50 km of Tunnels in Inner-City Areas – Rock Mechanics and Tunneling Issues in Connection with the large-scale Railway Project Stuttgart 21 – A Success Story

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ABSTRACT: For the large scale railway project Stuttgart 21 more than 50 km of tunnels were constructed in the city of Stuttgart. Currently, the tunneling works at the new airport station are carried out, while the other tunnels have already been finalized. In connection with the project, numerous challenges of rock mechanics and tunneling have been solved from the design point of view as well as from the construction point of view. These are – amongst others – 17 km of tunnels in anhydrite, full face excavation of large cross sections with A > 200 m², compensation grouting, TBM tunneling in sedimentary rock, various underpinning measures and the excavation of complicated large shafts and tunnel structures in geologically pre-stressed clay stones of the Jurassic. The paper gives an overview on the project and presents some of the highlights of rock mechanics.

Keywords: Tunneling, Rock Mechanics, Swelling Rock, Large Cross Sections, Underpinning, AJRM.

1 INTRODUCTION

The tunnels of the railway project Stuttgart 21 have been designed and constructed following the AJRM, Wittke (2014). In connection with design and construction of these tunnels and also of the tunnels of the railway line from Wendlingen to Ulm, a considerable improvement of the understanding of the behavior of the various rocks of the Keuper formation as well as the Black, Brown and White Jurassic has been achieved, WBI GmbH (2015 - 2019, 2021 - 2022). After heading works – besides in the area of the airport – have come to an end in 2022, in the given article selected highlights in connection with this improved understanding will be presented.

2 RAILWAY PROJECT STUTTGART – ULM

The railway project Stuttgart – Ulm provides the high-speed connection between the cities of Stuttgart and Ulm in Germany (Fig. 1). In the area of the city of Stuttgart, the existing dead-end station will be changed to an underground through-going station, which in view of the topographic situation in the area will be connected to the existing line in the Northwest through the Tunnel

Feuerbach. Further connections to the existing railway network will be provided through the tunnels to Bad Cannstatt as well as the Tunnels to Ober- and Untertürkheim. The longest tunnel of the project, the Fildertunnel, will provide the connection to the airport of Stuttgart, where a new underground station is under construction, as well as to the new high-speed railway line to Ulm, which has been partially inaugurated in December 2022.

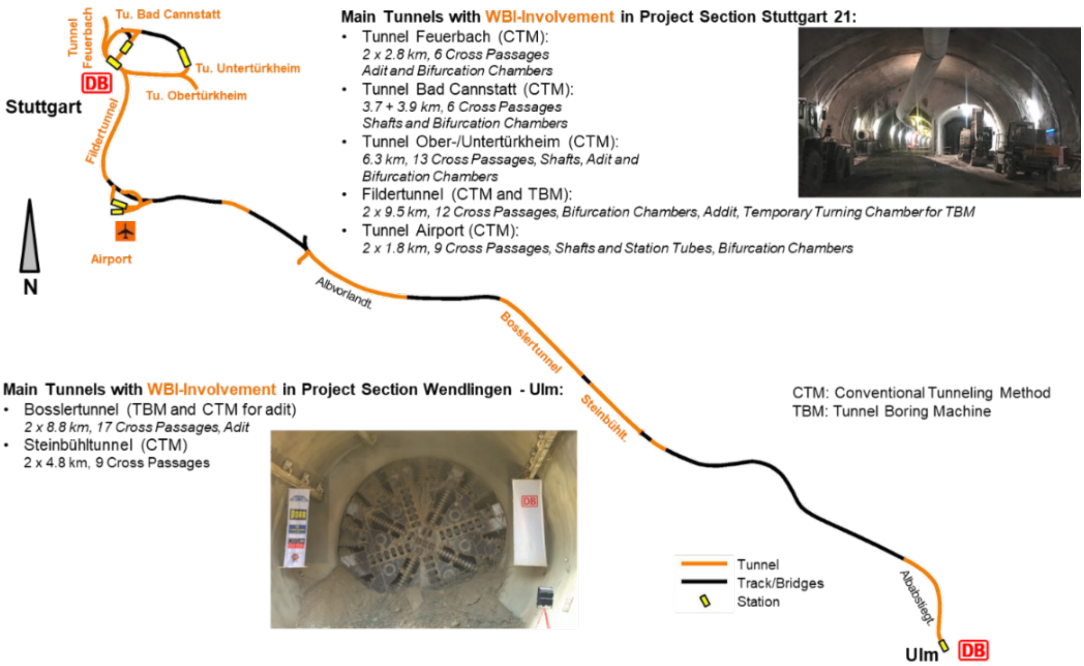

Figure 1. Railway Project Stuttgart – Ulm.

3 GEOLOGICAL OVERVIEW

The tunnels of the high-speed railway line to Ulm are located in the rocks of the Black, Brown and White Jurassic. The tunnels in the area of the city of Stuttgart, on which the paper focuses, are mainly located in the Triassic Keuper Formation (Fig. 2, Geologisches Landesamt Baden-Württemberg (1963, 1986, 1994)). Only in the southern section of the Fildertunnel as well as in the area of the connection to the Airport of Stuttgart, the rocks of the Black Jurassic prevail. Details on the different formations can e. g. be found in Wittke (2014), WBI GmbH (2015 - 2019, 2021 - 2022).

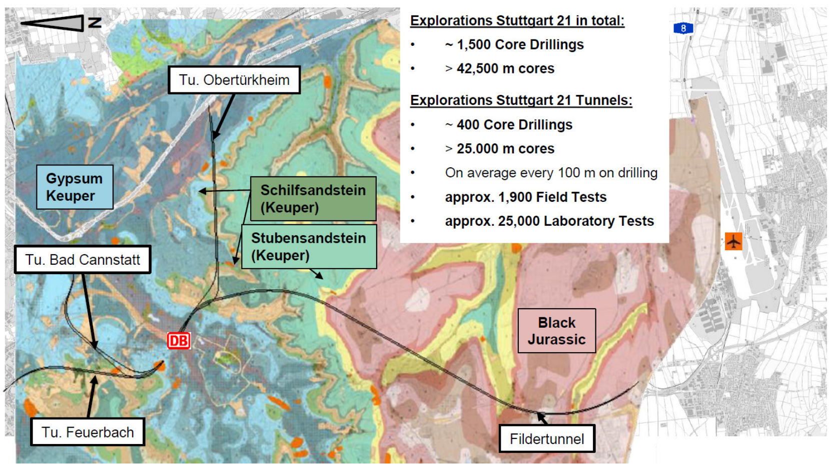

Figure 2. Plan View of Stuttgart 21 and Geological Units at Surface.

4 ROCK MECHANICS AND TUNNELING IN GYPSUM KEUPER

In the given paper, special emphasis is placed on the rock mechanics as well as special boundary conditions for tunneling in the Gypsum Keuper, which is the lowest part of the Keuper formation encountered in the tunnels of the project. The Gypsum Keuper prevails in three different types.

The unleached Gypsum Keuper is a silt-/claystone which contains sulfate (Fig. 3, Wittke-Gatterman (1998), Wittke (2003), Wahlen (2009), WBI GmbH (2015 - 2019, 2021 - 2022), Wittke (2020)). In the original state the sulfate within the rock mass mainly consists of anhydrite ($CaSO_4$), which in geological times as a consequence of water penetration by means of seepage, capillary suction and diffusion is transformed into gypsum ($CaSO_4 \cdot 2H_2O$). The gypsum again is dissolved in groundwater and is transported to the recipient. The remainder is the so-called leached Gypsum Keuper, a sulfate-free residual rock.

The rock mass of the unleached Gypsum Keuper in the area of southwest Germany is more or less horizontally bedded (Fig. 3). The permeability of the unleached Gypsum Keuper is mainly determined by the discontinuities. On the basis of numerous field tests and back-analyses it can be shown that the permeability of the rock mass is much higher parallel to than perpendicular to the bedding. For the design of the support and lining (cast-in-place or segmental) as well as the prediction of the displacements the rock mechanical parameters listed in fig. 3 have been considered. These parameters were determined on the basis of the results of laboratory and field tests as well as back-analyses for executed projects. Special emphasis had to be placed on the swelling potential of the anhydritic rocks, which for full transformation of the anhydrite into Gypsum and for zero displacement can lead to swelling pressures of up to 9 to 10 MN/m² (Fig. 3, Wittke et al. (2004)). The analyses carried out to design the internal linings of the tunnels are based on the Finite Element Method. The corresponding code FEST03 enables simulation of the transient seepage, the water uptake as well as the elastic-viscoplastic behavior including swelling as well as the corresponding interaction between these phenomena (Wittke, M. (2003)).

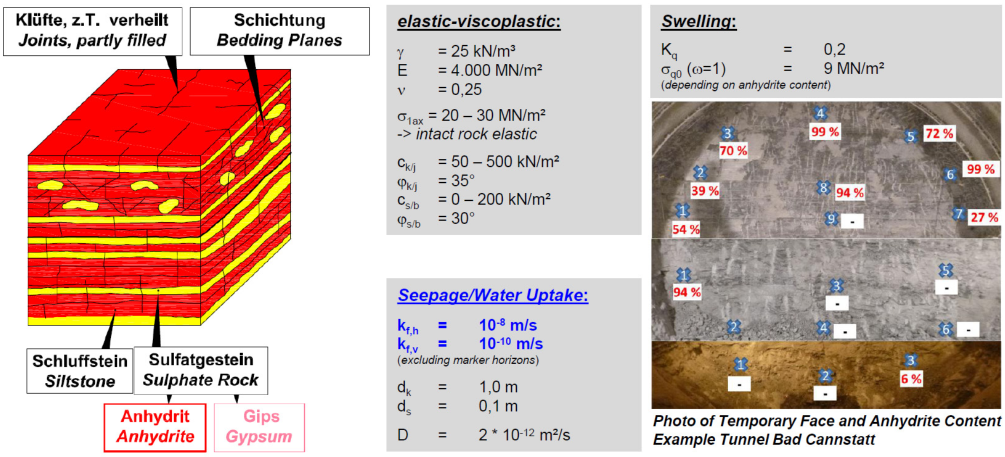

Figure 3. Unleached Gypsum Keuper, Rock Mechanical Model.

The tunnels to Feuerbach, Bad Cannstatt and Ober-/Untertürkheim were excavated by means of the conventional tunneling method (CTM, Fig. 1). Also the transition zones from the water-bearing rocks to the swelling rocks in the Fildertunnel were constructed by CTM. Only the so-called dry zones, where the water-bearing rocks have a sufficiently large distance to the tunnel and which are protected in longitudinal direction against wet areas by means of sealing structures, were constructed by TBM with a single-shell segmental lining (Fig. 1, Wittke & Breidenstein (2015)). The annular gap was filled with a special phosphate-based gap grout, Bayer et al. (2019).

It goes without saying that the construction works in the areas of the swelling rock were conducted completely dry. This requirement yielded in large efforts for dust prevention. E. g. the dust resulting from dry drilling of holes was collected immediately at the borehole by vacuum suction. In addition, in certain areas a combination of blowing ventilation and exhaust ventilation was applied. To limit formation of dust as a consequence of movement of equipment, salts were applied to the temporary roads.

In order to limit water penetration from the surrounding rocks, the leaching front was sealed by means of advanced grouting with polyurethane during heading. In addition, the remaining seepage was collected by means of vacuum lances. Radial anchors were omitted wherever possible in order to avoid potential drainages paths. After completion of heading, sealing structures and extensive grouting works using acrylate gels have been carried out in order to reduce the permeability of the rock mass in the surrounding of the tunnels practically to the natural level (Fig. 4, Wittke (2020)). The use of both grouts – polyurethane and acrylate gels – was approved by the environmental authorities.

By means of the applied measures, the headings works in the 17 km of tunnels located in swelling rocks were successfully completed when the TBM in the Fildertunnel ended its fourth drive in August 2019. For the conventional tunnel sections mean rates of advance from 2 m/d up to 5 m/d were achieved. The TBM-headings were conducted with an average rate of advance of approx. 14-15 m/d.

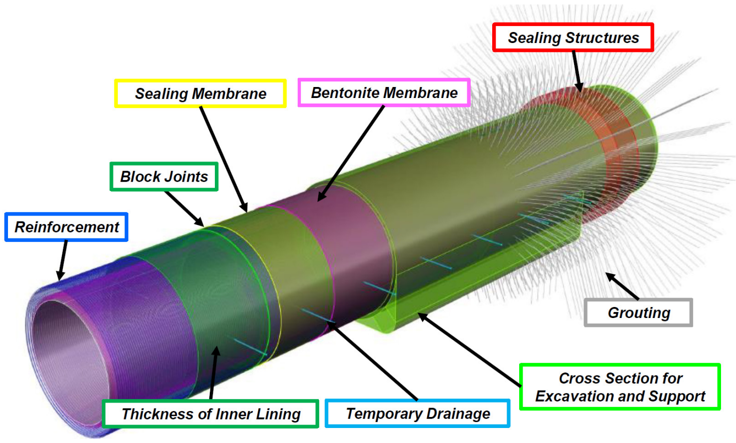

Figure 4. Measures for Successful Tunneling in Anhydritic Rocks.

5 ROCK MECHANICS AND TUNNELING IN BLACK JURASSIC

For the connection of the new railway line from Stuttgart to Munich with the airport of the city of Stuttgart, two approx. 435 m long underground station tubes have been constructed which will be connected to the main line by approx. 2 x 2.2 km long single tunnel tubes, which – as the station tubes – are mostly constructed by the conventional tunneling method CTM (Fig. 5 and 6, WBI GmbH (2015 - 2019, 2021 - 2022), Berghorn et al. (2021).

The CTM-tunnels are located in the lime- and claystones of the Black Jurassic (Fig. 7). In the latter high horizontal in-situ stresses are present, which result from a former high overburden in geological times, Wittke (2014). Based on experience and back-analyses carried out for projects in the past, horizontal in-situ stresses of approx. 0.5 MN/m² were to be expected for the tunnels in question.

The stability analyses and the prediction of the displacements were carried out on the basis of AJRM using the Finite Element Method. Special emphasis had to be placed on the consideration of the reduced shear strength along the bedding planes and the bedding parallel discontinuities respectively as well as the transversely anisotropic elastic behavior of the rock mass.

In 02.2023 already major parts of the western access, the station tubes including the bifurcation chambers for the Pfaffensteigtunnel, which will be constructed at a later point in time were successfully excavated. For all structures, the prediction of the displacements at the surface and underground were in very good agreement with the monitoring results (accuracy in the range of mm).

A special challenge were the underground connections between the station tubes and the access shafts (Fig. 5, 6 and 8). Also for these structures, modern rock mechanics enabled a safe and economic design.

As mentioned above, also parts of the Fildertunnel are located in the rocks of the Black Jurassic. Here tunneling was carried out using a TBM. By applying compressed air, it was possible to undercrosss buildings with shallow overburden without any settlements, despite of the narrow spacing of the bedding planes, which usually leads to a certain loosening in the area of the roof, Wittke & Breidenstein (2015).

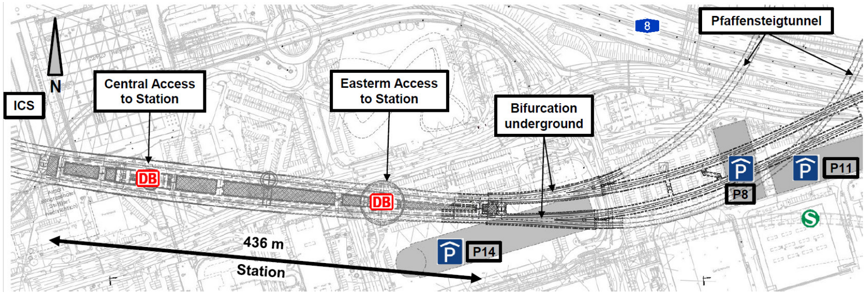

Figure 5. Station Airport, Plan.

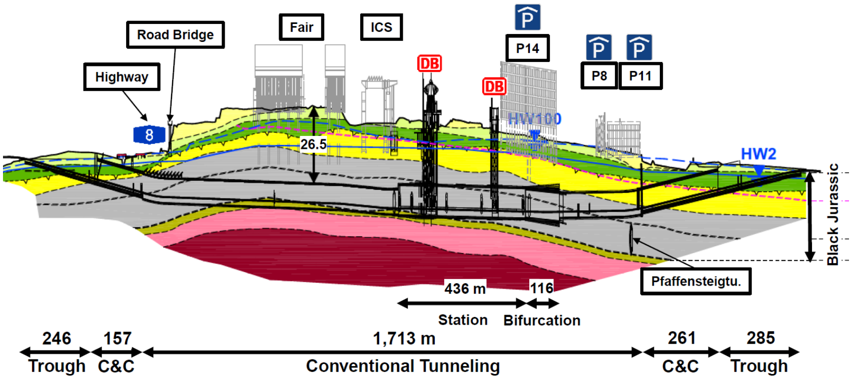

Figure 6. Connection to Station Airport, Longitudinal Section, Northern Tube.

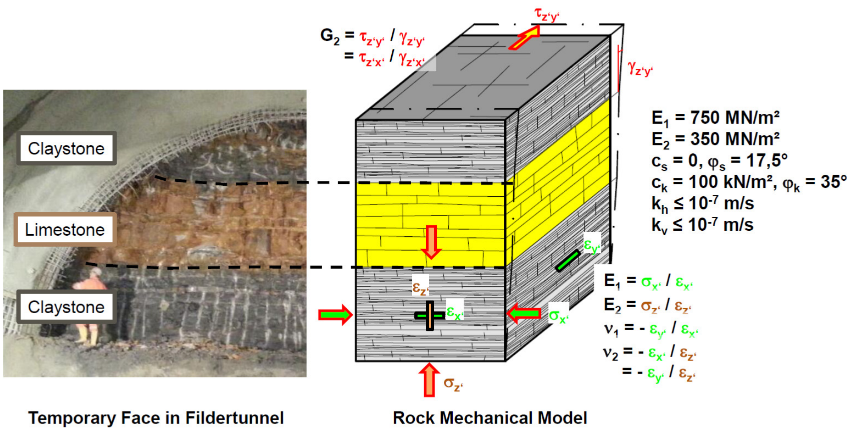

Figure 7. Black Jurassic, Intercallation of Limestones and Claystones, Rock Mechanical Model.

6 SUMMARY AND CONCLUSIONS

In October 2022 major parts of the tunnels of the railway project Stuttgart – Ulm were successfully excavated. The design and construction of > 70 km of these tunnels were based on the AJRM. It could be proven that modern rock mechanics enabled a safe and economic design for all structures.

Figure 8. Central Access to Station during Construction.

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