 2021.

The core component of the section Wendlingen-Ulm is the Albaufstieg, which includes the 8.8km long Bossler tunnel and the 4.8km long Steinbuehltunnel. Two ca. 480m long bridges will span across the Filstal valley between the tunnels.

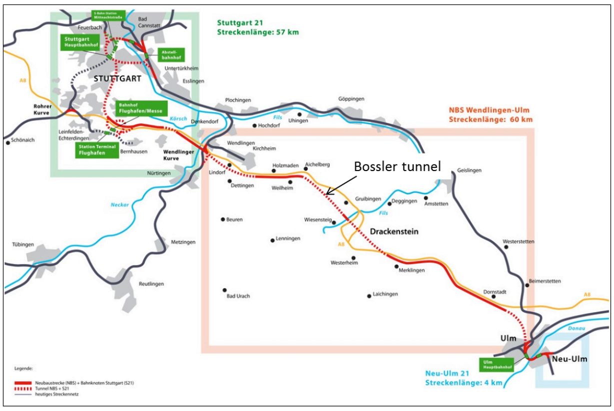

Figure 1. New railway construction Stuttgart 21 and Wendlingen-Ulm.

2 GEOLOGICAL SITUATION

In the lower section of the tunnel the geological situation is characterized by claystones and mudstones with minor layers of sandstones (Figure 2). The lower 3km of the tunnel are in reasonably strong Opalinus clay (brown in Figure 2). The following mudstones (orange) are relatively weak. In the upper section of the tunnel limestones dominate (pink and blue). Close to the upper tunnel portal significant carst features were expected. Mainly, two sets of discontinuities were predicted in the claystones, the almost horizontal bedding planes and subvertical joints. A number of faults were predicted, where the rock mass has a vertical offset. The extent of the faults was considered to be very small.

3 THE FEASIBILITY PROBLEM

During the early investigation period in the late 1990's and early 2000's a considerable number of deep core drillings had been driven into the rock formation to determine the build-up of the layers and to establish the rock mass properties. Dilatometer tests were made together with laboratory tests at cores to determine UCS and E-Modulus. Based on analyses in the earlier design phases Deutsche Bahn concluded that a TBM drive would not be feasible in major sections of the tunnel and allowed alternative bids using TBM only for a length of 2.8km from the lower portal (Figure 2).
In the geotechnical baseline report the rock mass was characterized by stiffness data for the mass, and strength data for the rock and discontinuities. This characterization is geared to the use of a multilaminate (or ubiquitous joint) constitutive model (Wittke, 2014) where the shear strength of the rock mass is mainly driven by the yield criteria in the planes of the discontinuities. The use of this constitutive model was a requirement of the tender. Further, the relaxation of the rock mass in the shield section of the TBM was limited to elastic deformation; all plastic deformation had to be charged to the segmental lining.

The clay- and mudstones in the lower half of the tunnel were characterized by the parameters in the tender documents given in Table 1. Feasibility calculations with the ubiquitous joint model and 250m overburden produced very high forces in the segmental lining: ca. 12.000kN normal force for the normal load case; more than 20.000kN normal force was expected for the case of a stopping TBM drive where time-dependent deformation of the rock mass might occur. With the 65cm thick segmental lining in the middle section of the tunnel, and the reduced capacity at the longitudinal segment joint these loads could not be allowed for. Therefore, the owner's consultant declined the feasibility of the TBM drive in 4 sections in the middle of the tunnel (Figure 2, black lines) and considered the NATM tunnel more flexible and therefore feasible for squeezing rock conditions.

Table 1.Rock mass characteristic parameters.

	E [MPa]	UCS [MPa]	Cs [MPa]	f [°]
Al 1	1300-2000 (500-1000) **1300-2000**	10.0 (3.0) **10.0**	0.1 (0.05) **0.1**	20 (15) **20**
Al 2	300-600 (200-400) **1000-2500**	3.0 (1.5) **5.0** **(2.5)**	0.05 (0) **0.2** **(0.1)**	17.5 (15) **17.5**
Bj	1000-2000 (500-1000) **2000-3000**	5.0 (3.0) **5.0**	0.1 (0.05) **1.0**	20 (15) **20**

Legend:

Al 1	Aalenium 1 (Opalinus clay)
Al 2	Aalenium 2
Bj	Bajocium
(…)	Lower bound parameters
Cs	Cohesion at bedding planes
f	Friction at bedding planes
2000	Parameters after additional investigations

4 VALUE ENGINEERING APPROACH

The Joint Venture Porr-Hinteregger-Östu Stettin-Swietelsky (ATA) won the design and construction contract with an alternative bid including a TBM drive for the first 2.8km from the lower portal and conventional tunneling for the remaining 6.0km (two tubes each, scenario 0 in Figure 8). The design team from iC together with ATA strongly believed that the real rock conditions would be better than those expressed by the parameters of the tender. This assumption was based on experiences made at deep tunnels which showed that in-situ properties of well confined clayey rock mass are generally more favorable than what can be determined through coring and testing, which causes relaxation and weakening by moisture changes and thus changes in properties. With this in mind, the goal of the contractor was to extend the TBM drive to the maximum feasible length. However, since the achievement of this goal was not certain and the construction time running, the intermediate access tunnel had to be started; also the NATM excavation of the east tube in the downwards direction had to proceed for the case that the central section for a length of approx. 2.0 - 2.5km needed to be built by NATM.

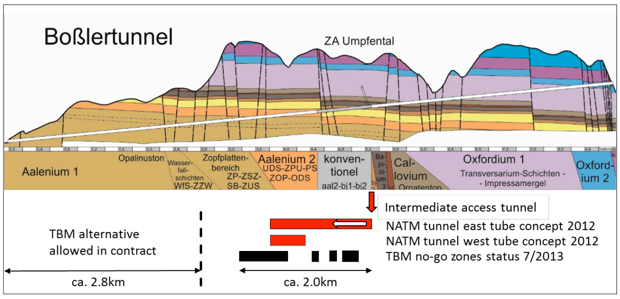

Figure 2. Sections of NATM/TBM tunnel in first value engineering approach.

The construction schedule required an intermediate access tunnel (Umpfental) to be built in the middle of the tunnel for the purpose to excavate 4 directions from there. The initial value engineering approach considered the east tube to be driven with NATM for a length of approx. 1.5km downwards and about 500m in the west tube (red in Figure 2) to eliminate the most critical rock mass Al 2 from the TBM scenario and construct the rest of the tunnel by TBM. By July 2013 the owner's consultant gave his assessment of TBM no-go zones (black in Figure 2) which extended the critical section further down and covered a total length of almost 2.0km.

The access tunnel was planned to be excavated approximately one year before the TBM would be ready to start. Considering this time gap the design-build contractor proposed to use the initial conventional tunneling sections for additional investigations to verify the rock mass parameters. For this purpose the following additional investigation efforts were proposed:

- In addition to the normal 3D displacement measurements apply shotcrete stress cells in order to get a solid basis for back-analyses.
- Build a 50m deep, 8m dia. shaft and a 25m long test tunnel in the most critical claystone layer Al 2 to learn the full-scale behavior of this layer.
- Install horizontal inclinometers to assess the deformation ahead of the tunnel.
- Make several new dilatometer tests in the vicinity of the tunnel.
- Take additional cores from short holes and perform lab testing on UCS and E-Modulus.
- Make detailed geological classification of the tunnel faces to assess the properties of the bedding planes and joints.

Parallel to the technical concept of gathering new data the contractor ATA and the Owner Deutsche Bahn Projektbau GmbH initiated commercial negotiations to create mutual interest for various scenarios of extending the TBM drive. For the best case of continuous TBM drive in the Western tube, a considerable, two-digit million Euros benefit was expected to be recovered by both parties.

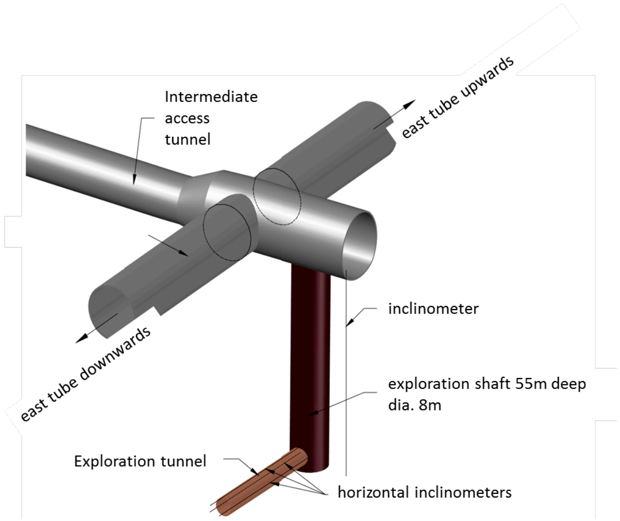

Figure 3. Layout of exploration shaft and tunnel.

5 RESULTS OF NEW INVESTIGATIONS

A first and very useful input regarding the Bajoicum (Bj) formation was provided by back analyses in the lower section of the access tunnel based on the combined data from displacement and shotcrete stress measurement. The direct stress measurements were very useful, although the interpretation of the stress cell pre-stressing was difficult. In the later stage, the pre-stressing was therefore omitted. A horizontal inclinometer was useful to assess the deformation in front of the tunnel face. Dilatometer tests gave additional input regarding the stiffness of the rock. It was remarkable that the dilatometer test that were performed in dry holes gave results which could be directly correlated to reasonable values from the back analyses, without considering scale effects. The tests in wet holes gave too low values.

The combination of many data allowed a relatively narrow assessment of the rock mass parameters and even the primary stress conditions. The small displacements suggested that the stiffness of the Bj rock mass should be considerably higher. The swift decay of the displacement trends suggested predominantly elastic behavior. The distribution of displacements and stresses in the circumference (see Figure 4) of the tunnel could only be correlated to the upper boundary of horizontal stresses with k_0=1.0.

The most critical formation Aalenium 2 (Al 2) was investigated mainly by a 3.6m dia. test tunnel (Figure 5). The lining of the test tunnel was interrupted by 4 longitudinal 'slots' with low-resistance deformation elements (200kN), see Figure 6. This arrangement was intended to provide the most direct response of the rock mass to the excavation of the tunnel with least influence of the lining support. In fact, the displacement in this tunnel was in the range of 1cm and the deformation elements showed a maximum contraction of 2cm. The face of the tunnel stood without visible deformation. This almost full-scale test convinced the parties that the potential highly yielding rock conditions would not occur. The parameters for the Al 2 formation could thus also be modified through back-analysis, additional dilatometer and laboratory tests.

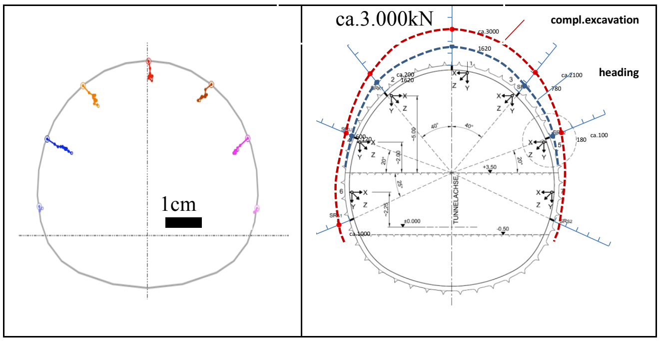

Figure 4. Typical displacement measurement in Bj formation (left) and normal force in lining (right).

The less critical Aalenium 1 formation was not tested to the same extent. However, the data gained from additional boreholes in the shaft bottom allowed eliminating the lower parameters as basis for design.

The new parameters, agreed after all additional investigations, are given in table 1 in red. The stiffness of the rock mass could now be assumed mostly with a factor of 2 to 3 higher, the strength of Al 2 considerably higher, and lower values could be eliminated. The in-situ stress conditions were then considered to be close to k_0=1.0. This formed a new basis for numerical analyses and design of the segmental lining. The feasibility of the segmental lining was subsequently confirmed in due course.

Figure 5. Exploration tunnel in Aalenium 2 formation.

Figure 6. 200kN yielding elements.

6 PERFORMANCE OF TBM DRIVE IN CRITICAL SECTION

In the initial 3km of the tunnel within the opalinus clay the TBM drive went very well. The tool wear was very low, the rock mass almost tight and homogenous. Air pressure of 1.0 bar was used to facilitate TBM steering. A bi-component mortar was used to fill the annular ring. The accuracy achieved with this measure with respect to the position of the lining segments was excellent.

Figure 7. Accurate segmental lining

Within the Aalenium 2 formation the mix of sandstones and weak claystones caused water ingress, considerable tool wear, clogging and minor face instability. The TBM mode was therefore changed to EPB and thus enabled regular conditions. The average speed in this section was finally some 12 – 14 m/d. Tools had to be changed every 50 to 80m. All in all this section went without major problems and the TBM could drive successfully into the NATM tunnel driven 800m downwards from the intermediate access tunnel. Within this section the final lining was also built with the TBM in segments. For that purpose rails were installed in the invert and the tunnel backfilled to about 50% of the height.

7 CONTRACTUAL DEVELOPMENTS

The fact that the site was progressing while the construction method for the tunnel was under development caused considerable uncertainty and stress for all parties (Breidenstein 2016). All together some 11 scenarios (Figure 8) were negotiated within the time period from 2012 to 2016. Besides the section with the weak claystone in the middle of the tunnel a carstified zone in the upper end of the tunnel was under dispute and required considerable additional investigations. After 18 months of tunneling the TBM broke into the South portal in November 2016.

In the end, 90% of the east tube was driven by TBM and it is expected that 100% of the west tube will be built with the TBM (scenario 11 in Figure 8). A huge effort for additional investigations and contractual negotiations was rewarded by a big result.

8 CONCLUSION

Based on the earlier investigations from vertical boreholes weak claystones were expected in the middle section of the Bossler tunnel. Expected heavily squeezing conditions caused Deutsche Bahn to exclude a TBM drive in the tender requirements. The contractor ATA, hoping that the in situ rock conditions would be good enough for TBM construction, proposed a major additional investigation program parallel to the initial construction stages. This program included a 55m deep shaft, a test tunnel and a full scale NATM excavation of some 1.700m tunnel. The properties of the rock mass determined by back analysis and in-situ tests were considerably better than originally anticipated and highlight the difficulty to assess rock mass parameters for weak rocks from deep core holes. Based on the new data the feasibility of the TBM drive could be confirmed step by step with a very short lead time to the progressing excavation works. In the meanwhile the east tube is completed and the west tube will be entirely built by TBM from April 2017 onwards.

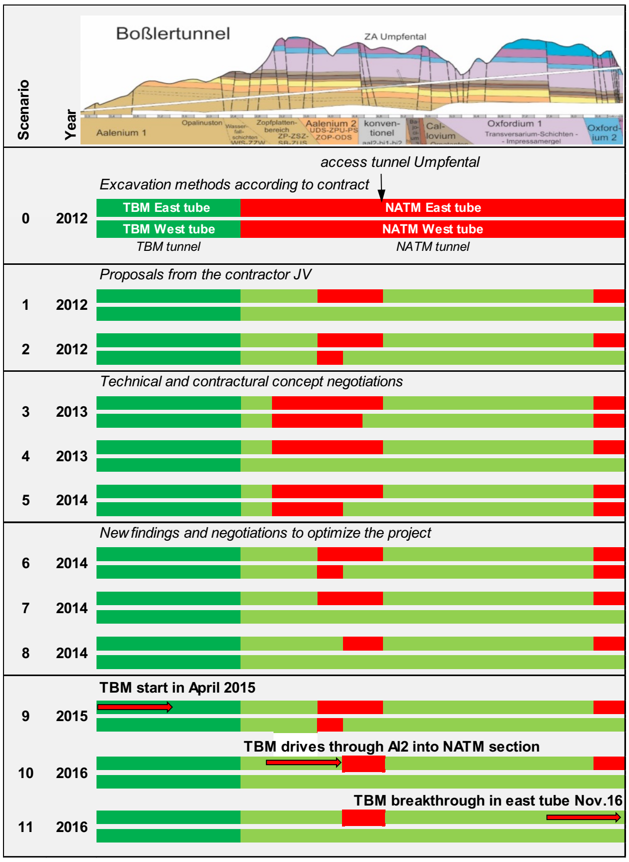

Figure 8. Contractual scenarios during evolution of the technical concept.

REFERENCES

Wittke, W.: Rock Mechanics based on an Anisotropic Jointed Rock Model (AJRM), Verlag Ernst & Sohn GmbH & Co. KG, Berlin 2014. ISBN-Nr.: 978-3-433-03079-0.

Breidenstein, M.: Bahnprojekt Stuttgart–Ulm: Der Albaufstieg – Partnerschaftliche Anpassung eines komplexen Bauvertrags nach Vertragsschluss TASCHENBUCH FÜR DEN TUNNELBAU 2016 Deutsche Gesellschaft für Geotechnik e.V., Pages: 285–306, 2016