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Semmering Base Tunnel – Extraordinary deformations in a major fault system

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Abstract

The Semmering Base Tunnel (SBT) with its total length of 27.3 km comprises many geotechnical challenges including the crossing of the more than 1 km long Grassberg-Schlagl fault system consisting of a wide range of heavily sheared lithologies. A major part of the fault zone has undergone a secondary cementation by sulphatic minerals which caused a significant improvement of rock mass properties. However, the core zone of the fault system consists mainly of faulted schists and phyllites without competent rock bodies and consolidation. Thus, the rock mass properties are very poor similar to fine grained soil even aggravated by the remnant schistosity of the cataclasite. With an overburden up to 550 m this zone turned out to be one of the biggest challenges of lot SBT 1.1.

During the early design stages different support concepts for these squeezing rock mass conditions were discussed. Due to the proposed radial displacements of several decimetres, a ductile support system with yielding elements occurred as necessary. Depending on the predicted displacement level, different support concepts ranging from light to heavy were designed. In 75 % of the fault system the measured displacements were within the predicted range and the original design approach worked well. With the transition to the core zone, the total displacement of the rock mass increased up to 2 m. An ongoing modification of the excavation and support concept was necessary to deal with an initial displacement up to 20 cm. Amongst other measures a much more ductile support was developed to an extent never done before in the world of tunnelling. An additional pilot tunnel was executed for stress relief in advance of the main excavation.

Keywords

Semmering Base Tunnel, fault system, squeezing ground conditions, yielding elements, NATM

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1 Introduction

The Semmering Base Tunnel (SBT) is part of the Baltic-Adriatic railway corridor and one of the major infrastructure projects in Europe (Gobiet, Wagner 2013), and includes two single-track tunnel tubes as well as cross-passages with a spacing of 500 m. The project is located at the eastern end of the Austrian Alps and connects Gloggnitz (federal state of Lower Austria) and Mürzzuschlag (federal state of Styria). Due to its total length of 27.3 km and complex rock mass conditions, the project is divided in 3 construction lots. The eastern construction lot SBT 1.1 Gloggnitz Tunnel crosses major fault zones, especially the more than 1 km long Grassberg-Schlagl fault system, which consists of a wide range of heavily sheared lithologies. In order to reduce the total construction time of lot SBT 1.1 an additional intermediate access is located at Göstritz, nearby the southern end of the Grassberg-Schlagl fault system. This access consists of a 1.2 km long access tunnel and two 250 m deep shafts (Hauer et.al. 2022). The excavation in the Grassberg-Schlagl fault system is mainly carried out from the intermediate access Göstritz. The total length of the construction lot is approx. 7.4 km (see Fig. 1).

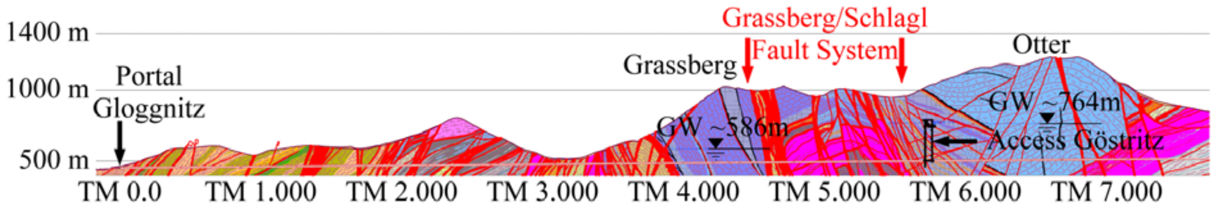

Fig. 1 Geological longitudinal section SBT 1.1 at the time of tender design

2 Geological conditions

The "Grassberg-Schlagl fault system" is one of the largest tectonic lineaments on the eastern edge of the Alps with active seismicity. The total thickness encountered during construction is approx. 2 km, which is double the assumptions made prior to project execution. Lithologically, a predominantly silicate area in the north can be differentiated from a predominantly carbonate area in the south. The silicate area represents the most challenging part of the Semmering Base Tunnel in geotechnical aspects, with an expected displacement in the middle decimeter range. Finally, this section had an extension over approximately 1.2 km.

The rock mass can be described as a “tectonic melange” or as a BiM-rock (block-in-matrix). Characteristic is the small-scale change of the different lithologies, which strength is mainly reduced by the intensive tectonics. The matrix consists of mostly greenish sericite phyllite, which occur as cataclasites with partial properties of plastic soft rock but with relict schistosity and thus geomechanically effective anisotropy. This matrix contains sheared strata and shear bodies of quartzites, brecciated dolomites, dark limestones alternating with slate as well as sulphate rock bodies in the form of gypsum breccias and, locally, anhydrites. The dimensions of the shear bodies are very different and range from block sizes to 10-metre-thick layer structures. Quartzites occur on the one hand as a low-anisotropic, softened grit with relict fracture bodies, and on the other hand as competent, moderately anisotropic shear bodies with sometimes high strength.

The phyllitic fault matrix is often sulphate-cemented, especially in the vicinity of the gypsum breccias, so that the strength of the cataclasite in these areas is significantly higher than predicted. This has a positive impact on system behaviour of the tunnel excavation. In the north of the fault system, however, this secondary consolidation subsides within a short distance, which led to extremely challenging geotechnical conditions over an extension of about 600 m. Moreover, the rock mass on the northernmost 400 m consists of rather homogeneous fault rocks of a mica schist with almost no competent components. This challenging zone extends to nearly three times the length predicted in the geological prognosis.

3 Design concept with a ductile shotcrete lining

3.1 Alignment and general design concept

In the early design stages, the challenging part of the Grassberg-Schlagl fault system was expected with a length of about 880 m (Daller et.al. 2011). In order to reduce the major difficulties, an alignment was chosen, where the fault zone is crossed almost perpendicular by the track tunnels. The overburden along the fault system is up to 550 m. In the carbonate rock bodies next to the fault zone (Grassberg and Otter), the ground water level reaches up to 300 m above the tunnel level, resulting in a corresponding high water pressure.

The geological investigation indicated that the total Grassberg-Schlagl fault system could be divided in individual fault zones. These zones were given thicknesses of several tens of metres in the geotechnical model, while core zones were modelled in the lower 10-metre range.

Numerical calculations indicated significant displacements in the decimetre range due to highly stressed rock mass and existing overburden. To maintain an intact support, a ductile design approach for the shotcrete lining was foreseen.

3.2 Ductile support system with yielding elements

Large displacements often lead to damage and cracks in rigid shotcrete linings, reducing their resistance of the support and necessitating repairs. The first simple design approach was developed by Rabzewicz (1950), where slots in the shotcrete lining filled with wooden crushing elements are foreseen. Following a railway tunnel failure in Austria during the 1990s led to a further development of the principle and to an increased use of yielding elements (Schubert et.al, 1996) in squeezing ground conditions.

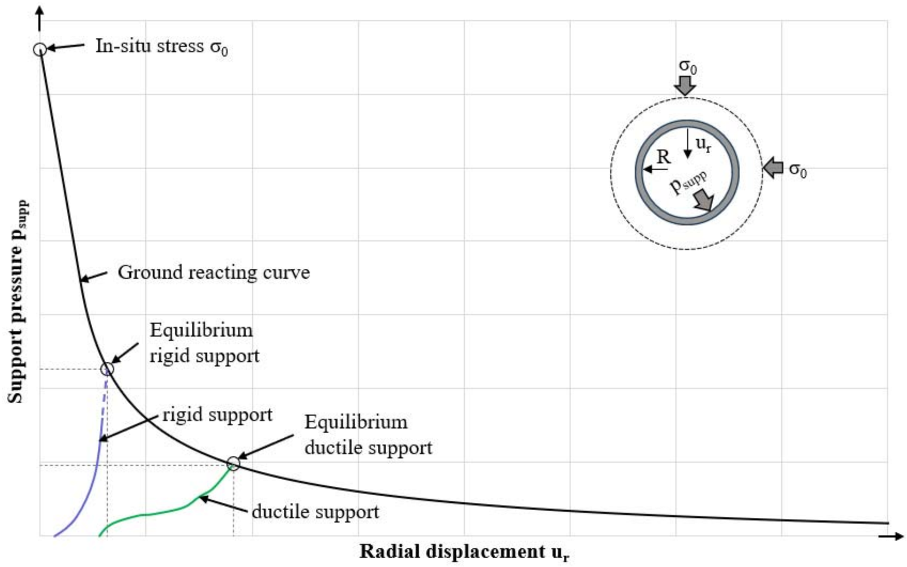

Fig. 2 Ground reaction curve and support reaction curve for a rigid and ductile support system

Fig. 2 illustrates the relationship between the ground reaction curve and the support reaction curve for both rigid and a ductile ground support (Entfellner 2024). In overstressed weak ground, a rigid support requires very high resistance to achieve equilibrium. However, shotcrete and other support materials often fail to provide this resistance early on, leading to damage. In contrast, a ductile support accommodates significant displacements before reaching equilibrium with much lower resistance. In the Grassberg-Schlagl fault system, only a ductile support concept is appropriate. During early design stages, various support types - from low to high ductility, including additional shotcrete linings - were configured based on expected displacements (Fig. 3).

The primary supports are installed in a fixed order, regardless of the support type:
Before excavating each round, spiles are installed in advance. The tunnel face is then excavated in sections and initially supported with a thin shotcrete layer. Once the entire cross-section is excavated, the first layer of wire mesh, lattice girder, and yielding element are installed. This is followed by the first shotcrete layer. Finally, a second shotcrete layer is applied, and anchors are installed in the penultimate round before the spiles are added in the next round (Entfellner et.al, 2024).

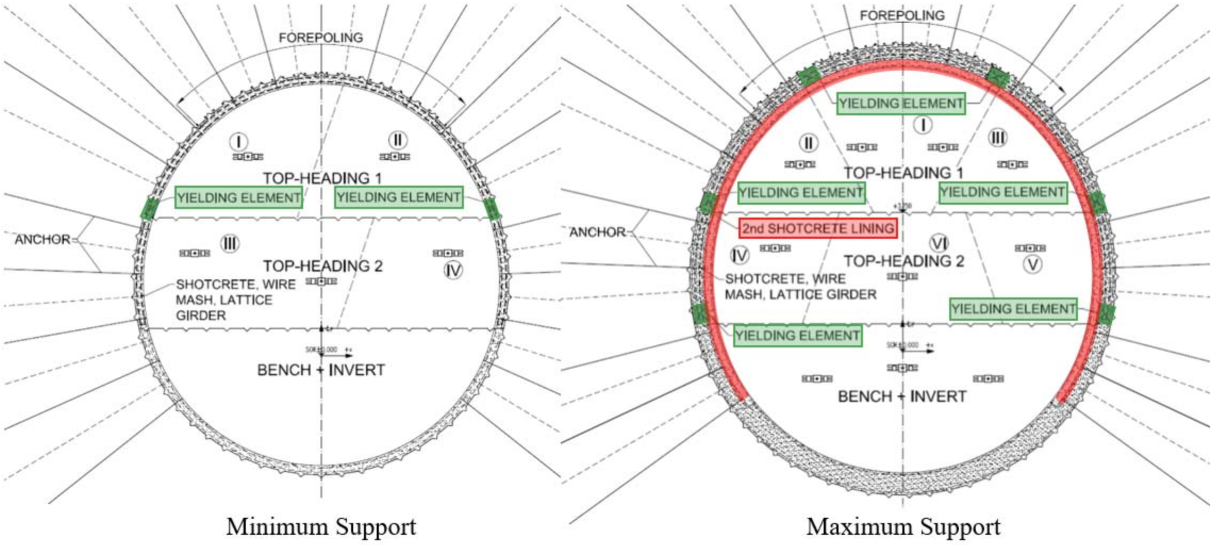

Fig. 3 Schematic illustration of different support types for the Grassberg-Schlagl fault system (left: low deformation; right: high deformation)

4 Construction phase and geotechnical interpretation

Along 75 % of the fault system the measured displacements aligned with predictions, and the original design approach performed well. In these cases, the fault system has the structure assumed in the design stage with a sequence of highly stressed, cataclastic rock types with competent areas with e.g. sulphate-cemented rock types.

However, after approximately 600 m of excavation in the Grassberg-Schlagl fault system, competent rock decreased while cataclastic formations became dominant. With incompetent sections extending up to 200 m, displacement levels increased sharply. High initial displacements caused early shotcrete lining damage, necessitating adjustments to the support and excavation concept.

4.1 Geotechnical system behaviour in a typical "tectonic melange"

Starting from the intermediate access Göstritz, the transition to the Grassberg-Schlagl fault system is located after approx. 200 metres of excavation. This is marked by an increase in displacement from a few centimetres to over 10 cm radially. To cope with this level of displacement, a ductile support was used in throughout the fault system, whereby at least two yielding elements were arranged in the top-heading. Due to geological conditions, displacement vectors were generally radially symmetrical. However, over long sections, an anisotropic rock mass intersected the excavation from the right at a 30–45° angle, often causing asymmetric displacements and uneven support utilization.

The measurement cross-section CS-438 is presented in detail as an example of the system behaviour in changing conditions. The excavation profile was nearly circular, with a radius of approx. 5.0 m. Around CS-438, alternating layers of cataclastic sericite phyllites and competent quartzite were present. Rapid rock mass relaxation, combined with unfavourable block intersections, led to potential face instabilities. To mitigate this, partial face excavation was executed alongside a subdivided top-heading with a two-round advance sequence.

Based on previous findings, a support system with 4 yielding elements (see Fig. 5 left) type LSC (lining stress controller) was selected due to the expected displacements. At CS-438 initial displacements of up to approx. 50 mm were measured, primarily in the side walls (see Fig. 4). With increasing distance from the face, the growth rates decreased, with a significant reduction observed after the ring closure (bench/invert). A characteristic of the fault system were long-lasting displacements, with growth rates of 1-2 mm/day extending several tens of metres behind the face. This leaded to a compression of the yielding elements, in the ideal manner (see Fig. 5 right). By covering the LSC yielding elements with shotcrete, it was possible to increase the resistance of the support and stabilise the displacement.

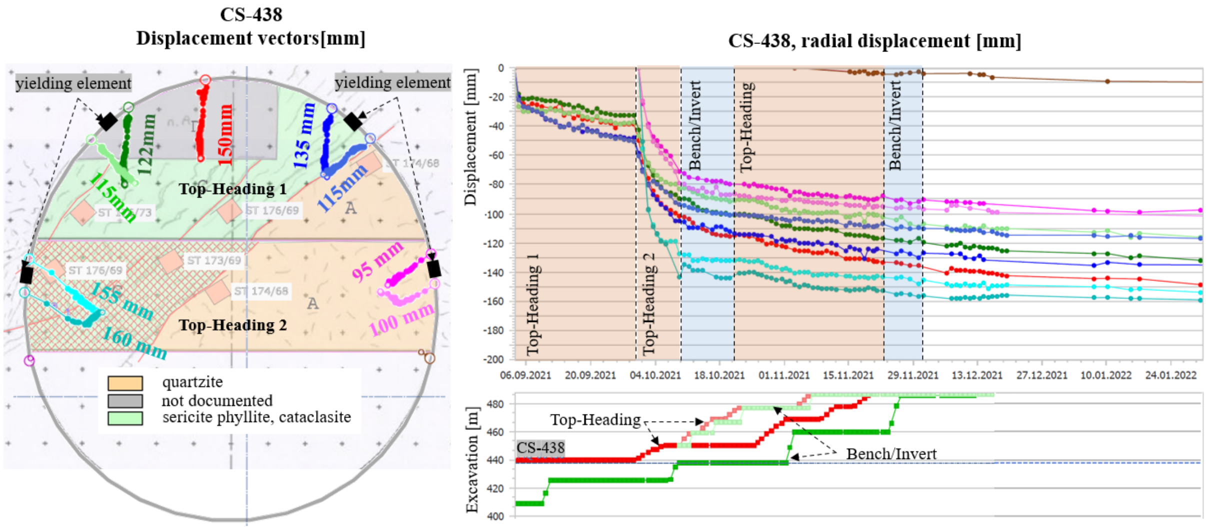

Fig. 4 CS-438, Displacement vectors in the cross section overlaid with the documented geology (left) and time-displacement graph for the radial displacements (right)

To ensure that the shotcrete and yielding elements can accommodate displacements without damage, their working lines must be coordinated (Radončić et.al., 2009, Moritz 2011, Entfellner 2024). The highest displacements occur in the initial phase, as seen in the example CS-438, when the young shotcrete has a low strength. To prevent overstressing the shotcrete lining in this early phase, the yielding elements must have a softer working line at this point. However, to achieve equilibrium later, their stiffness must increase with compression. The following case study examines the challenges of applying this design approach under conditions with very high displacements.

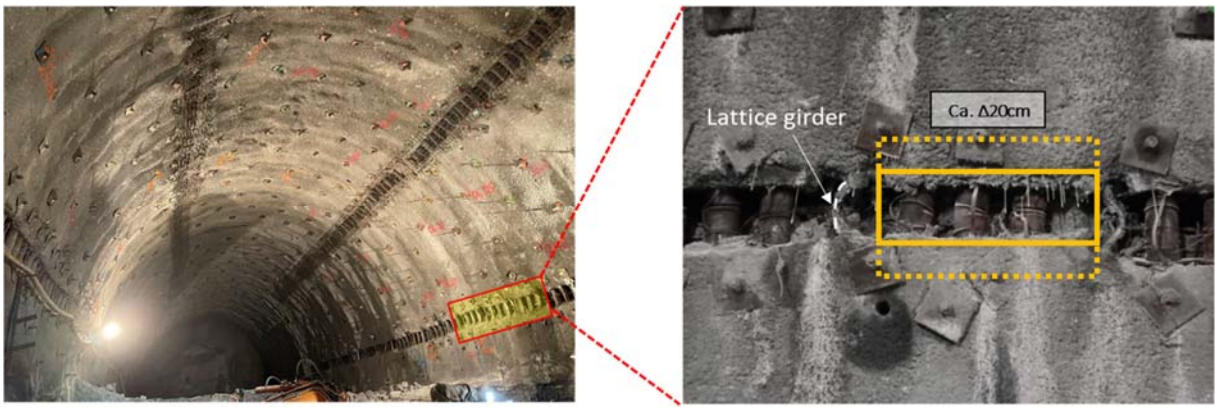

Fig. 5 Tunnel support with 4 rows yielding elements, typ LSC (left) and in detail (right), a approx. 50% compression of the yielding element.

4.2 Dealing with a rock mass displacement up to 2 metres

Approximately 600 m into the Grassberg-Schlagl fault system, the transition to an incompetent, predominantly cataclastic fault zone becomes evident, which led to a sudden increase of the initial displacements. During the design stage, additional yielding elements and a second shotcrete lining were planned to accommodate increasing displacements. This second lining enhances support resistance and can be installed once displacement growth rates decline to an acceptable level. However, rapid early displacements caused shotcrete damage within the first few metres in this zone. As a result of this damage, there was no decreasing displacement trend with further excavation and an early reconstruction of the shotcrete lining became necessary. In close collaboration between the contractor, site supervision, designer/geotechnical engineer, and tunnelling expert, it was decided to continue the excavation with an additional pilot tunnel. The primary function of the pilot tunnel was a pre-relaxation of the rock mass ahead of the main excavation. To achieve a controlled stress relief, a ductile design of the pilot tunnel was required. The pilot tunnel and the additional shotcrete lining led to modifications in the work sequence (see Fig. 6 and Fig. 7).

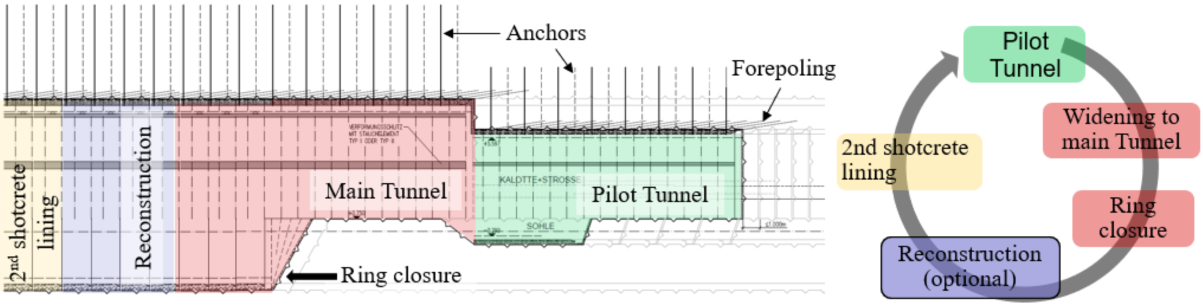

Fig. 6 Construction sequence with pilot tunnel and second shotcrete lining

The pilot tunnel was excavated ahead of the main excavation by approximately 30 metres due to the large increase in displacements, the increasing damage to the shotcrete lining and construction process influences. This was followed by a 20-metre widening of the pilot tunnel to the main tunnel. By not fully extending the pilot tunnel over the entire 30 m, the geotechnical benefits of the pilot tunnel were maximized. The ring closure (bench/invert) in the main tunnel was executed about two tunnel diameters (2D) behind the transition to the pilot tunnel. As creeping displacement was still evident after the ring closure, an additional shotcrete lining was installed at approximately 2D from the ring closure to enhance the bearing capacity. Ultimately, this approach resulted in a stable system behaviour.

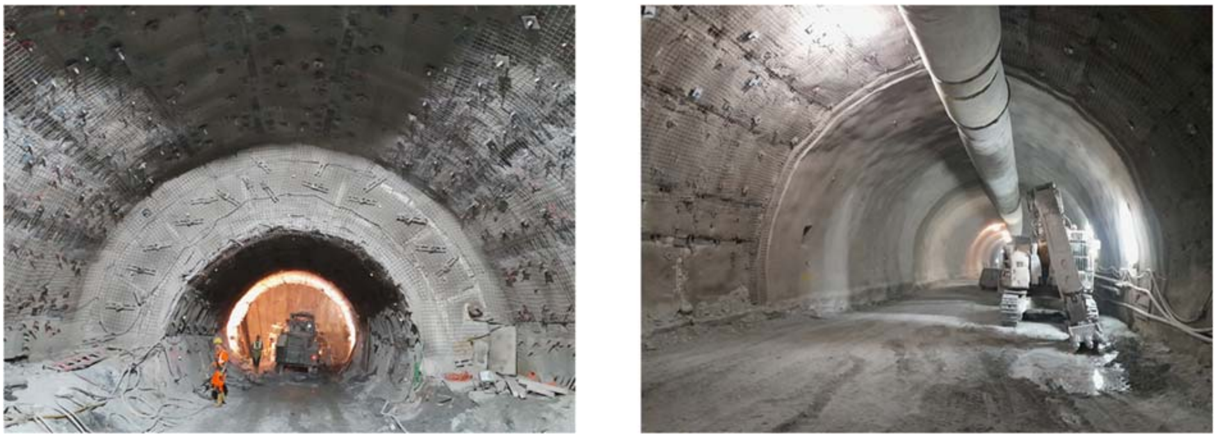

Fig. 7 Tunnel excavation with 10 rows yielding elements and an advanced pilot tunnel (left) and the transition from a ductile support system to a rigid support system with a second shotcrete lining (right)

As a case study for the zone with the highest measured rock displacements, measurement cross-section CS-1236 is analysed in detail. Located approximately 50 m into a predominantly cataclastic mica schist zone, this section exhibits highly asymmetrical displacement behaviour. Due to extreme total displacements, a pilot tunnel with a ductile shotcrete lining was excavated ahead of the main tunnel, incorporating soft HS-EPS yielding elements (Entfellner 2024). Once the maximum support resistance was reached in the pilot tunnel, excavation was stopped, and the cross-section was expanded to the main tunnel. Due to the persistently high rock pressure, a support system with sufficient compression capacity was necessary. Up to 12 HS-EPS yielding elements, each 20 - 25 cm high and configured for increased stiffness, were installed to enhance support resistance as displacements grew. As shown in Fig. 8, equilibrium was ultimately achieved only after installing an additional rigid shotcrete lining.

At CS-1236, initial displacements of up to approximately 188 mm were recorded in the pilot tunnel (see Fig. 9). As excavation progressed, high but steady displacement growth rates of up to 35 mm/day were observed. The displacement pattern is asymmetrical, with the highest amounts in the crown, influenced by the anisotropic properties of the mica schist. After total radial displacements of up to approximately 550 mm, the pilot tunnel was expanded to the main tunnel. The yielding elements in the pilot tunnel exhibited compression between 50 - 100 % (see Fig. 10, right). Once their compression capacity was reached, systematic shotcrete lining damage occurred, increasing with continued displacement and required an immediate widening of the pilot tunnel. The pre-relaxation effect of the pilot tunnel significantly reduced initial displacements in the main tunnel to about 74 mm. Long-lasting displacements with growth rates of up to 20 mm/day can still be seen, depending on the advance rate. A gradual, uniform increase in displacement was observed across the cross-section over time. However, once individual yielding elements reached their capacity, damage occurred, leading to an asymmetrical displacement pattern. When the maximum radial displacement of 792 mm was reached, a complete reconstruction of the top-heading became necessary (see Fig. 10, left).

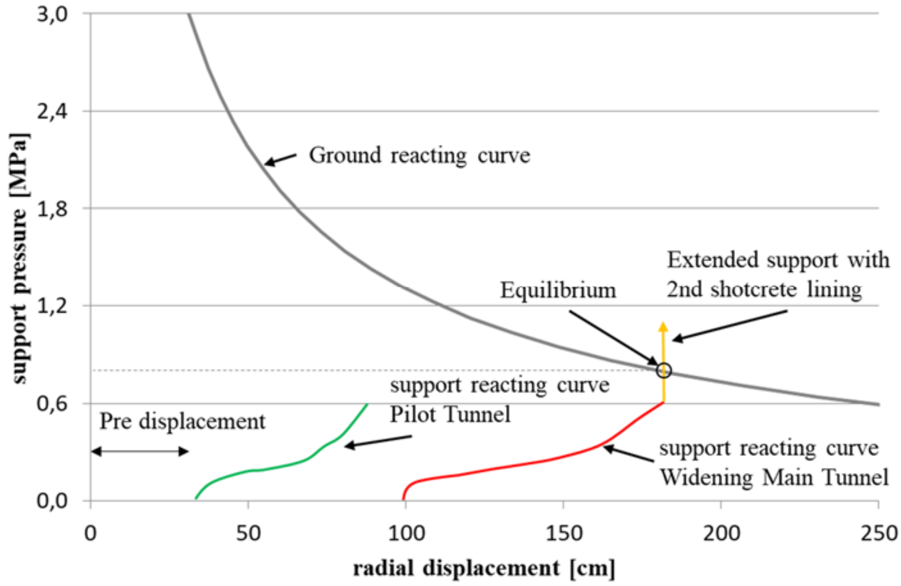

Fig. 8 Ground reaction curve and support reaction curve for a ductile support system with pilot tunnel and additional shotcrete layer

After rehabilitation, displacement rates of the shotcrete lining were reduced to a maximum of 10 mm/day, though persistent creeping displacements continued. Once maximum radial displacements reached approximately 230 mm, an additional rigid shotcrete lining was installed around 5D from the main tunnel face, leading to a stable system behaviour. Including the unmeasured displacements ahead of the tunnel face, the total rock-mass displacement at CS-1236 reached up to 2 metres.

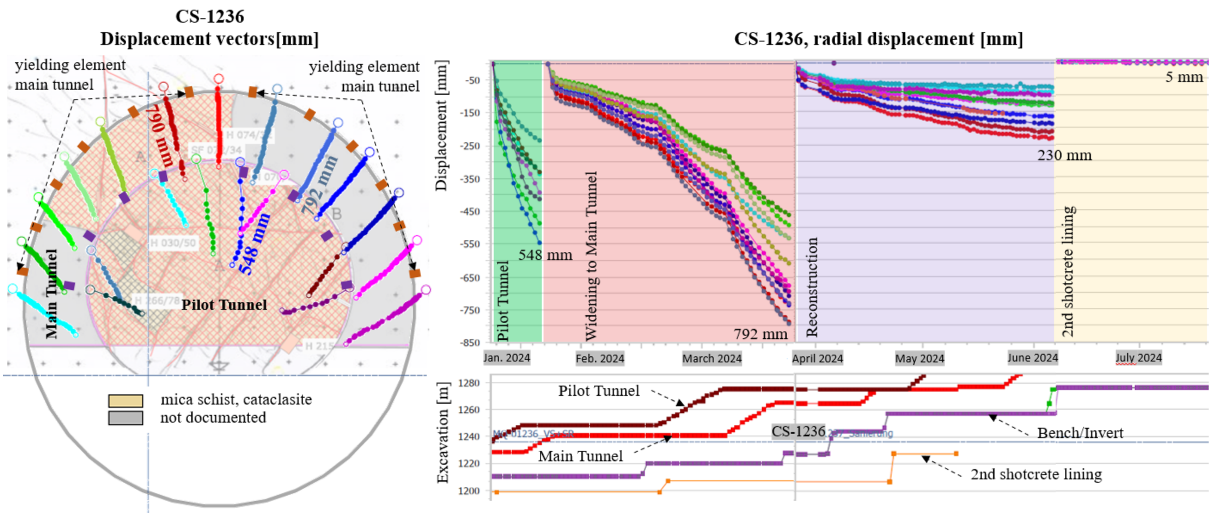

Fig. 9 CS-1236, displacement vectors in the cross section overlaid with the documented geology (left) and time-displacement graph for the radial displacements (right)

5 Conclusion

A ductile shotcrete lining combined with yielding elements represents the state-of-the-art approach for tunnelling through fault zones of this magnitude. Tunnelling in accordance with the principles of NATM made a rapid response to changing conditions possible. This requires a comprehensive geotechnical understanding of the system behaviour. On-site geotechnical engineers play a key role in this process. By interpreting geotechnical measurements and field observations, the geotechnical engineer - working closely with the geologist and designer - evaluates the system behaviour and provides short-term excavation forecasts, including necessary support measures. For sections with extreme displacements, a small team consisting of the contractor, site supervisor, designer/geotechnical engineer, and tunnel expert collaboratively adjusted the tunnelling concept, successfully passing the fault system.

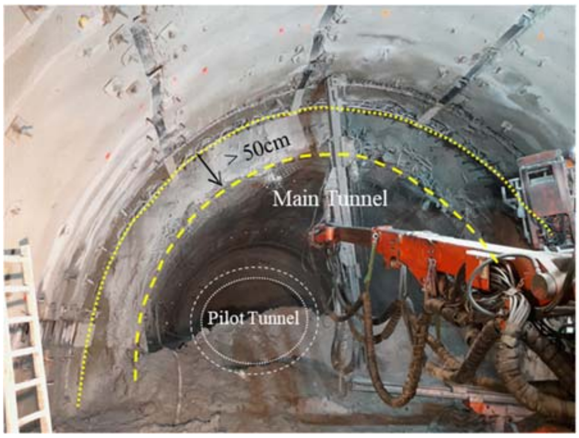

Fig. 10 Reconstruction main tunnel after a displacement > 50 cm and a damaged shotcrete lining (left), HS-EPS yielding elements in the pilot tunnel with a compression > 50% (right)

The use of a pilot tunnel led to a pre-relaxation of the rock-mass and reducing the rock pressure on the main tunnel. Both tunnels were constructed with a ductile shotcrete lining incorporating HS-EPS yielding elements in this section. Due to the constantly changing geological conditions, a symmetrical arrangement of the yielding elements was generally the most effective. The number of yielding elements should be selected based on expected displacements, with each element capable of compressing over 50% under optimal loading. In addition to predicted displacements, the size of the shotcrete segments also influences the number of yielding elements, with segments up to approximately 2 m demonstrating a satisfactory system behaviour.

The installation up to 12 HS-EPS yielding elements in the top-heading of the main tunnel effectively compensated for radial displacements of up to approximately 75 cm, largely without damage. However, ongoing creeping behaviour necessitated an increase in support resistance to balance rock pressure and structural stability. This was achieved by adding an additional shotcrete lining, ultimately ensuring stable system behaviour. In the core zone of the predominantly cataclastic mica schist section, total rock mass displacements reached up to 2 metres.

The successful crossing of the Grassberg-Schlagl fault system was made possible by the close cooperation of all parties involved and a shared commitment to continuously optimizing excavation and support methods. The final breakthrough of the Semmering Base Tunnel took place in November 2024.

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