Semmering Base Tunnel – Geotechnical challenges at crossing a fault system in combination with high water pressure

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ABSTRACT: The Semmering Base Tunnel (SBT), one of the major infrastructure projects in Europe is part of the Baltic-Adriatic railway corridor and connects the two federal states of Lower Austria and Styria. Due to its total length of 27.3 km and complex rock mass conditions, the project is divided into 3 construction lots. The eastern construction lot SBT 1.1 Gloggnitz Tunnel crosses major fault zones adjacent to water-bearing carbonatic rocks (Grassberg), with a potentially high water inflow in combination with high water pressure. Crossing the fault system north of the Grassberg is one of the biggest challenges of lot SBT 1.1, due to the poor rockmass quality within the fault system and 10 bar water pressure within the Grassberg. Systematic probe drillings indicated a complex sequencing of geological units at the transition from the fault zone into the water-bearing Grassberg unit and required a modification of the original design approach.

Keywords: Semmering Base Tunnel, grouting, monitoring, high water pressure, high permeability.

1 PROJECT DESCRIPTION

The easternmost part of the Semmering Base Tunnel (SBT), lot SBT 1.1 Gloggnitz Tunnel, comprises the construction of two single-track tunnel tubes being undertaken conventionally with excavator and drill & blast (Gobiet, G.; Wagner, O.K. 2013).

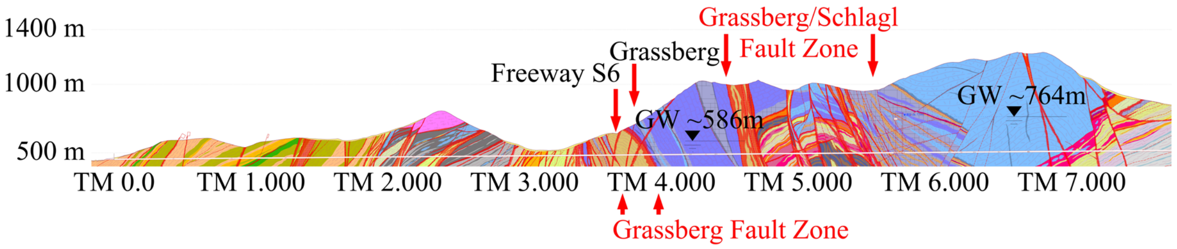

Figure 1. Geological longitudinal section SBT1.1 at the time of tender design.

Due to the complex rock mass conditions at SBT 1.1, the tunneling work is carried out from the portal at Gloggnitz and the intermediate access Göstritz, with a 1.2 km long access tunnel and two 250 m deep shafts (Hauer, H. et.al. 2022). The total length of the construction lot is approx. 7.4 km (Figure 1).

At chainage 3900 m, starting from the portal Gloggnitz, an approx. 50 m long fault system was predicted, marking the northern border of the Grassberg, an approx. 800 m long carbonatic rock mass, with a groundwater pressure of 10 bar.

2 GEOLOGY

The carbonatic rocks of the Grassberg are part of a permomesozoic stratification, which is formed by silicious rocks (schists, phyllites, quartzites) and carbonatic members (limestone, dolomite, rauhwacke, breccia). The whole sequence has undergone a multi-phase tectonic imbrication followed by large displacements along major strike-slip-faults, which caused the embedding of other stratigraphic units (e.g. crystalline rocks of the Semmering) within the formation. Such strike-slip-faults are adjacent to the Grassberg in the north and the south. Therefore, the border areas of the Grassberg are considered a geotechnically challenging zone, where water-bearing, jointed carbonatic rocks occur in the close vicinity of cataclastic mica schists with very low permeability.

The Grassberg Northern Fault Zone (GNFZ) has already been identified during the stage of the tender design as a zone with a lot of geological and geotechnical challenges. For this reason, it was planned to accompany the excavation of this zone by overlapping exploratory drillings. One of these reached the border between faulted mica schist and the also faulted carbonatic margin area of the Grassberg approx. 100 m earlier than predicted. This also means that the fault zone coincides with the location, where a freeway crosses the tunnel axis at the surface with an overburden of approx. 160 m. Due to this circumstance, a modification of the original design approach was required to increase the level of safety. To pass GNFZ, an extensive grouting programme is necessary, which also started earlier than originally predicted.

The injection drillings showed that, contrary to the geological model of the design stage, the border of the Grassberg was dipping north. The following detailed geological model off the margin area of the Grassberg was derived from findings of numerous exploratory and injection drillings:

- Fault Zone of mica schist
- Transition Zone consisting of mica schist and carbonatic rocks
- Faulted carbonatic rocks (breccias and heavily fractured limestone)
- Firm, jointed limestone

The first exploratory drilling showed water ingress of about 100 l/s in combination with eroded material from the mica schist and the breccia. Hydraulic testing carried out at a later date showed a permeability of the carbonatic margin zone comparable to sandy gravel (kf= 1.9E-03 to 6.3E-04 m/s) at an initial pressure of 9 bar. At this point, it became clear that major grouting works prior to the excavation would be necessary to provide an adequate level of safety for the following excavation works. The risks were not only the potentially high water ingress of several 100 l/s causing geotechnical challenges but especially erosion of the breccia and faulted mica schist.

3 EXCAVATION AND GROUTING CONCEPT

Following the exploratory drilling (Chapter 2), a large grout-umbrella (GU1 –Figure 2) with 99 drillings was executed. The goal of this grout-umbrella was the reduction of the permeability and the water inflow into the tunnel.

The excavation concept was to excavate the top heading in excavation steps of 7 m with accompanying grout-umbrellas until the competent carbonatic rock mass was reached. After reaching the competent rock mass, bench and invert should be excavated.

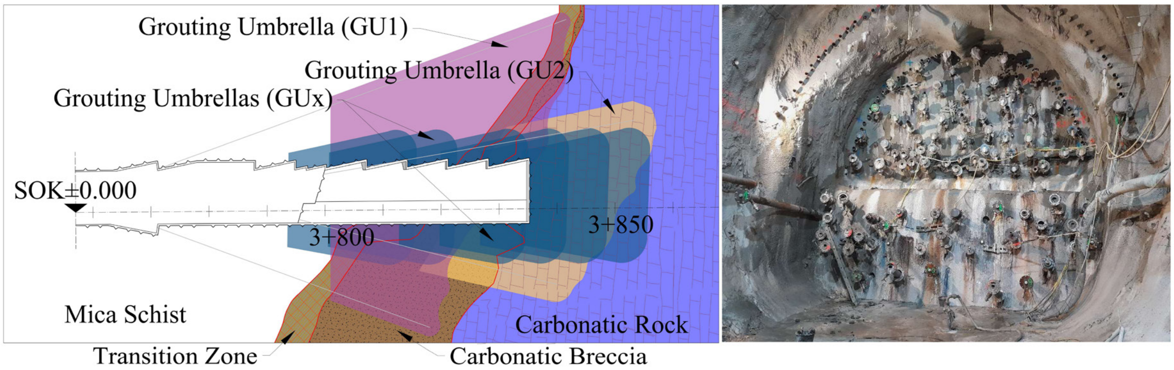

Figure 2. Grassberg Northern Fault Zone (GNFZ), track 2 - overview over excavation and grout concepts (left), Face at chainage 3800 after completed grouting work (right).

3.1 *Grout-Umbrella (GU1) and subsequent excavation*

Because the exact geological makeup was unknown and the standard length of drillings of 50 m proved insufficient due to the low dipping angle of the target area, the length of the drillings was adapted to the water ingress encountered during the drilling procedure (average length equaled to 60 m). Grouting-pipes with grouting-valves were used, due to lack of borehole stability and high risk of erosion. The downside of grouting-pipes is that most of the grout is injected only at the bottom of the borehole, leaving the rockmass along the borehole insufficiently grouted.

Initially the grouting material used was Portland cement grout but due to the large grout intake levels Hybrid-Grout (Portland cement with approx. 20 % added Polyurethane) was introduced as an additional grout-medium. The Hybrid-Grout improved the stability of the medium on the one hand, but its main purpose was to restrict the distribution of the grout medium outside of the target zone and to reach small joints with grouting material. The intake levels varied between the drills with a range between 100 l and 140,000 l per drill.

After the completion of the grout-umbrella, the excavation of the top heading followed with overlapping pipe roof umbrellas to ensure stability of the tunnel crown and to minimize settlements. Additionally, smaller grout-umbrellas (GUx) with a maximum length of 24 m (Figure 2) were executed. Unlike the first grout-umbrella (GU1), these much smaller umbrellas focused on the injection of the tunnel face and the area immediately surrounding the excavation.

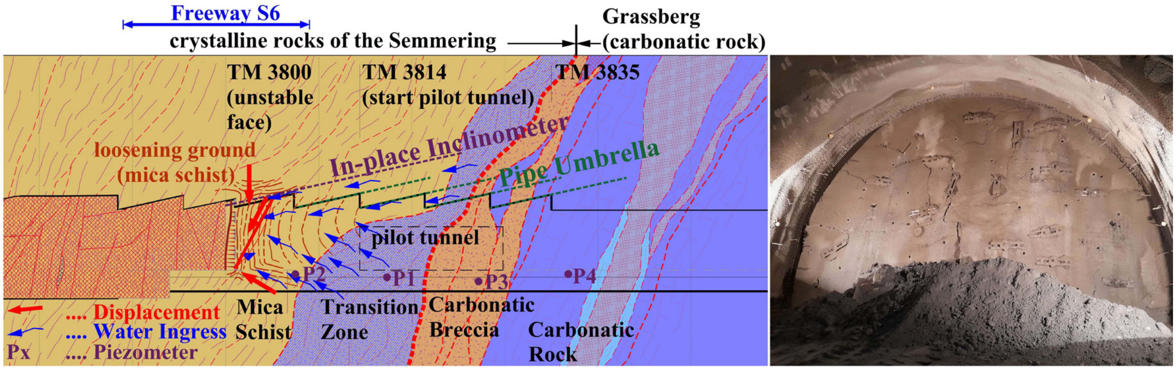

Figure 3. SBT1.1 - Grassberg Northern Fault Zone (GNFZ), track 2 - geological longitudinal section with geotechnical issues at chainage 3800 (left) and the face at chainage 3800 (right).

The excavation proved increasingly difficult with displacements at the face of up to 500 mm and unstable conditions including increasing water inflow at the tunnel face after approx. 30 m of excavation at chainage 3800 (Figure 3). After immediate mitigation measures, such as a backfilling of the face area, grouting of the face with polyurethane and drainage drillings, the excavation- and grouting concept was evaluated and adjusted.

3.2 Unstable face conditions at chainage 3800

Approaching chainage 3800, the saturated mica schist showed deteriorating properties, which encouraged unstable conditions at the tunnel face. The formation of slip circles was also favored by the dip of the fault, which is inclined against the direction of advance. In the excavation area, invert heaves of up to 120 mm were observed. With the quick installation of a temporary invert and additional reinforcing frames anchored down through the invert, it was possible to rapidly stop the displacement. However, the prevailing system behavior made it necessary to reduce the water pressure acting on the fault zone (mica schist and carbonate breccia), as discussed below.

3.2.1 Hydraulic Testing and additional extended grout-umbrella (GU2)

Hydraulic testing showed that due to the heterogeneity of the rock mass, the reduction of permeability was equally heterogeneous and therefore insufficient. The grout-umbrella GU1 mostly reached the transition zone and part of the breccia (Figure 2). To reduce the probability of uncontrolled water ingress into the mica schist during the excavation, it was necessary to reduce the permeability of the breccia and the adjacent part of the competent limestone to a larger extent. Therefore, another grout-umbrella (GU2) with a wider reach was executed. GU2 was designed to be performed in two stages. After the initial grouting, each drill was rebored, extended, and grouted a second time. In GU2, though the grout intake in total was similar to GU1 (in relation to the target area), the intake levels rarely reached above 10,000 l for a single drilling, meaning the intake levels can generally be considered more constant than they were during the grouting of GU1. After GU2 was finished, another round of hydraulic testing showed the success of the additional grouting works with the permeability (k_f) of the grouted area being evenly reduced to about 3.6 E-06 m/s.

3.2.2 Reduction of the pressure in the immediate excavation area and continued excavation with adjusted excavation profile

Drainage drillings within the grouted area verified the reduction of permeability and showed an average water ingress of about 1.1 l/s per drainage drilling without any content of eroded material. The influence on the water pressure is monitored with piezometers (see Chapter 4.1).

During the excavation of the top heading the support was reinforced by a temporary invert dedicated to prevent shearing and heave in the invert. In addition, a pilot tunnel entering the carbonatic breccia reduced the risk of a large-scale face collapse due to erosion. Smaller grout-umbrellas and pipe umbrellas every 7 m accompanied the excavation works. These were grouted with PU-resin to seal even the last potentially water bearing joints and cavities. During this excavation a bed load barrier was readily available to be installed quickly in case uncontrollable erosion occurred. Due to the extensive grouting work the pilot tunnel could be excavated in almost dry conditions.

4 GEOTECHNICAL MONITORING

Geotechnical monitoring in areas with changing ground conditions usually consist of 3D displacement monitoring sections every 5 – 10 m. Due to the unstable face at chainage 3800 and the challenging boundary conditions for further tunneling work, in combination with the freeway above, additionally piezometers and in-place inclinometers were installed.

4.1 Pressure Monitoring with Piezometers

The unstable conditions at chainage 3800 demonstrated, that a water pressure of approx. 10 bar leads to a problematic situation with mica schist immediately ahead of the face. To get detailed information about the in-situ water pressure in the different geological layers, 4 piezometers were installed. All piezometers are situated within the grout-umbrella (Figure 3). The piezometers which were installed ahead of the tunnel face extend into the breccia and the limestone. For these piezometers, limits for the maximum acceptable water pressure in the mica schist and the transition zone were implemented to the safety management system. If required, additional drainage drillings reduced a rising pressure level.

The grouting measures after each 7m long excavation step raised the water pressure (Figure 4).

With an advanced excavation and additional grout-umbrella, the piezometer didn't respond to drainage drillings in the expected dimension. With an advancing degree of grouting the permeability decreased, but the functionality of new drainage drillings was increasingly limited. After each excavation step the situation was evaluated.

The measures described above ensured a successful tunnel excavation in this challenging situation.

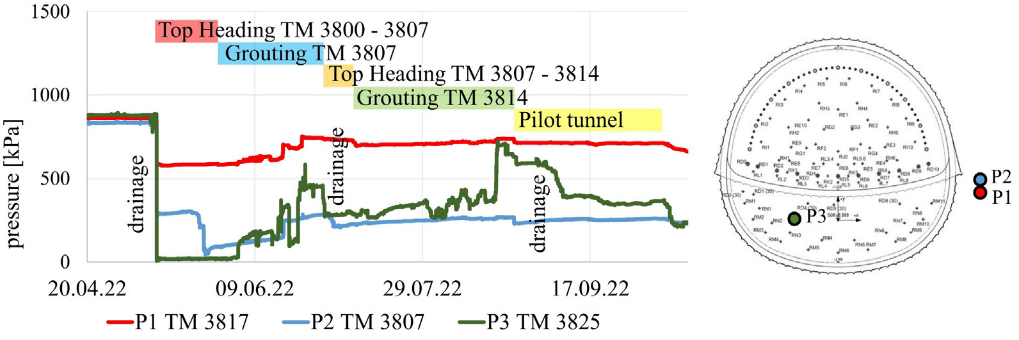

Figure 4. Track 2 – Time-dependent water pressure monitored with piezometers.

4.2 *Settlement surveillance with in-place inclinometers*

The analysis of the face instability at chainage 3800 concluded that the mica schist provides little resistance to gravitational forces from above, under the prevalent circumstances. In addition to the measurable displacements behind the face, pre-displacements in front of the tunnel face occur. Their share of the total displacement is determined by the ground conditions. To get information about the value of this pre-displacement, an in-place inclinometer with a length of 24 m was installed in the crown at chainage 3800 ahead of the excavation work. The measuring tube is friction-locked with a pre-drilled steel pipe, which is part of the pipe umbrella at this chainage. The inclinometer consists of a chain of sensors, each 1 m long (Geodata ZT GmbH. 2023). A measurement frequency of 30 minutes was chosen to correlate the settlement surveillance with an excavation step.

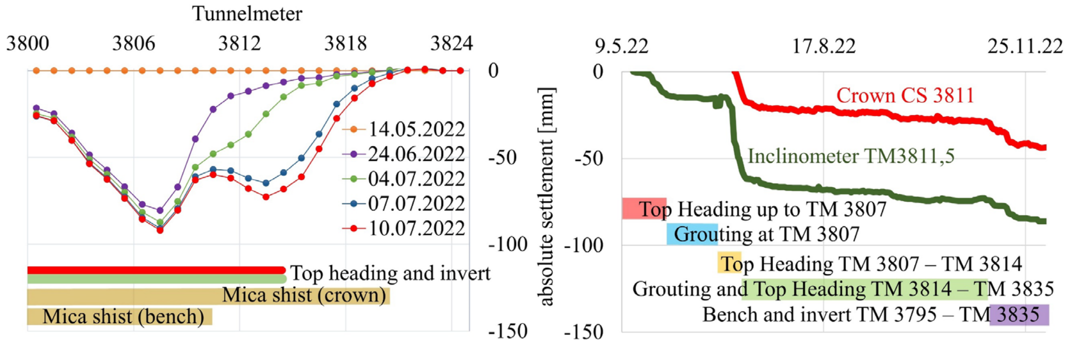

Figure 5. Track 2 - In-Place inclinometer at chainage 3800. Settlement surveillance during excavation work over time (left) and comparison with 3D measurements CS-3811 (right).

The maximum settlement was observed at the end of the first excavation step at chainage 3807, because of the weak conditions of the mica schist and the increased cross section of the top heading. A pre-displacement in the lower cm- range is observed up to approx. 4 m in front of the face (Figure 5). In correlation with increased settlements and a very time-consuming excavation, the number of partial excavation steps was increased at chainage 3805. The in-place inclinometer showed a total settlement of maximum 110 mm in the mica schist. A major part of the settlement in the crown occurred during of top heading. While excavating bench and invert, another 20 mm of settlement was recorded.

Comparing the in-place inclinometer with the 3D-measurement shows the amount of undocumented displacement, which is not measured with the 3D displacement monitoring. For example, CS 3811 shows a pre-displacement of approx. 20 mm before opening the face and additional approx. 20 mm till the reference measuring of the monitoring targets (Figure 5). In the mica schist of the transition zone, around 50 % of the total displacement is not registered by the 3D-displacement monitoring. After the reference measurement, both systems deliver the same displacement increments.

4.2.1 3D displacement monitoring at the surface and under ground

During excavation of the top heading the faulted mica schist shows the largest displacement of up to 30 mm. The installation of the temporary invert leads to a quick reduction of the displacement velocity. In the breccia the displacement level decreases until it reaches a level of approx. 10 mm in the carbonatic rock.

The excavation of bench and invert leads to a displacement increase of up to 80 mm in the mica schist, with the highest increase in the bench area. After completing the ring closure, a quick displacement rate reduction is observed.

Surface settlements of approx. 10 mm (overburden 160 m) were recorded, while passing GNFZ with the first tube (track 2). The lagging second tunnel, track 1, has already passed the freeway, so the expected additional settlement while crossing the GNFZ on the surface is low.

5 RESUMEE

By means of exploratory drillings, the boundary between the disturbed mica schist and the equally disturbed carbonatic margin zone of the Grassberg was found on track 2 about 100 m earlier than predicted. Already with the first drilling a strong water ingress with potential material discharge in the mica schist became apparent. Extensive grouting measures were used approaching the fault zone. Geotechnically challenging situations, such as an unstable working face, required ongoing adaptation of the grouting and tunneling concept and extensive geotechnical monitoring.

By the end of 2022, after extensive grouting measures, track 2 was finally successfully excavated through the Grassberg margin zone and reached the competent carbonatic rock.

Subsequently the GNFZ track 1 will be excavated, considering the insights gained from track 2. Further exploratory drillings in the Grassberg have already identified further weak zones, which still hold some challenges to be mastered for the entire team of the SBT 1.1 construction lot.

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