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Brenner Base Tunnel – interaction between underground structures, complex challenges and strategies

R. Insam
BBT SE, Innsbruck, Austria

R. Wahlen & G. Wieland
Amberg Engineering AG, Regensdorf-Watt, Switzerland

ABSTRACT: The 64 km long Brenner Base Tunnel is the core of the SCAN-MED Trans-European Corridor. This railway tunnel consists of two single track tubes, cross passages every 333 m, an exploratory tunnel – which lies between 12 to 18 m below the main tunnels, and three emergency stops. Especially in the area of the emergency stops, a variety of underground construction activities are carried out in the immediate vicinity, partly in very difficult geological conditions. The complexity of the surrounding conditions, with distances between cavities of a few meters only, intersecting structures, excavation sections up to 300 m^2, overburden up to 900 meters, in partly squeezing rock conditions lead to a significant interaction between the structures. To cope with these complexities is a major challenge for all involved. The paper describes and shows in several examples, the problems and the measures applied to the planning and construction process.

1 INTRODUCTION

The Brenner Base Tunnel is a complex underground tunnel system consisting of various structures with excavation cross-sections between approx. 25 m^2 and 300 m^2. The complexity of the surrounding conditions, with distances between cavities of a few metres only, many structure intersections, overburden up to 1700 metres and, in part, squeezing rock conditions lead to a significant structure interaction. Managing these complexities is a great challenge for everyone involved.

During the excavation of the Innsbruck emergency stop, the first structural interactions with the underlying exploratory tunnel were detected, which led to local damage on the rock support – coupled with subsequent refurbishment measures. This article outlines and explains the interaction between the structures using the example of the node of Wolf which will be excavated by drill and blast as part of the H51 “Pfons-Brenner” construction lot. All the parallel running excavation works have to be considered in the context of the overall system and not as a traditional singular tunnel excavation.

2 PROJECT OVERVIEW

2.1 *Brenner Base Tunnel System*

The Brenner Base Tunnel is the core of the Pan-European Transport Corridor Helsinki – Valletta. To the north, the BBT tunnel system is not only linked to the Innsbruck Central Station but also to the access routes in the Lower Inn Valley and, to the south, to the planned new railway stretches running toward Verona and connecting the railway station in Fortezza, on the existing railway line.

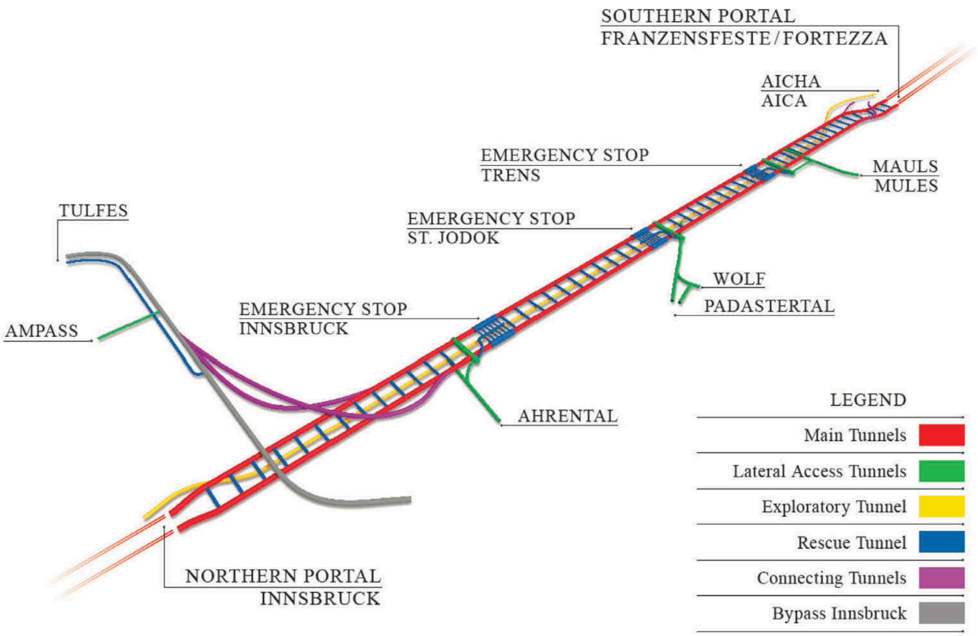


Figure 1. Brenner Base Tunnel system.

The tunnel system (Figure 1) is divided into two 55 km single-tube main tunnels, four connecting tunnels in the north and south, which join the existing lines and a deeper exploratory tunnel, which is located between the main tunnel tubes and runs underneath them. In addition, the twin-track Inntal Tunnel, which was completed in 1994, will be upgraded with structural safety measures and integrated into the tunnel system, resulting in a total tunnel length of 64 km between the portals in Tulfes (Austria) and Fortezza (Italy) (Bergmeister 2011).

The main tunnel tubes run 70 m apart from one another and are linked every 333 m by cross passages. The exploratory tunnel runs between the main tunnel tubes at a depth of approx. 12 to 18 m below them.

Three emergency stops are located at maximum intervals of 20 km: south of Innsbruck, St. Jodok, and Trens. A cross cavern is located at each emergency stop, which houses most of the technical operation and maintenance systems. Each emergency stop is accessible from the cross cavern through an access tunnel, and can be reached with road vehicles. The access tunnels have a maximum slope of about 10% and run directly to the underlying exploratory tunnel. In the Brenner Base Tunnel, a tunnel cross over is planned south of the St. Jodok emergency stop.

2.2 *H51 "Pfons-Brenner" Construction lot*

The H51 "Pfons-Brenner" construction lot (Figure 2) which stretches from km 13.5 to the state border at km 32.1 is the largest construction lot on the Austrian side of the project and was awarded to an Austrian-Italian joint venture in spring 2018 for just under one billion Euro. Construction will begin in Autumn 2018 and is expected to take 6 years.

The following works will be carried out on the construction lot:

– Drill and blast excavation of the exploratory tunnel towards the south (L = approx. 5.5 km) and towards the north (L = approx. 3.2 km);
– Drill and blast excavation of the node of Wolf which includes the St. Jodok emergency stop and tunnel cross-over with all the corresponding structures;

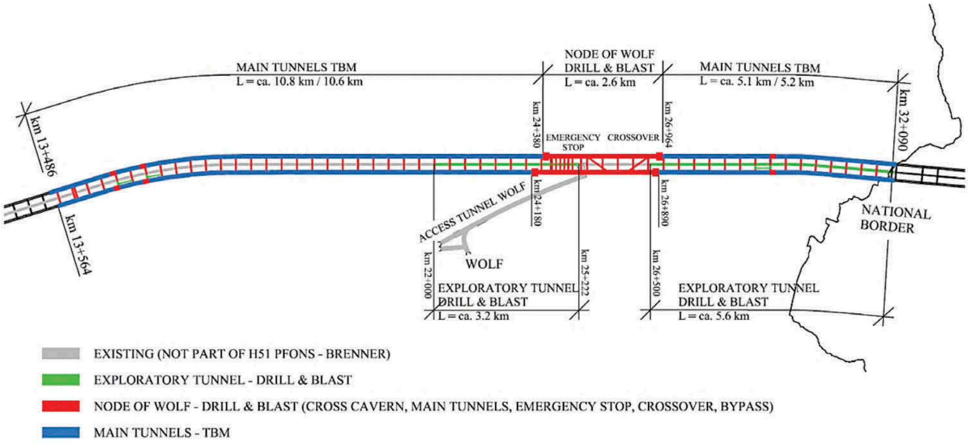


Figure 2. Overview of the H51 “Pfons-Brenner” construction lot.

– TBM excavation of the main tunnel tubes using shielded tunnel boring machines (TBM-S) and segmental lining towards the south (L = approx. 5.2 km) and towards the north (L = 10.8 km);
– Drill and blast excavation of 55 connecting cross passages;
– Internal lining for all tunnel structures in the construction lot, such as the main tunnels, cross passages, St. Jodok emergency stop and tunnel cross over, exploratory tunnel as well as the lining of the Wolf access tunnel, including the lining of the ventilation and junction chambers and other auxiliary structures which were excavated in a preliminary lot.

In addition, approximately 500 m have to be excavated in the Hochstegen area, which must first be sealed from the exploratory tunnel by means of rock grouting works. An approx. 30 m thick fault zone consisting of rauhwacke is predicted at the northern range of the Hochstegen area, which requires consolidation and sealing grouting works.

The technical cross passages, which are generally 2.0 km apart, are also directly connected to the exploratory tunnel by vertical shafts which have an internal diameter of at least 3.90 m.

The construction works will be carried out with a maximum of seven parellel running drill and blast excavations which will lead to a great effort in terms of logistics. All the parallel running excavation works must be carried out within the context of the overall system and taking into account different framework conditions from the construction process.

2.2.1 *Node of Wolf*

The “Node of Wolf” includes-drill and blast excavations for the following structures (Figure 3):

– Main tunnels:
  – East tunnel (from km 24.365 to km 26.979), length: 2614 m, excavation area: approx. 90 m²
  – West tunnel (from km 24.165 to km 26.905), length: 2740 m, excavation area: approx. 90 m²
– St. Jodok cross cavern (at km 25.243) length: 100 m, excavation area: approx. 230 m²
– St. Jodok emergency stop:
  – Extended main tunnel in the emergency area, length: 470 m, excavation area: approx. 100 m²
  – 1 central tunnel, length: 900 m, excavation area: approx. 116 m²
  – 1 pressure relief tunnel, length: 60 m, excavation area: approx. 116 m²
  – 6 exhaust cross tunnels, length: 60 m, excavation area: approx. 41 m²
  – 6 connecting tunnels, length: 60 m, excavation area: approx. 38 m²
  – 1 turning niche
  – 2 niches for railway tunnel doors

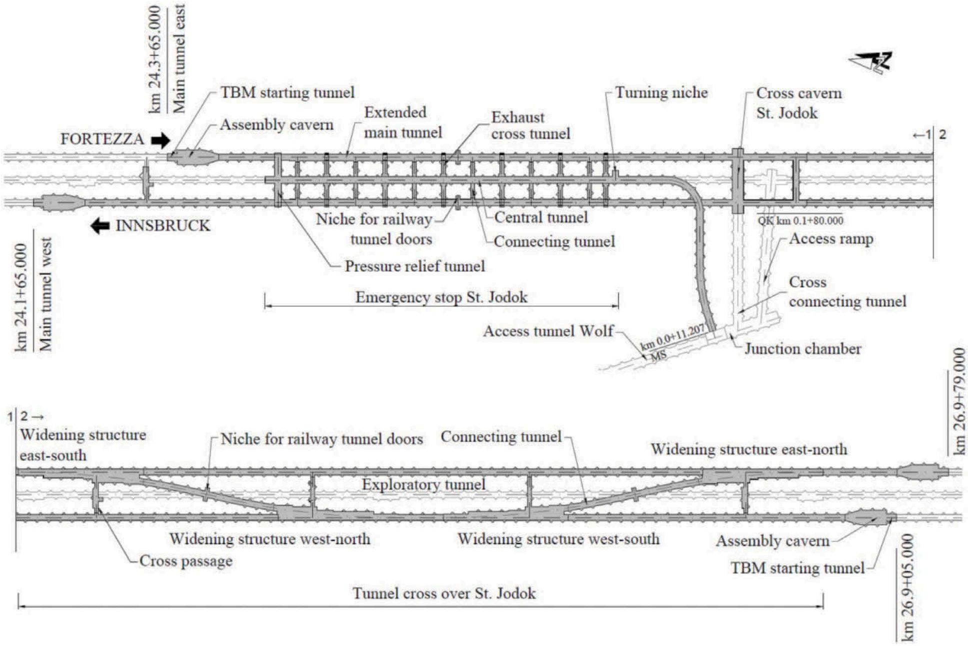


Figure 3. Overview of the Node of Wolf.

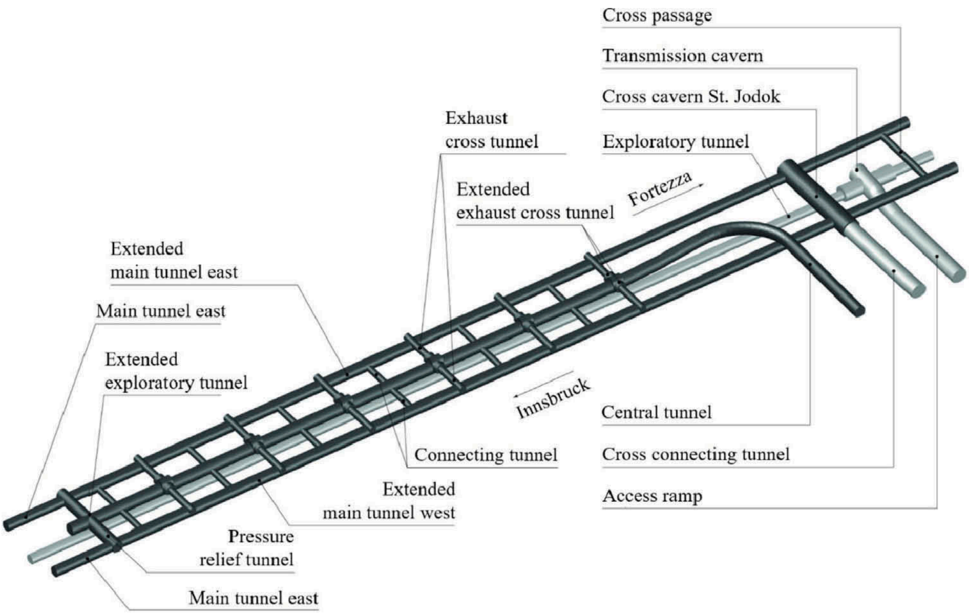


Figure 4. Overview of the Node of Wolf Nord with the underlying exploratory tunnel.

- St. Jodok tunnel cross over, total length: 1200 m:
  - 4 widening structures with excavation areas of up to approx. 300 m²
  - 2 connecting tunnels, excavation area: 90 m²
  - 2 niches for the railway tunnel doors, each one in the middle of the connecting tunnel
- 4 assembly caverns and TBM starting tunnels

The exploratory tunnel is located directly below the central tunnel of the emergency stop.

3 GEOLOGICAL, HYDROGEOLOGICAL AND GEOTECHNICAL BOUNDARY CONDITIONS

3.1 *General overview of the geological and hydrogeological conditions of the H51 "Pfons-Brenner" construction lot*

The project area for the construction lot ranges from the Pfons area in the north to the main chain of the Alps in the south. Figure 5 shows a schematic geological longitudinal section of the Austrian project area. Therefore, the H51 "Pfons-Brenner" construction lot cuts through (from north to south):

- the East Alpine quartz phyllite zone from km 12.8 to km 14.0. This largely consists of metamorphic sediments from the Palaeozoic Era;
- the Pennine Upper Schieferhülle from km 14.0 to km 28.5. This mainly consists of the Bündnerschiefer Group and Triassic formations which represent the basal detachment horizon;
- the Sub-Pennine Lower Schieferhülle from km 28.5 to km. 30.3. This can be subdivided along the line into the lying Hochstegen zone and the hanging Flatschspitze nappe with interjacent Triassic units;
- the Sub-Pennine Basement in the central Tux gneiss from km 30.3 to km 32.1.

From a hydrogeological point of view, it can be assumed for the H51 "Pfons – Brenner" construction lot that:

- dry to dripping and slightly trickling rock mass conditions prevail over long sections (class 0–0.2 l/s/10 m);
- unsteady inflows can arise from the individual discrete zones which, at a maximum, can be assigned to the class 5 l/s to 10 l/s;
- the largest ingress volumes are to be expected (10 to 50 l/s) in the section of the Triassic nappe boundary and Hochstegen marble without precautionary rock mass sealing and improvement measures to reduce hydraulic permeability.

In summary, it can be stated that the exploratory tunnel and the main tunnel tubes of the H51 "Pfons-Brenner" construction lot are located in dry to moist rock mass conditions for up to approx. 95% of the stretch which has to be excavated.

The largest overburden is found in the area around the border in the Sub-Pennine Basement in the central Tux gneiss and lies between 800 m and 1700 m.

4 GEOTECHNICAL DESIGN AND INTERACTION OF STRUCTURES

The geotechnical design was carried out according to the Geotechnical Design of Underground Structures with Conventional Excavation of the Austrian Society for Geomechanics. The basis for the design of the tunnel structures is the geological and hydrogeological forecast which includes, among other things, the following information:

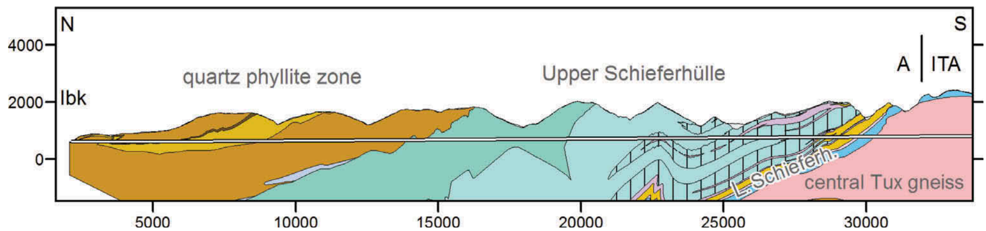


Figure 5. Schematic geological longitudinal section on the Austrian side of the project.

– Tectonic unit/subunit
– Lithological description
– Information on the discontinuities
– Information on the fault zones
– Water ingress and permeability
– Forecast of the rock mass types (rock mass with similar characteristics)

The following parameters have been derived for all types of rock mass based on the geological exploration campaigns and extensive laboratory tests:

– Mechanical properties of the rock
– Orientation, distance and mechanical properties of the discontinuities
– Mechanical properties of the rock mass

The Node of Wolf is situated in the area of the Upper Schieferhülle, where predominantly Bünder schist and Triassic rocks are predicted. The overburden fluctuates depending on the location of the mountain valley between approx. 400 m and 900 m. Predominantly calcareous (GA SH-KS) and non-calcareous (GA SH-KPh) Bünder schist and subsidiary black phyllite (GA SH-SP), chlorite schist (GA SH-SC), rauhwacke (GA SH-RW), calcareous marbles (GA SH-M) and fault zones are forecasted for this area.

Based on the distribution and the properties of the rock mass types (mechanical properties of the rock mass, orientation and properties of the discontinuities), the hydrogeological conditions and the primary state of stress, the ground behaviour has been determined according to the Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation of the Austrian Society for Geomechanics and has been divided into behaviour types (BT) using suitable demarcation criteria. No lining or support measures have been considered in the analysis of the ground behaviour. The GSI (Geological Strength Index) value, rock mass loading, depth of the yielding zone and radial displacements were used as the main demarcation criteria. The main instrument of the analysis was the analytical ground reaction curve. The following behaviour types were determined according to the Geotechnical Design of Underground Structures with Conventional Excavation of the Austrian Society for Geomechanics:

Predominant – for the rock mass types SH-KS, SH-KPh, SH-SP, SH-CS, SH-M:

– BT 2: Potential of discontinuity controlled block fall – Voluminous discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure on discontinuities;
– BT 3: Shallow failure – Shallow stress induced failure in combination with discontinuity and gravity controlled failure.

Secondary – for the rock mass types SH-RW and fault zones:

– BT 4: Voluminous stress induced failure – Stress induced failure involving large ground volumes and large deformations;
– BT 9: Flowing Ground – Flow of intensely fractures, poorly interloocked rocks or soil with high water pressure.

Thus, in the area of the Node of Wolf, can be predominantly expected discontinuities dominated ground behaviour and only secondarily stress dominated ground behaviour in the area of fault zones and poor BT3. The interaction of the structures was not considered in the analysis of the ground behaviour (analytical ground reaction curve). The construction concept (lining, subdivision of excavation profile, round length, etc.) was subsequently designed based on the identified ground behavior types in accordance with the Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation of the Austrian Society for Geomechanics. As discontinuities dominated ground behaviour was predominantly expected, a rigid lining concept consisting of a reinforced shotcrete lining, steel lattice girders and system bolting was designed for a large part of the structures. Consequently, the system behaviour (behaviour of the rock mass in combination with the rock mass support) was investigated for the selected construction concept using wedge analysis and numerical 2D and 3D

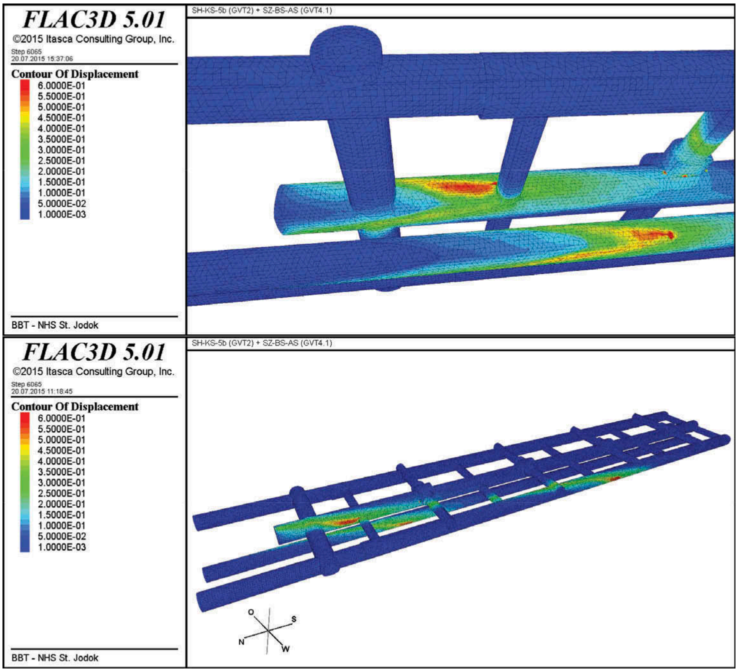


Figure 6. Numerical 3D FD-Model from the emergency station.

calculation models. The whole tunnel system was modeled in the numerical calculations and thus the interactions of the structures could be fully captured.

The numerical calculations have shown that significant mutual interactions of the structures have to be expected based on the partly short distances between the structures combined with the size of the excavation profiles. The rigid lining in previously excavated structures will be so highly loaded, as a result of the stress redistribution caused by subsequently excavated neighbouring structures, that the shotcrete shell will be overloaded. Even increasing the thickness of the shotcrete lining to a technically and economically useful level, it was still not possible to proof the structural safety. In addition, it became apparent that the construction process has a decisive influence on the loading of rock support. The construction concept has been revised with regard to these findings.

1. A ductile rock support with open slots has been planned for the structures which are situated in relatively competent rock mass conditions with a ground behaviour which is prevalently dominated by discontinuities (BT2 and good BT3) and where an interaction of structures is expected. As the expected additional displacements caused by the interaction of neighbouring structures are relatively small (a few cm), no yielding elements have been planned for smaller profiles. For structures where no mutual interactions are expected, a rigid lining concept has been chosen.
2. A reinforced ductile rock support with yielding elements has been planned for structures in relatively poor rock mass conditions with ground behaviour which is prevalently stress dominated (poor BT3 and BT4). As the expected displacements caused by the excavation of the structures (up to 40 cm) as well as the mutual interactions of the structures are relatively large (up to 10 cm), a controlled guidance of the shotcrete lining using yielding elements will be required.

The numerical analyses have shown that the exploratory tunnel directly below the central tunnel is a particularly critical area. The central tunnel will be previously excavated to the exploratory tunnel. It runs approximately 600 m directly above the exploratory tunnel with a remaining rock bar thickness between the exploratory tunnel and the central tunnel of about 3 m.

While the tender planning of the H51 construction lot was taking place, the H33 Tulfes-Pfons construction lot was already under construction and the Innsbruck emergency stop, which has essentially a similar layout to the St. Jodok emergency stop, was being excavated. Even if the geological situation is different, the findings on the interaction of the structures from the H51 tender planning were essentially confirmed. Especially in the previously excavated exploratory tunnel, where a rigid rock support has been installed without deformation slots or yielding elements, the shotcrete lining became overstressed over wide ranges at the crown area due to the excavation work in the overlying central tunnel. For occupational health and safety reasons, the damaged area had to be refurbished by completely replacing the shotcrete lining in the crown area.

The exploratory tunnel is a central element in the logistics concept for the construction lots to the north of the Brenner pass. Due to the high relevance of the structure, the computational investigations and the excavation of the Innsbruck emergency stop in the neighbouring H33 Tulfes-Pfons construction lot (Lussu et. al. 2019), appropriate measures were evaluated during the H51 tender design to minimize the risk of damage in the exploratory tunnel. The following framework conditions had to be considered:

– The risk of damage in the exploratory tunnel must be minimized;
– Occupational health and safety in the exploratory tunnel must be ensured at all times;
– A change in horizontal alignment was not possible;
– A change in vertical alignment was possible in principle, whereby fixed points in the previously excavated access structures and maximum gradients (construction operation) had to be considered.

Different variants were analyzed with regard to the location of the structures and the lining concept. The evaluation showed that the following measures could minimize the risk of damage in the exploratory tunnel taking into account the aforementioned framework conditions:

– The vertical alignment of the exploratory tunnel was adjusted to maximize the distance in the area of influence of the central tunnel. It was possible to increase the rock bar between the exploratory tunnel and the central tunnel approximately from 3 m to 6 m (Figure 7).
– A ductile rock support concept was planned, consisting of a steel fibre reinforced shotcrete lining with an additional layer steel mesh on the cavity side, mortar rock bolts and 4 rows of deformation slots with or without yielding elements depending on the expected system behaviour. After the completion of the tunnelling works in the exploratory tunnel in the area of influence of the central tunnel, a rockfall mesh will also be installed on the interior edge of the shotcrete lining as an occupational health and safety measure (Figure 8).

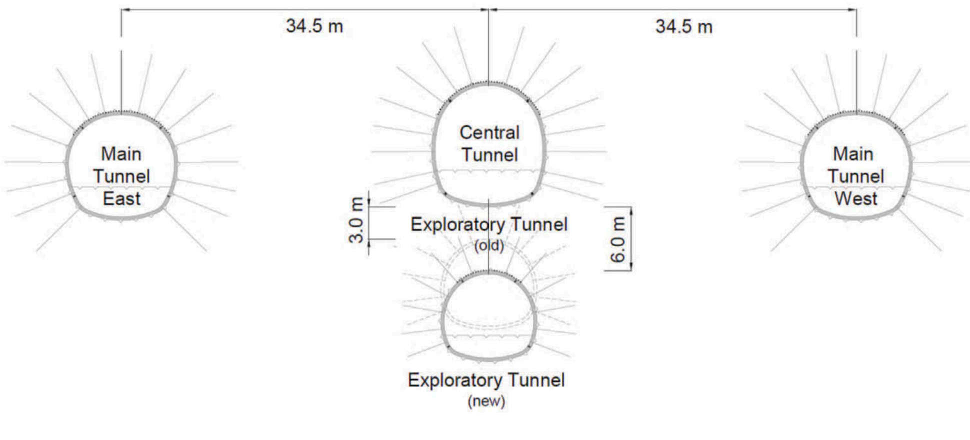
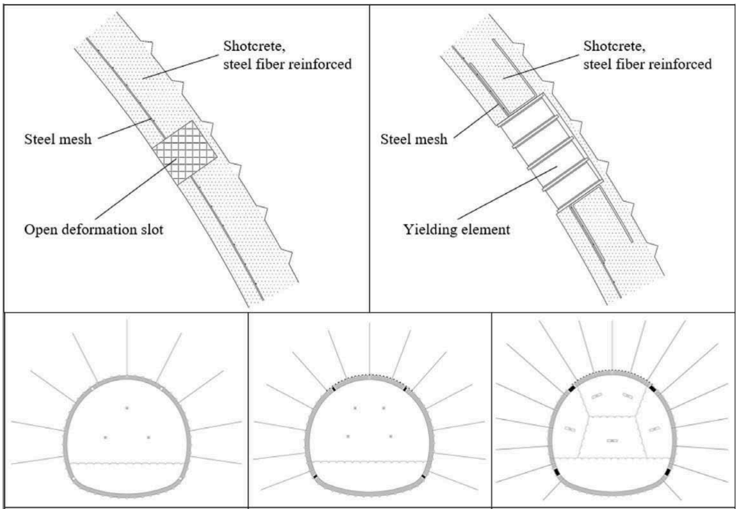


Figure 7. Cross-section through the St. Jodok emergency stop – Lowering of the exploratory tunnel.



Round length Top heading: 1.7 m Invert: 3.4 m **Shotcrete lining** ds = 20 cm steel fiber reinforced with one layer steel mesh **Systematic bolting:** SN rock bolts 250 kN, L=4 m bolt pattern: 1.7 m x 2.0 m **4 Rows of open deformation slots**	**Round length** Top heading: 1.3 m Invert: 2.6 m **Shotcrete lining** ds = 25 cm steel fiber reinforced with one layer steel mesh and lattice girder **Systematic bolting** SN rock bolts 250 kN, L=4 m bolt pattern: 1.3 m x 1.5 m **Spiles umbrella** **4 Rows of yielding elements**	**Round length** Top heading: 1.0 m Invert: 2.0 m **Shotcrete lining** ds = 30 cm steel fiber reinforced with one layer steel mesh and lattice girder **Systematic bolting** Self-drilling rock bolts 350 kN, L=6 m bolt pattern: 1.0 m x 1.3 m **Spiles umbrella** **4 Rows of yielding elements**

Figure 8. Ductile lining in the exploratory tunnel in the area of influence of the overlying central tunnel.

5 CONCLUSIONS

During the tender design for the H51 “Pfons-Brenner” construction lot, very detailed investigations were carried out for the Node of Wolf, which consists of several complex structures, such as a cross cavern, emergency stop and tunnel cross over, taking into account the overall tunnel system, the geological conditions and the construction processes. It emerged that the excavation of different structures can partly lead to significant interactions with adjacent previously excavated structures and the underlying exploratory tunnel. Based on these investigations, various measures for excavation and rock support were subsequently identified and established. The selected measures are aimed primarily to minimizing the risk of damage on the rock support and at ensuring occupational health and safety in the various working areas. The structures which have been excavated in the meantime in the neighboring construction lots have shown that the influence between adjacent structures can be significant and confirm the results of the conducted investigations as well as the selected construction measures for the H51 “Pfons-Brenner” construction lot.

REFERENCES

Austrian Society for Geomechanics 2010. Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.

Bergmeister, K. 2011. Der Tunnel kommt. *Brenner Basistunnel*. Lana: Tappeiner Verlag.

Lussu, A. & Kaiser, C. & Gruehlich, S. & Fontana, A. Innovative TBM Transport Logistic in the constructive lot H33 – Brenner Base Tunnel. Neaples: WTC 2019.