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Construction Challenges of the Karavanke Tunnel's Eastern Tube in Water-Bearing Conditions

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Abstract

The construction of the new eastern tube of the Karavanke Tunnel was completed in 2025, while it was opened to traffic in March 2026. Excavation works, accomplished in 2024, were carried out under highly variable geotechnical conditions, including several sections with high-capacity aquifers. The first critical section passed through the Werfen Formation, where the transition from clastic rocks to carbonates was water-bearing. The crossing of an approximately 100 m long fault zone involved significant water inflows, reaching up to 35 litres per second. Another major water-bearing zone was encountered at the transition from the Werfen Formation to the Schlern Dolomite at the Goliški Fault, where tunnel excavation passed through a short fault zone of mylonitic dolomite. The latter section posed almost insurmountable challenges during the construction of the existing western Karavanke tunnel approximately 30 years ago. Caused by the surge of the water inflow of up to 5,000 l/s tunnel a collapse occurred, accompanied by a devastating debris flow of more than 3,000 m³ of material. Following thorough preparations for the excavation of the eastern tube several measures were implemented to ensure effective pre-drainage of the water-bearing sections to prevent high water inflows. These measures enabled the safe continuation of excavation works and provided valuable insights into the hydrogeological conditions of the Karavanke mountain range. The improved understanding was subsequently used to optimize design of the planned underground water collection system, which was constructed to capture and distribute high-quality groundwater for public use.

Keywords

Tunnel Karavanke, Water inflows, Underground water collection system, Anhydrite.

1 Introduction

The 7.9 km long Karavanke Tunnel is located on European Transport Corridor X, connecting Slovenia and Austria, and represents one of the most important north–south transport links in the Alpine region. The existing western tube, constructed between 1986 and 1991, required rehabilitation and, being non-compliant with the European Directive 2004/54/EC (Official Journal reference: 167, 2004) on minimum safety requirements for tunnels posed both traffic and safety risks. Experience gained during the construction of the western tube revealed highly complex geological and hydrogeological conditions and was instrumental in preparation for the excavation of the eastern tube.

One of the most critical sections encountered during the construction of the western tube was the Goliška fault zone. In this zone, extremely high water pressures and a high-capacity aquifer led to one of the most significant water inrush events recorded in tunnel construction, both in terms of energy release and discharge (Petkovšek B, 1990). This event resulted in the collapse of a previously constructed tunnel section in the immediate vicinity of the fault zone, as well as a major failure of the fractured rock mass above the tunnel. Remedial measures required the construction of a bypass tunnel, which enabled the continuation of excavation beyond the Goliška fault zone (Mikoš B., 1991). The bypass tunnel was subsequently repurposed to accommodate a pumping station for the permanent supply of drinking water.

The paper presents key aspects of the construction of the new eastern tube under water-bearing conditions based on invaluable experience gained during the excavation of the existing western tube. Targeted measures were developed and implemented to ensure effective pre-drainage of water-bearing zones, thereby limiting groundwater inflows and reducing the risk of excavation-induced instabilities. In this context, the drainage function of the existing tube was systematically utilised during both the site investigation and construction phases.

2 Construction of the western tube

During the construction of the western tube, significant water inflows were encountered within the Werfen Formation, reaching up to 100 l/s. These inflows were accompanied by local instabilities and the displacement of crushed material by water, which caused major difficulties during excavation due to high water pressures.



Fig. 1 Conditions during excavation through the fault zone in the Werfen Formation in the western tube (Mikoš B., 1991).

The construction of the western tube in the Werfen Formation included regular geological probe drilling and the installation of drainage boreholes. However, due to the low permeability, trapped water in the rock mass exerted pressure on the primary lining, leading to the formation of cracks, followed by yielding and eventual collapse of the primary lining. The tunnel section was temporarily supported with timber beams (Figure 1), additionally anchored, and subsequently reprofiled to the required cross-section.

Excavation of the western tunnel tube later entered the Schlern Dolomite, where, due to the limited extent of deep investigations available at the time, conditions at tunnel level at depth of some 900 m were less well known, particularly between chainages 2.4 km and 3.4 km. As a result, predicting geological and hydrogeological conditions along the tunnel alignment in general, and especially at neo tectonic fault zones within Triassic rocks, such as Goliška fault zone, was not possible. The contractors applied the same approach as in the previously mentioned Werfen Formation, where probe drilling served both for geological investigation of the rock mass ahead of the excavation face and for drainage of fracture-related water inflows. Despite regular probe drilling and drainage, water inflows reached up to 90 l/s and were significantly hampering the excavation progress.

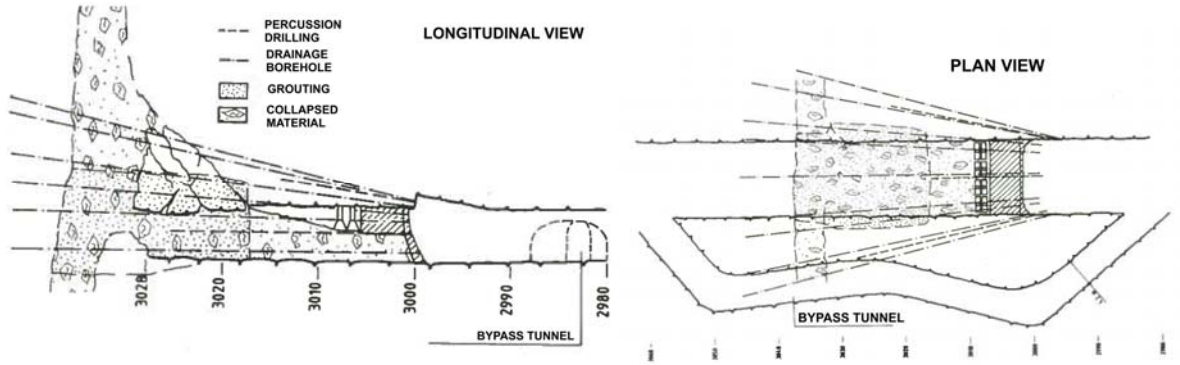


Fig. 2 The longitudinal and plan view show the estimated void space above and in front of the tunnel following the inflow of water and material caused by a hydraulic fracture at the excavation face (Mikoš B., 1991).

At chainage 3,030 m, a Goliška fault zone was identified through probe drilling; however, further excavation proved impossible. During an attempt to advance, in and partly controlled event, a tunnel collapse occurred, accompanied by water inflow of up to 5,000 l/s and a debris flow exceeding 3,000 m³ of material. Fortunately, there were no casualties among the workforce, but significant material damage occurred. Figure 2 presents a schematic longitudinal and cross-section of the collapsed area following the event. Even after 15 days, water inflow remained as high as 385 l/s, stabilizing at approximately 150 l/s after five months. Extensive remediation measures were required, including stabilization of the collapsed tunnel face and grouting of cavities. Concurrently, excavation continued through a smaller bypass tunnel which was later used for a permanent drainage of the groundwater.

3 Construction of the eastern tube in Werfen formation

The design of the eastern tube began in 2016 and was strongly influenced by the conditions encountered during the crossing of the Goliška fault in the western tube, as well as by the associated tunnel collapse. Construction of the eastern tube commenced in 2020 and revealed that, unexpectedly, the Werfen Formation fault zone was more challenging for excavation than the previously confronted Goliška fault zone.

The Werfen Formation is heterogeneous, consisting of marly limestones, dolomites, sandstones, locally also oolitic limestones, and grey micaceous sandstones with gypsum lenses. The rock mass is characterized by intense tectonic fracturing and heterogeneity, resulting in fracture porosity being the dominant mechanism for groundwater flow. Based on experience gained from the western tube, construction of the eastern tube along Werfen Formation was managed in a more systematic manner. Key measures included the timely use of exploratory boreholes for drainage, advance probe drilling ahead of the excavation face, and the installation of sufficient drainage boreholes.

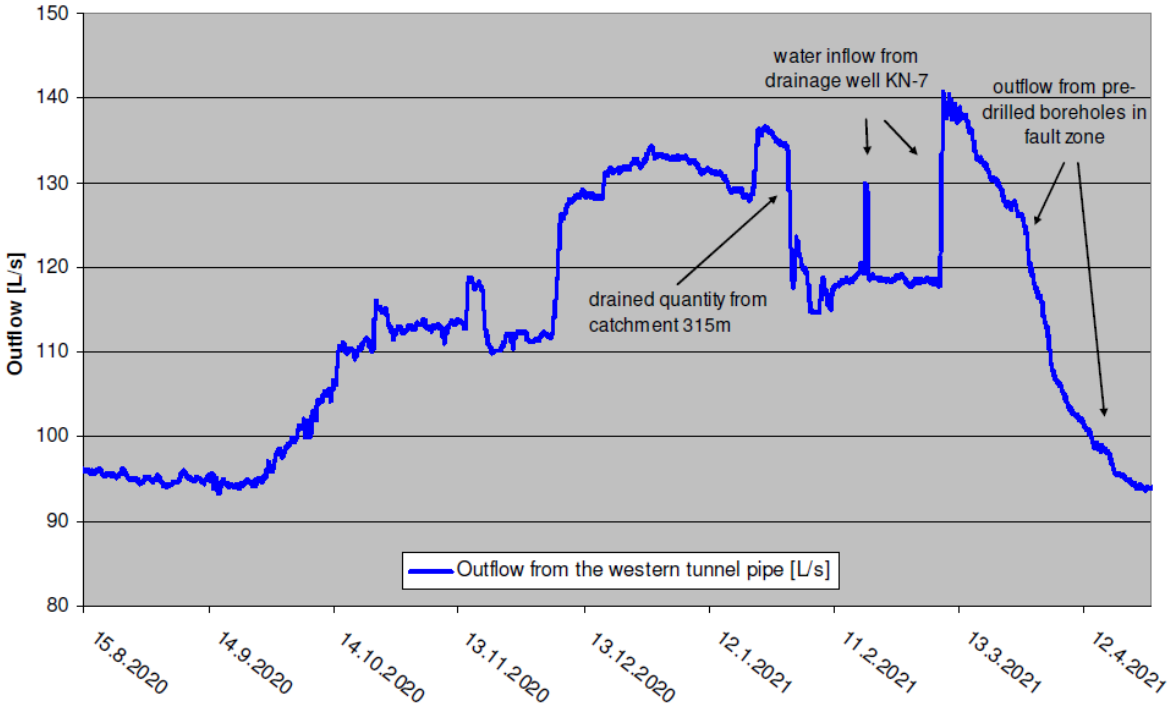


Fig. 3 Total outflow from the west tube, showing the significance of drainage from borehole KN-7 and drainage boreholes at the excavation face (Ratej J, 2024).

Important data were obtained from the exploratory borehole KN-7, drilled from a previously partially constructed cross passage in the western tube, which enabled the monitoring of pressures and inflows for several years before the start of construction of the eastern tube (Ratej J, 2024). With the start of excavation of the eastern tube at the beginning of 2021, measurements showed that pressures were around 5 bar, while inflows at the opening were approximately 30 l/s and occasionally higher. The geological and hydrogeological prognosis indicated that inflows in this area could reach magnitudes of 40 to 90 litres per second. Measured pressure values ranged between 2.5 and 5.5 bar, clearly demonstrating the dynamic response of the system to precipitation and seasonal variations. This confirmed that the aquifer has high permeability within fractured and tectonically deformed zones. To reduce the risk, a controlled release of groundwater pressure was carried out through borehole KN-7 into the drainage system of the western tunnel tube.

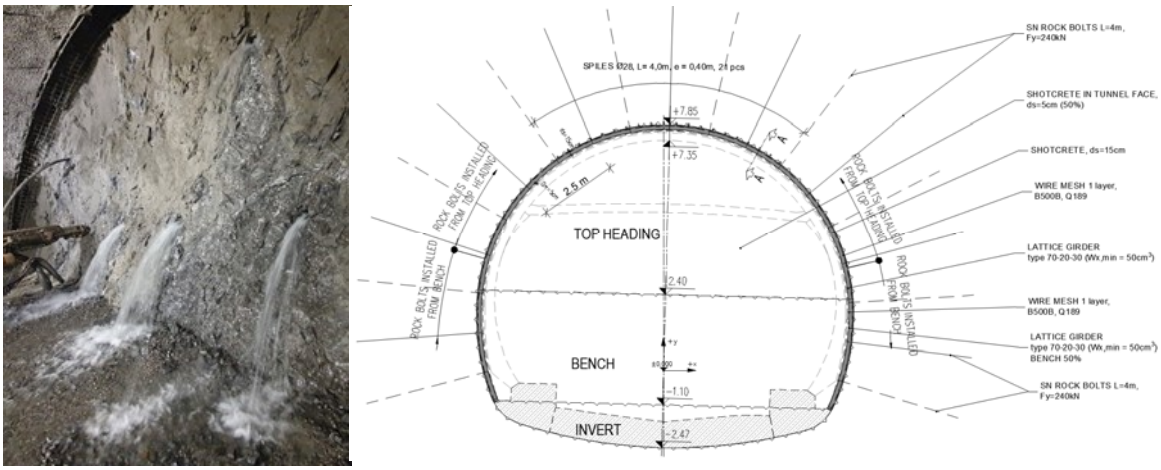


Fig. 4 Water inflow in the area of the Werfen Formation with a representative support type.

Following the start of drainage in March 2021, pressure at borehole KN-7 decreased to 2.6 bar and inflow to approximately 23 l/s. Continuous monitoring of total outflow from the western tube confirmed the effectiveness of the drainage measures (Figure 3). Simultaneously, local inflows in the eastern tube during excavation of the Werfen Formation were linked to drainage from KN-7, confirming a shared aquifer system. This significantly improved excavation conditions by reducing the risk of uncontrolled inflows and erosion. With continued drainage, pressure at KN-7 dropped to 0.22 bar and inflow to 1.6 l/s before crossing the critical zone.

The Werfen Formation exhibits a dual hydrogeological character, combining low-permeability clay layers with highly permeable fractured zones, leading to uneven inflow distribution. These conditions require continuous monitoring and adaptable measures. Long-term observations at KN-7 and in the western tube proved essential for timely and informed geotechnical decision-making.

The key strategy for tunnel construction in the Werfen Formation was systematic probe drilling and installation of 30 m long drainage boreholes with at least 15 m overlap. This enabled effective pressure relief and safe excavation with relatively light support (Figure 4), unlike the extensive remediation required in the western tube (Jovičić & Volk, 2022). Local high inflows (up to 60 l/s) were successfully controlled with additional drainage boreholes. Excavation remained stable, with primary lining deformations limited to a few centimetres, resulting in safer, faster, and more cost-effective progress.

4 Construction of the eastern tube in Goliška fault zone

As previously mentioned, the Goliška fault zone represented the most challenging section of the western tube construction in terms of water-bearing conditions. It is a complex tectonic structure composed of several parallel slices of tectonized dolomite, with highly variable permeability. The inner cores are often mylonitized and act as local hydrogeological barriers, while the marginal zones are strongly fractured and enable rapid groundwater flow. During the investigation phase, exploratory boreholes were drilled from the existing western tube and cross passages, confirming tectonically disturbed dolomite and significant water inflows. The hydrogeological prognosis, based on transferring the permeability field from the western to the eastern tube under reduced hydrodynamic pressures (approximately 3.5 bar), indicated potential inflows of around 100 l/s. The predicted inflows were expected to decrease to 25–50 l/s over the entire Schlern Dolomite section, which was later confirmed during construction.

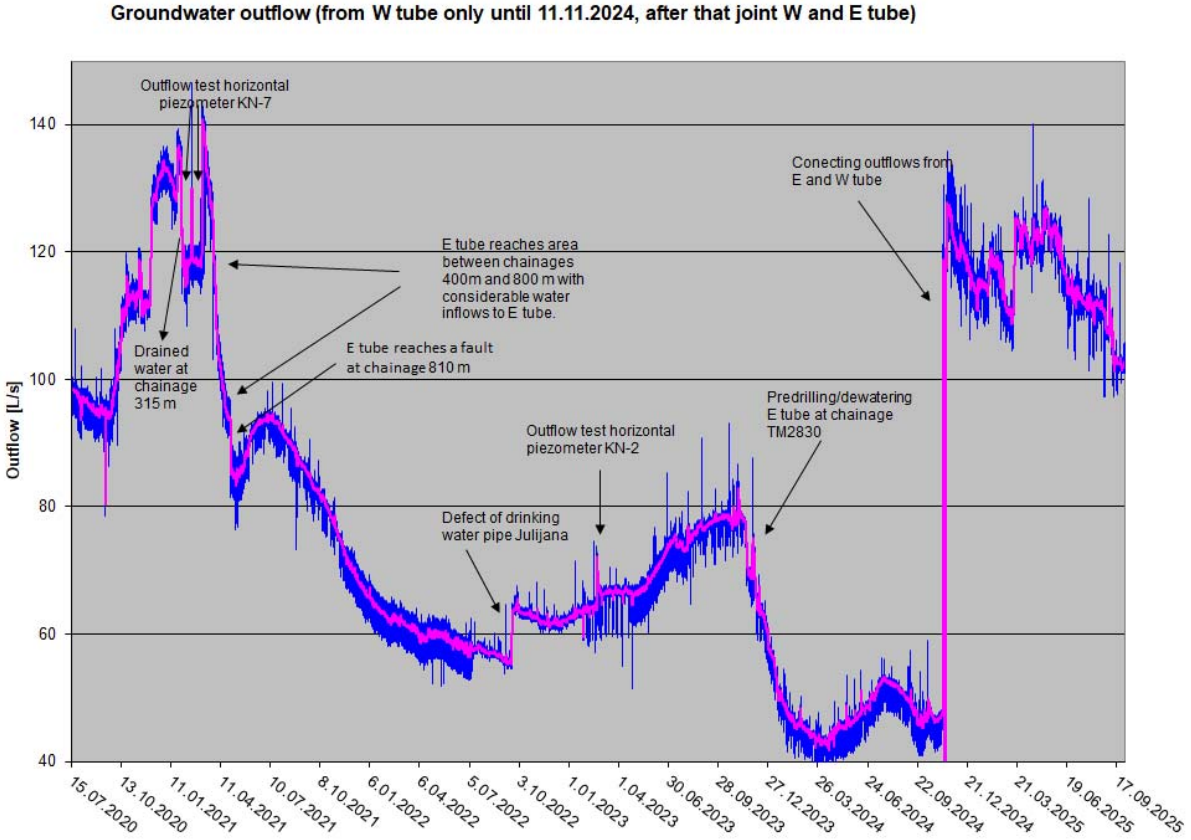


Fig. 5 Water outflows from the western tunnel tube showing the effect of drainage from boreholes KN-2a and KN-2b.

Due to the risk of water inrush, the design included several mitigation scenarios and safety measures, such as a pilot tunnel, pipe umbrella support, and grouting curtains. Additional measures were proposed in the hydrogeological report to facilitate safe excavation through the Schlern Dolomite and the Goliška fault zone. In addition to mandatory pre-drainage by probe drilling, drainage from existing

boreholes (KN-2a and KN-2b) in the western tube was also implemented. During construction of the eastern tube, nearly one year of continuous drainage through exploratory boreholes in cross passage KN-2 significantly reduced hydrodynamic pressures. As a result, the disturbed zone of the Goliška fault was no longer expected to collapse during excavation. Only minor, fracture-related inflows were encountered, and conditions did not deteriorate as the excavation approached the fault zone while no increase in inflow or material washout was observed. After completion of both drainage campaigns, total inflow was reduced to an insignificant 3 l/s.

Long-term drainage from boreholes in the western tube (KN-2a and KN-2b) proved crucial. As shown in Fig. 5, which presents total outflows from the western tube between July 2020 and March 2024, continuous discharge over nine months successfully reduced hydrostatic pressures within the wider fault zone and created a sufficiently deep depression cone, extending below the top heading level. Consequently, excavation took place in largely unsaturated conditions, with only vertically percolating water present, enabling significantly safer progress. As a result, originally planned measures such as grouting and pipe umbrella support were not required, and a standard support system for good rock mass conditions was sufficient.

Since the Goliška fault zone lies within a water protection area, part of the project also included the development of a new freshwater intake. Hydrogeological investigations were conducted to optimize its location. A blind cross passage with a collection basin and a system of wells was constructed, consisting of two wells 60 m long and two wells 100 m long, enabling efficient groundwater capture for drinking water supply.

5 Conclusion

The construction of the eastern tube of the Karavanke Tunnel clearly demonstrates that experience gained during the construction of the western tube, targeted investigations, and, above all, continuous monitoring during construction were crucial for the successful execution of this complex infrastructure project. While the western tube was marked by severe hydrogeological difficulties, water inrushes, and prolonged interruptions due to tunnel collapses, the eastern tube was constructed in a significantly more controlled, safe, and efficient manner. The key factors were a detailed understanding of ground conditions, conservative planning, and continuous monitoring, which enabled timely adjustment of measures.

In both the Werfen Formation and the Goliška fault zone, the main hazards were associated with water inrushes. These risks were effectively managed through systematic drainage. The existing western tube played an important role, as the effectiveness of drainage was verified through continuous pressure and flow monitoring from the boreholes installed during the site investigation campaign for the design of the eastern tube. Additional crucial measure was systematic installation of drainage boreholes throughout construction. These boreholes intercepted groundwater from water-bearing fractures, reducing pressures that could otherwise act on the tunnel walls and primary support system. As a result, water inrushes, and particularly the collapse of weakened and crushed rock were successfully prevented, enabling safe and uninterrupted construction progress.

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