Brenner Base Tunnel: three DS-TBMs excavating in parallel under the Alps in Italy – Findings, difficulties and achievements from a geological-geotechnical point of view

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ABSTRACT: The Brenner Base Tunnel is a railway connection running beneath the Italian and Austrian Alps for 64 km under high overburdens. In the Italian lot Mules 2-3 a 14 km long stretch of the Exploratory Tunnel has been completed by a DS-TBM with a diameter of 6.85 m and two twin DS-TBMs are currently excavating the Main Tunnels, which are of equal length but have a diameter of 10.71 m. The geological context consists of metamorphic geological units ranging from gneiss, micaschists, phyllites to marbles and intercalations of evaporitic units. About 21 significant fault zones were crossed. Due to different geological factors four standstills occurred in the Exploratory Tunnel, six in the western and two in the eastern Main Tunnels. In order to early detect and manage these critical zones, an accurate geological forecast, advance explorations, geological documentation and a continuous analysis of the machine and monitoring data are required.

Keywords: Brenner Base Tunnel, Double Shield Tunnel Boring Machine (DS-TBM), Exploratory Tunnel (ET), Main tunnels (MT-W, MT-E), High Overburden, Geological documentation.

1 INTRODUCTION

The BBT is a system of underground structures currently being excavated to build a high-speed railway connection between Fortezza (Italy) and the city of Innsbruck (Austria). The project consists of two main one-track tubes (MT-W, MT-E) and an exploratory tunnel (ET). (Fig. 1).

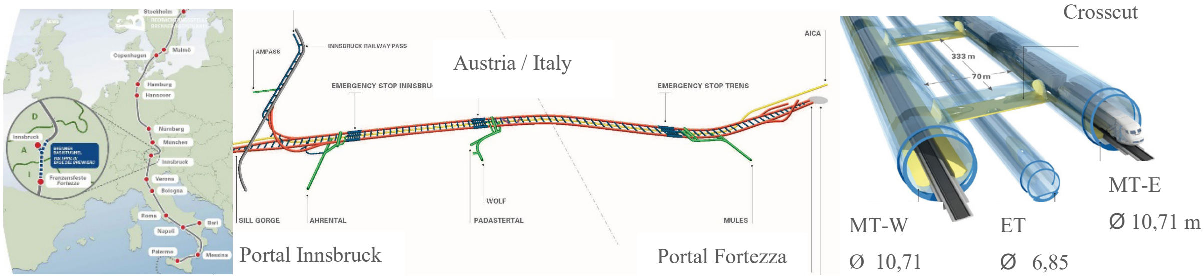


Figure 1. General layout of the BBT system (www.bbt-se.com).

2 GEOLOGICAL-GEOTECHNICAL PROGNOSIS VS AS BUILT

2.1 *Geological prediction and as built situation*

The geological hydrogeological and geotechnical model was created based on an extensive and state of the art exploration program (Skuk et al., 2022). The main predicted and encountered geological units and hazards along the tunnel route are described and briefly characterized as follows, from the South to the North (see Fig. 2. Geological forecast model for colors).

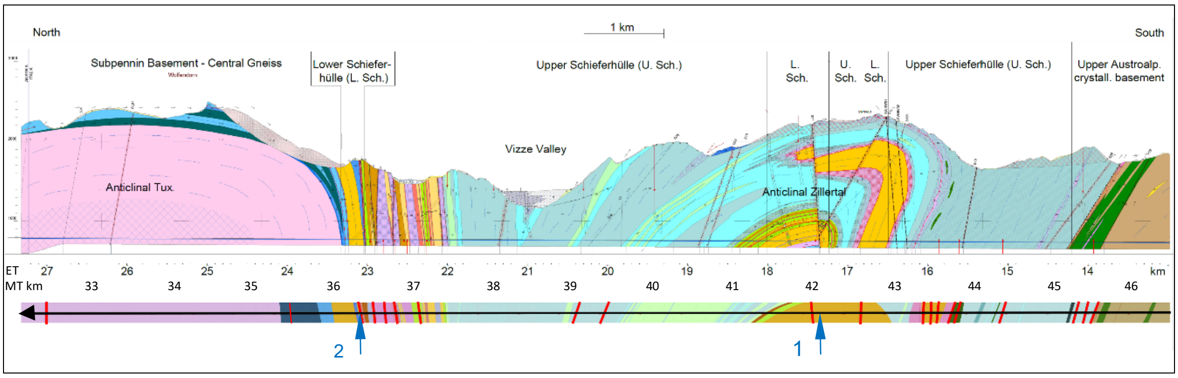


Figure 2. Geological forecast model (upper graphic) – black arrow representing the directions of the three TBM-drives and draft as built model (lower graphic) with the main encountered fault zones (red lines).

Upper Australpine crystalline basement (brown and dark green) with a total length of 1200 m and an overburden between 1000–1100 m. The most frequent rock types are paragneisses and mica schists and secondarily amphibolites.

Rocks of the Upper Schieferhülle with a total length of 7680 m and covers between 620–1580 m. The Bündner schists (light blue) represent the main unit and consist of heterogeneous rocks occurring in alternating layers: glimmer marbles, limestone mica schists, carbonate quartzites, phyllites and prasinites. In the contact zone of the Lower Schieferhülle there are formations with Triassic inclusions, namely the Seidlwinkel and the Aigerbach formations (green, brown and violet). The Seidlwinkel formation are massive layered limestone dolomite marbles. The Aigerbach formation consists of layers of chlorite phyllites and limestone schists, mica quartzites, dolomite marbles, meta-arkoses, meta-conglomerates and phyllites, besides anhydrite, chalk or rauhwacke.

Rocks of the Lower Schieferhülle (blue, orange) with a total length of 1440 m and overburdens between 740–1610 m. The lithologies are quartzite glimmer marbles and limestones and dolomite marbles, and Triassic units such as glimmer marbles, quartz schists, chlorite schists and anhydrite schists. Part of the anhydrite schists are present in a changed form, in layers of chalk and rauhwacke ranging from 1 to 10 m in thickness. Furthermore, there are the rocks of the Kaserer formation, consisting mainly of phyllites, mica schists, quartzite, metaconglomerates and prasinites. The Hochstegen formation at chainage 23.3 consists of a 40 m-thick layer of mostly dolomitic limestone.

Subpennine Basement – Central Gneiss (pink) with a total length of 3930 m and overburdens between 940–1720 m and consist mainly of granite gneisses, granodiorites and diorite gneisses.

During the excavation all geologic units were encountered and the shifts in the lithologic boundaries are within the range of normal forecast inaccuracy of deep-lying tunnels. The largest differences between forecast and as built situation are (Fig. 2):

- The contact between Upper Australpine crystalline basement and Upper Schieferhülle was encountered 300 meters further south than expected;
- The southern part of the Zillertal anticlinal is extended by 700 meters to the south;
- In the Upper Schieferhülle prasinitic units were encountered more frequently than predicted;
- Graphite-disthene quartzites were encountered instead of central gneiss for a stretch of nearly 500 meters, which had been predicted in the geological profile but not expected at tunnel level;
- The central gneiss was encountered 600 meters later than predicted.

From a hydrogeological point of view the temporary and stationary water inflows observed are lower than expected. The feared interference with surface hydrological systems, e.g. the Kaltwasser spring and the Brenner thermal spring in the Hochstegen marble zone, did not occur. The total amount of temporary water flows in the ET was predicted in 250-300 l/s, which has never been reached. The stationary water flow in the ET amounts to 60 l/s compared to the 80-100 l/s estimated.

2.2 Geotechnical aspects, main hazards - prediction and as built situation

The predicted main hazards were:

- Squeezing rock mass up to instability in the fault zones and due to sub-horizontal schistosity;
- Triassic units, rauhwacke horizons with potential unstable behaviour, anhydrite schists with possible swelling behaviour and water with aggressive properties towards concrete;
- Water inflows and interferences with the Brenner hot springs in the Hochstegen marble zone;
- Rock burst in areas of hard rocks with high overburden and close to fault zones.

The geotechnical prediction and the parameters for lithologies and rock masses proved to be correct. The rock mass was classified according to the RMR and GSI system and after the ÖGG-guidelines (ÖGG, 2014). Systematically every 500 meters and in fault zones, the lining segments were equipped with strain gauges. In general, a trend toward stabilization was observed after 3 to 6 months. In geotechnically weaker zones, the influence of the excavation of bypass tunnels or of the main tunnel, at a distance of 35 meters from the exploratory tunnel, became apparent but not critical. No new hazards were manifested and the predicted rock burst phenomena in the central gneiss did not occur. The greatest difficulties were related to:

- Dissymmetrical squeezing, caused by the horizontal schistosity in the Zillertal anticlinal, led to the shield jamming of the TBM in the ET;
- Squeezing rock mass up to instability in faults and rauhwacke horizons, led to a total of nine TBM standstills in all three tunnels;
- Squeezing rock mass together with water inflows caused a shutdown of the TBM in the MT-W.

3 THE TBM EXCAVATION OF THREE PARALLEL TUNNELS

3.1 The main characteristics of the DS-TBMs

The employed hard rock machines are specially designed and equipped by the manufacturer Herrenknecht to overcome the predicted hydro-geological hazards. The main technical features of the DS-TBMs are summarised in Table 1.

Table 1. Main technical features of the three DS-TBM S-1054, S-1071 and S-1072.

Technical features	S-1054 Exploratory Tunnel	S-1071 / S-1072 Main Tunnels
Main drive power	2,800 kW	4,200 kW
Thrust main cylinders (nr.)	42,750 kN (10)	95,000 kN (18)
Thrust auxiliary cylinders (nr.)	57,000 kN (16)	112,815 kN (38)
Shield + Cutterhead length	12,000 mm	12,480 mm
Conicity / Max overbore	95 mm / 224 mm	115 mm / 224 mm
Nominal torque / Rotational speed: range I and range II	I: 5,247 kNm / 0-9,0 rpm II: 10,574 kNm / 0-4,5 rpm	I:13,601 kNm / 0-5,11 rpm II: 27,524 kNm / 0-2,55 rpm
Cutter nr. / diameter / spacing	41 / 19 " / 90 mm	64 / 19 " / 90 mm
Shield monitoring (nr.)	Pressure cells (6) Fontimeters (5)	Pressure cells (6) Fontimeters (3)

3.2 The role of the exploratory tunnel

Thanks to the preliminary excavation of the exploratory tunnel it was possible to identify the local hydro-geological conditions and to monitor the system behaviour, in order to handle critical zones such as faults, extreme hard rock and squeezing rock mass conditions. An advanced prospection and monitoring plan was developed, consisting mainly of the following measures:

- Systematic 150 m long and overlapping boring with measurement while drilling;
- Systematic and overlapping seismic prospection using TSP (by Amberg Technologies);
- Continuous recording of TBM parameters at 3-second intervals and TBM shield monitoring;
- Continuous recording of acoustic emissions by geophones to prevent potential rock burst phenomena in zones with high overburden and extreme hard rocks;
- Periodical geological face mapping, rock mass classification and sampling of rock specimens during the daily maintenance phase to check both the forecast model and the results of the advance probing and to correlate this data with the TBM operational parameters;
- In fault zones and hydrogeological risk zones additional OPTV (Optic Televiewer) borehole cameras and core drillings up to a length of 30-40 m to improve the systematic advance probing.

3.3 Achieved advance rates

During the excavation of this 14.2 km stretch of the exploratory tunnel, over a period of about three and a half years, four standstills occurred due to adverse geological and hydrogeological conditions (Fig. 3). The significant events at chainage 15+689 (33 days), caused by a large fault zone and at chainage 17+332 (43 days), due to dissymmetrical displacements caused by horizontal schistosity in the Zillertal Anticlinal (chapter 3.4) are described in more detail in Skuk et al., 2022.

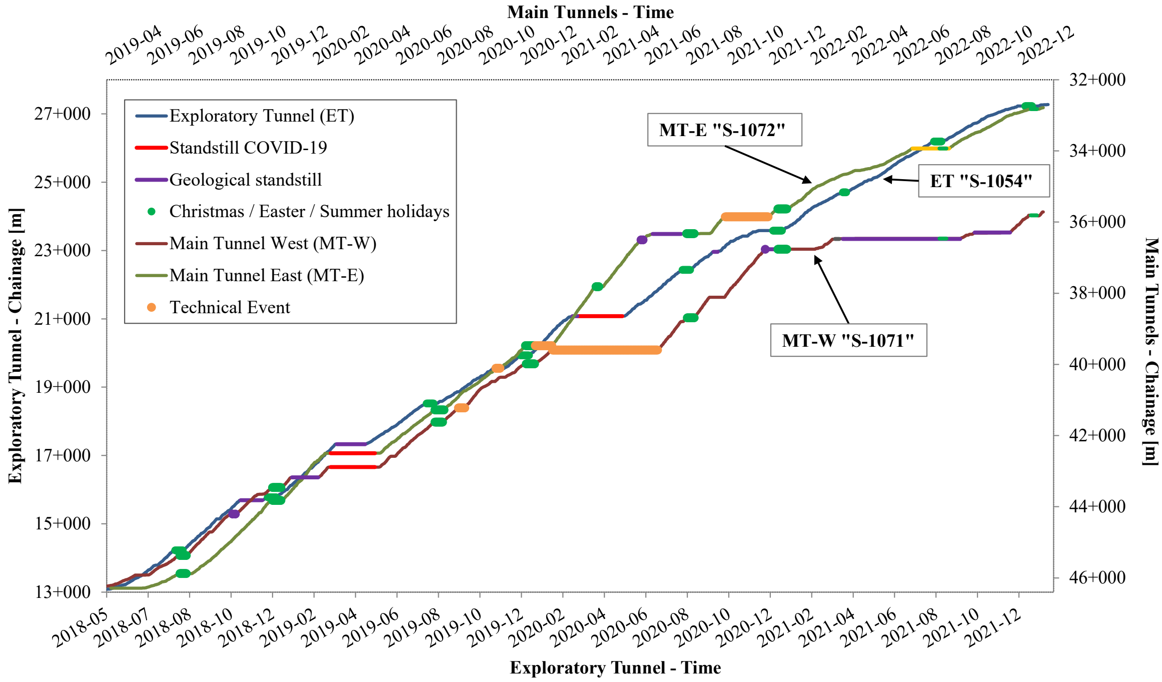


Figure 3. Advance rate of the DS-TBMs – total production and major standstills on 9th January 2023.

The TBM advance of the main tubes northwards started in spring 2019 and after three and a half years a total of 24.0 km have been completed. To date there have been six standstills caused mainly by critical geological conditions in the West MT (MT-W) and two in the east MT (MT-E). The most significant events in the MT-W occurred at chainage km 44+205 (6 days), 43+715 (14 days), 43+176 (39 days), 36+763 (71 days), 36+476 (176 days) and km 36+294 (51 days) due to significant fault zones and the necessity of detailed advance probing and rock mass drainage and consolidation measures to cross them. As regards the MT-E only two stoppages were necessary at chainage km 36+501 (4 days) and 36+336 (83 days) due to detailed advance probing and rock mass pre-consolidation measures to handle critical fault zones. Moreover, in both tunnels other significant stops occurred due to the Covid-19 pandemic, technical shutdowns for extraordinary maintenance and some breakages in the conveyor belt (Fig. 3).

3.4 Difficulties and solutions

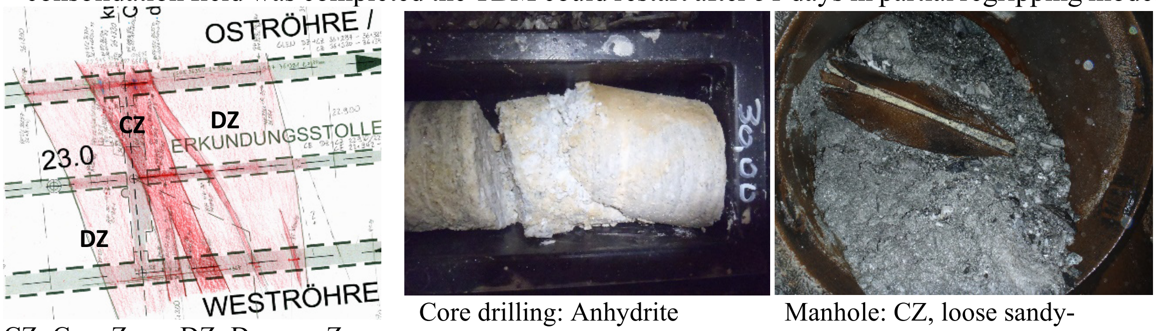
Due to the high overburden of 1500 m and the sub-horizontal schistosity close to the core of the large-scale Zillertal anticlinal, crown displacements caused shield jamming of the ET's TBM at chainage km 17+332 (see Fig 2 blue arrow no 1). The dry rock mass is composed of horizontal banks of meta-arcoses with cm-dm intercalations of quartz and layers of quartz mica schists characterized by medium to high UCS values (Kaserer Formation). To restart the TBM, a 13 m long lateral tunnel was excavated by drill & blast method, in order to free up the shields (Fig. 4). After filling the tunnel and the area in front of the cutterhead with pea gravel, cement injections and expanding urea-silicate resin, the TBM was freed through thrust attempts in single shield mode (Skuk et al., 2022).

Figure 4. ET standstill at chainage km 17+332. Pictures of the lateral tunnel to free the TBM.

To manage the sector subject to dissymmetrical displacements, based on back analysis of the shield monitoring data, it was decided to increase the standard gap by 100 mm, by shifting the cutterhead and using external cutters with a 20" diameter. After the excavation of the ET through this zone, this extraordinary cutterhead configuration was also successful applied in the main tunnels.

The largest fault zone of the Mules 2-3 lot (Fig. 5), predicted in the forecast model as fault Vi-5-755, develops in a lithologically highly heterogeneous sequence of the Aigerbach formation composted of quartz and black phyllites, anhydritic scists, gypsum (rauhwacke), chlorite phyllites and marbles (from south to north). Its total length is about 80 m (17 m CZ) in the ET, respectively 61 m (25 m CZ) in the MT-E and 73 m (17 m CZ) in the MT-W. The CZ consists of loose, fault rocks like kakirites (sandy-gravely material), subordinated fault gouge (plastic material) and decompressed anhydritic-cloritic schists partially converted in gypsum. There is negligible water inflow and the identified rock mass behaviour for the CZ is ravelling ground.

This fault zone was encountered for the first time during the TBM drive of ET at chainage km 22+962 (see Fig. 2 blue arrow no 2), where a 6-day standstill occurred due to face instability, advance probing and injections works of organo-mineral foams in the face and crown area. The TBM restarted in single shield mode and crossed the zone in partial regripping mode. The TBM of the MT-E crossed the fault for the second time between chainage 36+336 and 36+275, where due to extensive rock mass improvements a standstill of 83 days occurred. The geological information from the ET and MT-E proved to be essential to stop the TBM at chainage km 36+312 just in time for further investigations. By means of two core drillings, it was possible to design the rock mass consolidation measures in detail. It was performed in two main phases: Phase 1 – injection works at the crown by radial drillings through the front shield and on the face by sub-horizontal drillings through the cutterhead with organo-mineral foams; Phase 2 – pre-consolidation works at the crown by 8 drillings from the gripper shield up to 12 m beyond the face, cement mantle grouting through GRP sleeve pipes and subsequent selective micro-cement grouting valve per valve by using double packers. After the excavation of 8 m in single shield and partial regripping mode the phases 1-2 were repeated, subsequently an excavation of 10 m was performed with an average hub length of 1.75 m. Once the 3rd consolidation field was completed the TBM could restart after 51 days in partial regripping mode.



CZ=Core Zone; DZ=Damage Zone

Core drilling: Anhydrite gypsum

Manhole: CZ, loose sandy-gravely material

Figure 5. MT-W standstill at chainage 36+312. Model of the fault zone and photos of the fault material.

4 CONCLUSIONS

Our most important geological-geotechnical findings for the success of a project are listed below:

- An excellent geological, hydrogeological and geotechnical forecast is required.
- In the case of several parallel tunnels, an extensive exploration program must be carried out during the first excavation. Continuous overlapped advance probing and core drilling in case of uncertain geological conditions are a must to detect critical zones in time.
- The examination of the rock cores answers the question as to whether the TBM can pass through a geological fault zone without additional rock consolidation measures or not.
- A geologist has to be present on the TBM to perform a detailed geological face mapping once a day, to observe the rock conditions at the TBM windows continuously, to sight the tunnel face during short stoppages and to analyze the machine data in consultation with the TBM operator.
- Geological face mapping provides the most important information for further correlations with TBM parameters, advance drilling data, seismic data, and other geotechnical monitoring systems. Future systems will be based on artificial intelligence evaluations.
- During construction systematic geological-geotechnical laboratory tests must be carried out.
- In deep-lying tunnels, horizontal schistosity causes squeezing effects even in compact rocks. Overcutting should be applied in these sections.
- The detection of fault zones only by TBM parameter interpretation is diameter-affected. TBMs of larger diameter are much more sensitive to the higher fractured areas (Damage Zone) before they drive through the major disturbance zone (Core Zone).

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