Numerical modelling and tunneling experience of the Emergency Stop in Trens, Lots Mules 2-3 (Italy) - Brenner Base Tunnel

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ABSTRACT: The present paper focuses on the design and the construction experience related to Emergency Stop in Trens as a part of the Brenner Base Tunnel (BBT). This underground work consists in a 470 m long central tunnel excavated by conventional tunnelling connected through cross-passages every 90 m to the main tunnels excavated by TBMs-shield. The main design issues and construction challenges are represented by the complex interaction between underground structures located at two different elevations in combination with the high overburden about 1100 m and medium-low strength rock mass composed mainly of schists. The design involved 2D and 3D numerical analyses and also included swelling and creep. A comparison between the forecast geology and the cross-check will be analyzed also considering the data from the in-depth monitoring system. The comparison between Design and As-Built in terms of installed rock-supports, timing and costs will be examined in detail.

Keywords: TBM and conventional tunneling, deep and long tunnel, BBT, numerical analysis.

1 GENERAL LAYOUT

The Brenner Base Tunnel, with its 64 km long, will be the longest high-speed railway tunnel in the world (Fig. 1). It will cross the Alps between Italy and Austria with a maximum overburden 1800 m, being a part of the Scandinavian-Mediterranean European Corridor 5 (Insam et al., 2022). The project comprises two one-track 10m diameter main tunnels, each about 55 km long, located at 40 m-70 m. At 12 m below them, a 6.5 m diameter exploratory tunnel is built to minimize the risks during the excavation phase, and to optimize the logistical, safety and drainage aspects. The base tunnels are connected every 333 m by emergency tunnels. BBT project also includes a connecting tunnel to the existing Innsbruck connection, 3 Emergency Stops (FdE) 20 km spaced, 4 access tunnels, logistics caverns, rescue tunnels and ventilation shafts. The total excavation length is approximately 230 km, 70% of which will be excavated using gripper or shielded TBMs. The project is financed by the European Union (40%) as well as by the Austrian and Italian governments (30% each), and the overall costs amount to 10 billion EUR. The Brenner Base Tunnel (BBT) incorporates the latest safety standards in tunnelling. The present paper focuses on the construction experience related to the construction of the Italian Emergency Stop in Trens. The main design and construction challenges are: i) complex interaction between underground structures located at 2 different elevations; ii) medium-low strength rock mass composed mainly of schists as described in the following; iii) high overburden.

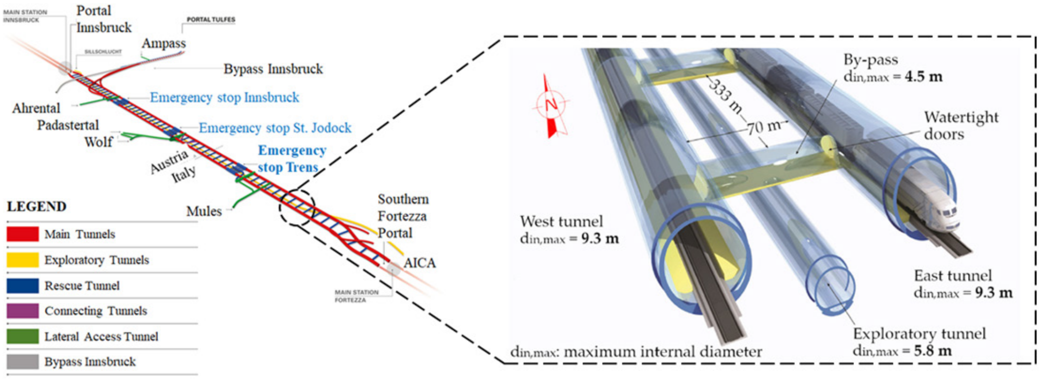


Figure 1. Brenner Base Tunnel overview and details.

2 DESIGN PHASE: THE EMERGENCY STOP IN TRENS, LOT MULES 2-3

2.1 General overview and adopted excavation techniques

The Emergency Stop in Trens (km 44+555 - km 45+025) which is part of the Mules 2-3 lot, mainly consists of a 470 m long central tunnel (FdE-CcT) connected every 90 m to the two-main tunnels via ventilation and emergency tunnels (Fig. 2). The central tunnel is divided in two parts by means of an intermediate slab that allows, in the case of a fire, the extraction of smokes and the supply of clean air. The upper part of the central tunnel is connected with the exhaust air ducts crosscut, while the lower part is linked with the cross-connection tunnels (CC) and ensures the access of the rescue vehicles and allows fresh air supply. Below the Emergency Stop is located the exploratory tunnel (CE).

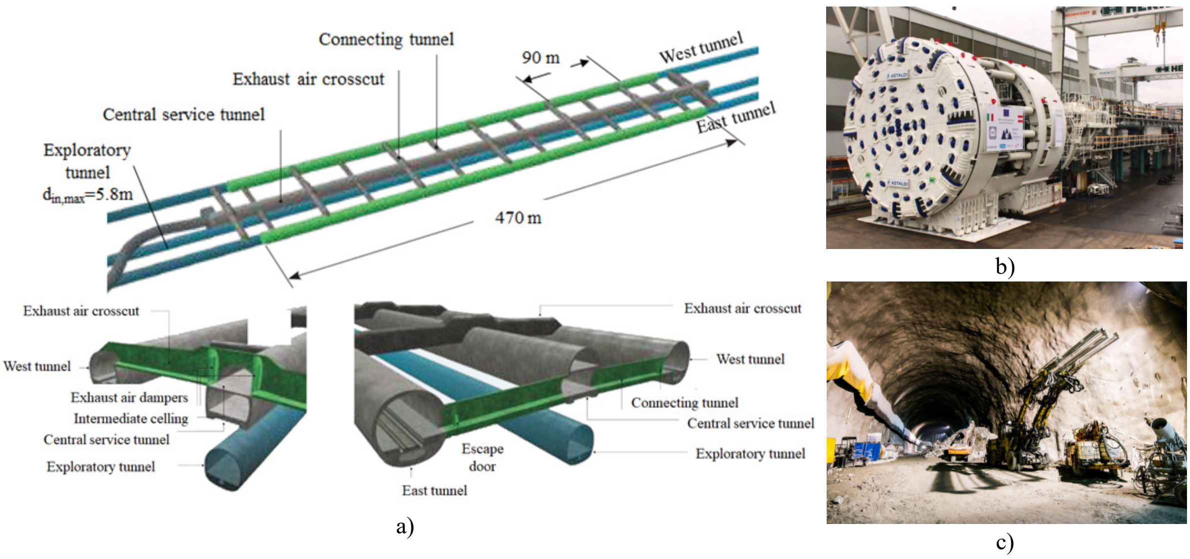


Figure 2. a) The Emergency Stop in Trens; b) The TBM used for the excavation of West main tunnel; c) Conventional methods adopted for the excavation of the central tunnel.

2.2 *Expected geological conditions*

The BBT lies in the central eastern Alps, crossing the collision area of the European and the African plate and the contact line between the two plates in this area is called Periadriatic Line (Marini & Venditti, 2023; Perello et al., 2023). During the design phase, the geological information in which the Emergency Stop will be excavated was based on the results of the surface surveys and one inclined borehole from surface. The maximum overburden in the area of the Emergency Stop is approximately 1100 m. Taking into account the following figure, the geomechanical units presents with an indication of the expected rock mass behaviour are summarized below. Despite the extensive investigations carried out, significant geological and mechanical uncertainties inside the tectonized materials within this geological structure still remain. To reduce the level of uncertainty, the exploratory tunnel has been designed to be excavated in advance at least 500 m before the excavation of the main tunnels.

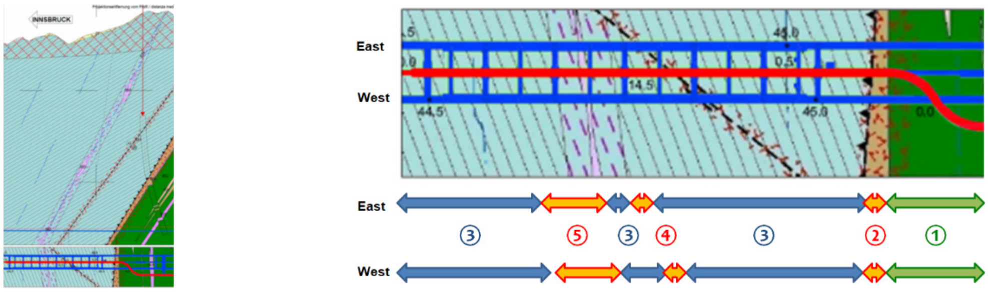


Figure 3. Longitudinal profile of Geology with main Lithological units.

Table 1. Geo-mechanical units inside the Emergency Stop in Trens.

Rock mass unit	RMR	Expected behaviour
1. Amphibolite	70±5	Slightly-moderately squeezing behaviour, slightly-moderately risk of tunnel face instability.
2. Tauri fault system	30 (damage zone) 20 (core zone)	Cataclasite, cachirite, fault gouge, phylonit rocks Behavior of Moderately high squeezing behaviour, high risk of rock-blocs instability, moderately-high risk of tunnel face instability.
3. Bündnerschiefer	60±5	Schists, phyllites and dolomites. Moderately high squeezing behaviour, moderately risk of tunnel face instability.
4. Avens fault system	30 (damage zone) 20 (core zone)	Cataclasite, cachirite rocks. Moderately high squeezing behaviour, risk of rock-blocs instability, moderately high risk of tunnel face instability.
5. Schists	60±5	Low carbonate, triassic and ophiolite. Moderately high squeezing behavior, risk of rock-blocs instability, moderately high risk of tunnel face instability.

2.3 *Rock support*

Based on the forecasted geo-mechanical risk scenarios, 5 standard support classes were designed for the main and central service tunnels (excavation area between 66 m^2 and 130 m^2) planned to be excavated using traditional methods (Tab. 2). For the enlarged sections crossing between the central tunnel and the exhaust air crosscuts (excavation area between 150 m^2 and 178 m^2), were applied other 2 rock supports classes excavated in sectors (crown and bench). The cast in situ final inner lining for the main tunnel and central service tunnel consists of C30/37 reinforced concrete 60cm thickness. For the exploratory tunnel 30cm thickness precast concrete segments C50/C60 together with 35cm thickness inner lining of C30/37 reinforced concrete with polypropylene fibers (for safety fire purposes) made the double lining system.

Table 2. Forecasted rock support classes for standard sections considered in the detail design using traditional methods for the excavation of emergency stop in Trens.

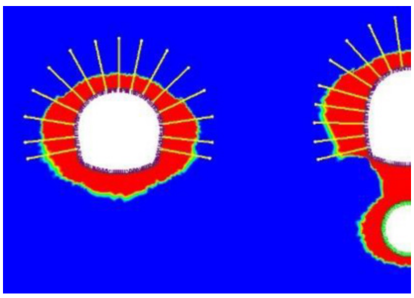
Class	Rock quality	Rock support
T2-T3	41≤RMR≤60 (amphibolite)	Fibre-reinforced shotcrete 15 cm, bolts Super-Swellex Pm24.
T4	21≤RMR≤40 (gneiss, paragneiss, quartzite)	Fibre-reinforced shotcrete (30cm), double 2 IPN180 ribs (distance 0.75-1.50 m), radial self-drilling R38N with length up to 6 m, forepoling R51N self-drilling cemented bolts L=12 m, 32 R38N self-drilling cemented bolts at face.
T5	21≤RMR≤40 (schists, cataclastic rock)	Fibre-reinforced shotcrete (30 cm), double 2 IPN180 ribs, radial self-drilling R38N with length up to 8 m, forepoling R51N self-drilling cemented bolts L=12 m, 58 R51N self-drilling cemented bolts at face.
T6	0≤RMR≤40 (faults zones)	Fibre-reinforced shotcrete (30 cm), TH36 ribs (distance 0.5-1.00 m), radial self-drilling R38N L=10m, forepoling R51N self-drilling cemented bolts L=12 m, 66 R51N self-drilling cemented bolts at face.

2.4 Finite Element analysis

Finite element, multi-stage analyses were performed by using the 2D code RS2 9.0 (RocScience), and 2D/3D models were implemented by MIDAS GTS NX code taking into account the different rock units and the intersection between tunnels. The excavation phases, the installation of the rock supports together with the inner linings were reproduced by an appropriate number of stages (1: exploratory tunnel; 2/3: two main tunnels; 4: central service tunnel). An elasto-perfectly plastic Mohr-Coulomb criterion was adopted with a lithostatic stress field of K_0=0.75. Detailed analyses were performed to design inner lining on the case of creep phenomena, anhydrite swelling phenomena. Moreover, were also performed in order to analyze the influence of the number of segments, the type of connection, the filling conditions of the annular gap with different assumptions that strongly influence the internal actions inside the inner liner of service tunnel. In Table 4, the geo-mechanical parameters assumed for T4 scenario are listed and numerical results are given in terms of yielded zone, total displacement (2D models) and internal actions at the connection zones (3D model).

Table 4. List of geo-mechanical parameters assumed for T4 scenario.

	GSI [-]	γ [kN/m^3]	E [kPa]	ν [-]	σ_{ci} [kPa]	Φ [°]	Ψ [°]
Schist	55	26.6	20’400	0.30	50’000	34	0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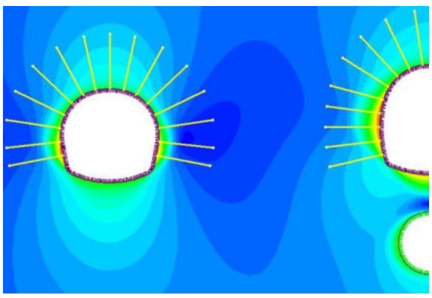
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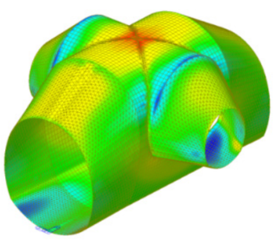
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Figure 4. a) yielded zone (red=100% yielding, blue=0% yielding); b) total displacements (max. 80mm) from 2D analysis at the end of the excavation, T4 scenario. c) bending moment at the connection zone between the central service tunnel and exhaust air crosscut from 3D analysis (M_{max}=805kNm).

3 EMERGENCY STOP IN TRENS: THE CONSTRUCTION PHASE

During the construction, the Contractor proposed some design optimization. In the zone of the FdE, the two main tunnels and the exploratory tunnels are excavated by means of double shielded TBM, while central and by-pass tunnels are excavated by conventional methods. The mechanized excavation of the Trens Emergency Stop involves a TBM machine misalignment in the horizontal direction of about 46 cm. To reduce the impact of possible interference between the tunnels, the Exploratory Tunnel has been moved down of about 3 m in the Emergency Stop area without impact to the general alignment. For the Emergency Stop a double system lining is proposed consisting of a precast segment lining 45 cm thick internal lining completed by means of a casted concrete layer. The two lining are made structural coupling with metal plugs in steel, between the two lining a spray waterproofing membrane has been introduced. Moreover, the expanded clay in place of the Pea-gravel on the main tunnels and the above exploratory tunnel were used. The excavations of the exploratory tunnel and base tunnels close to the FdE showed that the site is characterized by the presence of a rock mass better than those expected, with RMR values ranging from 50-60 and mainly consisting of the limestone complex (schists, phyllites, dolomites) and only some confined fault systems were encountered (Figure 5). The average excavation speed for the exploratory tunnel in correspondence of the FdE were quite good and equal to 16.1 m/d (max. 28.5 m/d), with average and maximum TBM thrust values of 6 MN and 10.5 MN, respectively. The average tunnel advance for the two main tunnels East (GLEN) and West (GLON) in correspondence of the FdE in Trens was about 20 m/d, with average and maximum TBM thrust values of 15 MN and 20 MN, respectively (Fig. 6). The excavation of the main tunnels, the central Trens tunnel and cross connections took place without any problems, with no impact on the linings installed. The average excavation speed of the central tunnel was 1.35 m/d, while the excavation of cross tunnels is completed by using rock support classes T3 and T4 with 45% and 55% of usage.

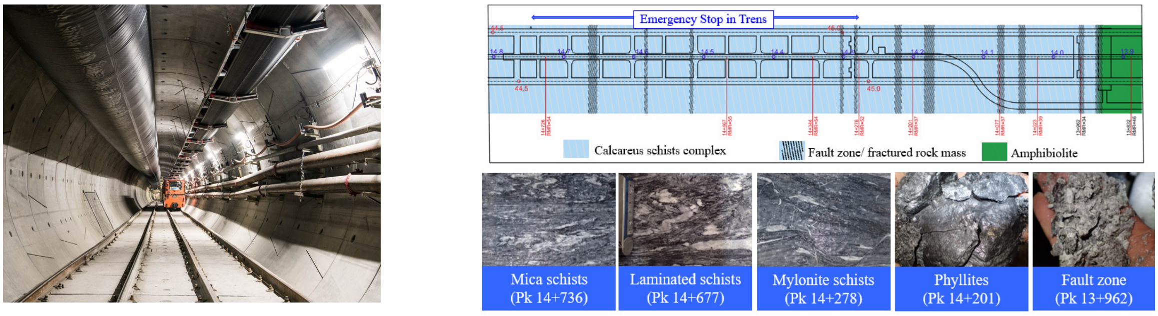


Figure 5. The exploratory tunnel (left) and Cross-check information close to the FdE in Trens after the exploratory tunnel excavation (right).

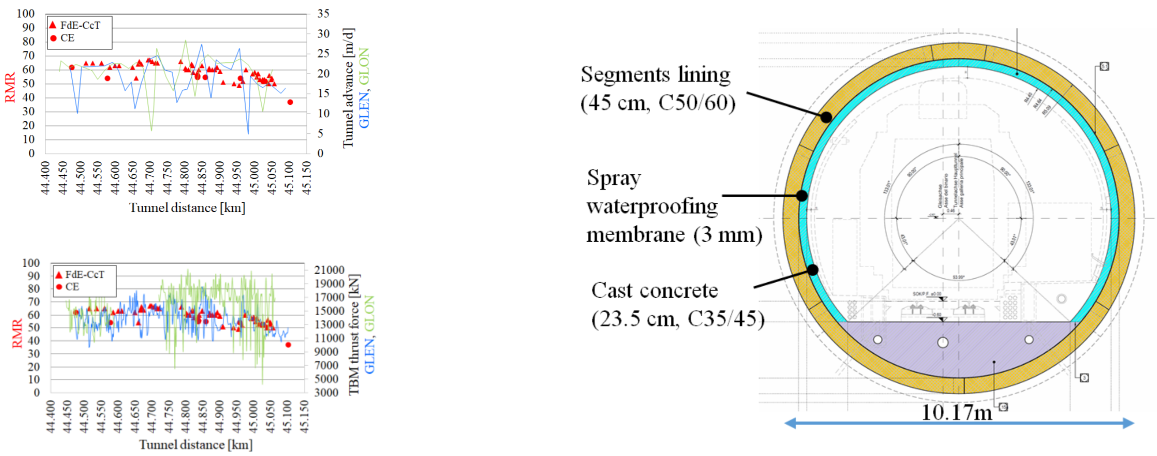
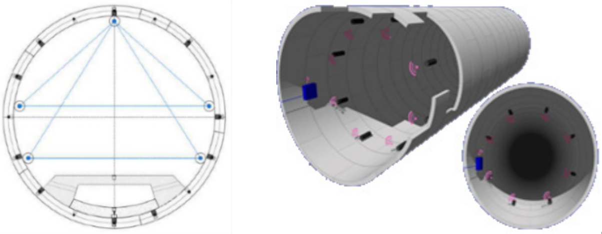


Figure 6. Main tunnels excavation: RMR, tunnel advance and thrust (left) and cross section of main tunnel inside Emergency Stop in Trens (right).

4 MONITORING SYSTEM

An extensive monitoring campaign was carried out during all excavation phases for the exploratory tunnel, the main tunnels and the central tunnel to monitor the behaviour of the rock mass and the stress/strain response of the installed supports due to the excavation of the nearby underground structures. The outcomes of the monitoring system during the construction phase were compared to the design solution, confirming the importance of the observational method to verify the assumptions used in the numerical modelling. For sections excavated by means of TBM, instrumented concrete segments with strain gauge bars were installed (Fig. 7). For the sections excavated by means of traditional methods, the convergence was measured by using optical targets; the induced stresses were measured by using instrumented bolts and load cells placed into the ribs.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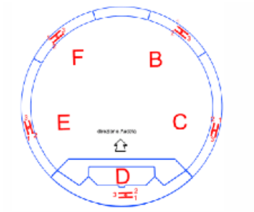

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Figure 7. a) convergence of segmental lining through AWCS system; b) Strain-gauges on segmental lining.

5 CONCLUSIONS

The excavation of the Emergency Stop in Trens started in December 2018. The excavation of the FdE in Trens was completed in October 2022, with the construction of the transverse ventilation and emergency tunnels by the cutting of the main tunnel segments. The final lining and finishing are in progress. For Lot Mules 2-3, works are in track with the contractual Construction Programme and scheduled to be finished in 2024. The whole project is scheduled for 2032. The total costs for the Emergency Stop in Mules resulting from the detail design solution amounted to approximately 44.2 M€, while thanks to the optimisations during construction phase, an expected saving of around 6 million will be attained.


a)


b)

Figure 8. a) Overview of central service tunnel, b) main tunnel in correspondence to the FdE.

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