Tunnelling in Slovenian Dinaric karst: challenges and solutions

Vojkan Jovičić
Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia

Boštjan Volk
IRGO – Institute for mining, geotechnology and environment, Ljubljana, Slovenia

Gregor Vesel
IRGO – Institute for mining, geotechnology and environment, Ljubljana, Slovenia

Jože Ratej
IRGO – Institute for mining, geotechnology and environment, Ljubljana, Slovenia

Markus Schmidt
Bo-Ra-tec GmbH, Weimar, Germany

ABSTRACT: Slovenian Dinaric Karst is an extensive karst area, 800 km long and up to 150 km wide, which is distinguished by large, closed planes, and variety of relief forms, deep caves, underground rivers, and karst springs. The main challenge for the construction of new Divača-Koper railway line that runs through Slovenian Dinaric Karst is the construction of two seven kilometers long tunnels T1 and T2. Due to scarcity of water resources in the area adequate measures for tunnel construction had to be developed to ensure the sustainability of water resources in the long term. The paper presents experience that was assembled in detection, evaluation and categorization of karstic phenomena that was encountered during the construction of tunnel T1. The temporary and final remedial measures of typical karstic features are presented in the paper highlighting the stability, functionality, and sustainability issues, which were subject to design evaluations and solutions.

Keywords: tunneling, karst features, remedial measures, sustainability of water resources

1 INTRODUCTION

The new railway line Divača-Koper connects the only Slovenian port Luka Koper with the logistics railway hub in Divača. The route is 27.1 km long and overcomes a 400 m height difference between the Slovenian karst plateau and sea level. The required maximum slope of the railway line, which amounts to a maximum of 1.7%, dictates the necessity that almost 75% of the railway must run underground. Tunnels T1 and T2, each approximately 7 kilometers long pass through a heavily karstified rock mass. Tunnel T1 is a two-tube tunnel, in which service tube will be used as a rescue route and an additional source of air for ventilation. The area of the excavation profile of both tubes is approximately 75 m^2, and the operating clearance width and height are 6.86 m and 7.00 m, respectively. Despite that the area of Slovenian karst is scarce with water, it is the only source of the water supply to the city of Koper and its surroundings. The design imperative for tunnel construction was not to deplete the water resources. The karst features had to be addressed in terms of tunnel construction both from the stability point of view and as a protentional loss of abundance of vital water supply for the region. The methodology of detection, evaluation, categorization, and remediation of the karstic phenomena during tunnel construction is briefly explained in the paper.

1.1 Geological and hydrogeological conditions

The karst plateau, through which tunnels T1 and T2 is a sequence of thrust faults that cover Cretaceous, Paleocene, Lower and Middle Eocene carbonate layers with transitional marl and flysch rocks of Eocene age (Celarc et al., 2012).

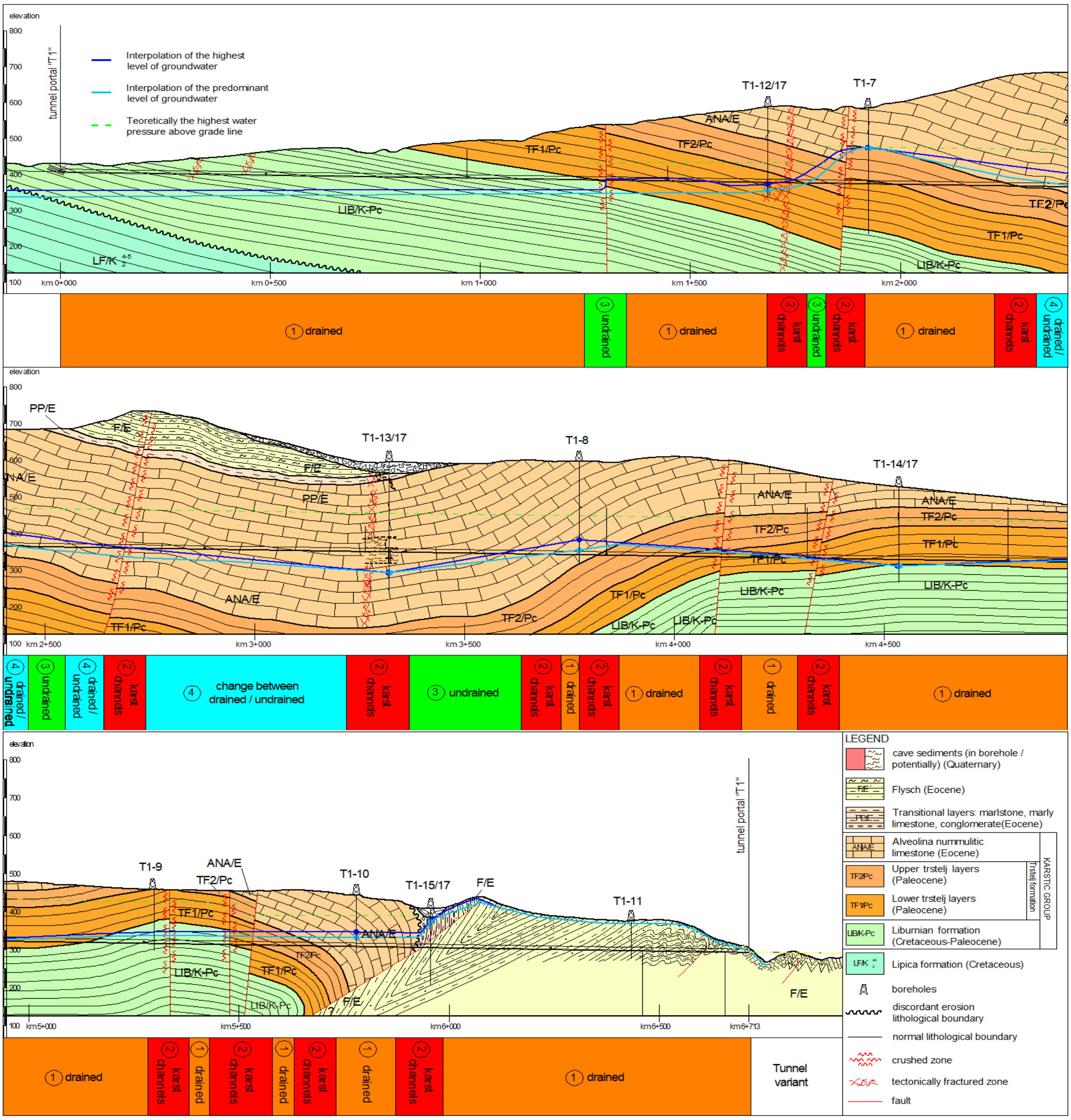

Figure 1. Geological structure along the route of tunnel T1, estimated groundwater levels, and prediction of tunnel variant cases; after (Dvanajščak et al, 2022).

The overlap of thrust faults created ideal conditions for the formation of karst phenomena, in which the underlying flysch acts as a subsurface reservoir that holds significant water in the aquifer limestone above (Prestor et al., 2019). Detailed site investigations, which were carried out in the period of the last twenty years, revealed zones of different degrees of karstification along the route of tunnel T1, differing in the diameter of the cavity and the frequency of the occurrence.

Site investigation for tunnel T1 comprised nine boreholes, which were supplied with equipment for the monitoring of the hydrogeological and hydrological characteristics of the aquifer so that valuable data were provided for the assessment of some 15 years of groundwater regime along the route of the tunnel. The longitudinal profile, which shows geological strata, and the detected levels of underground water table is presented in Figure 1. As indicated in the figure, the measurement in piezometer in borehole T1-7 showed that maximum height of the water table along the tunnel route is expected to be some 140 m.

2 DETECTION, EVALUATION AND CATEGORIZATION OF KARSTIC FEATURES

2.1 Detection of karstic features

A multi-stage detection of karstic features was developed to include 100 m long horizontal boreholes drilled along the full length of the tunnel in the karstic zones. Borehole, which is drilled parallel to tunnel axis, is used to perform geophysical and hydrogeological measurements. The borehole radar measurements are carried out to detect karstic features in the rock mass ahead of the tunnel face to a tunnel axis radial distance of up to 15 m. Horizontal borehole and geophysical investigations are carried out in zones with low level of karstification as a first stage detection, while in zones with medium and high karstification this is complemented with the second stage investigation boreholes.

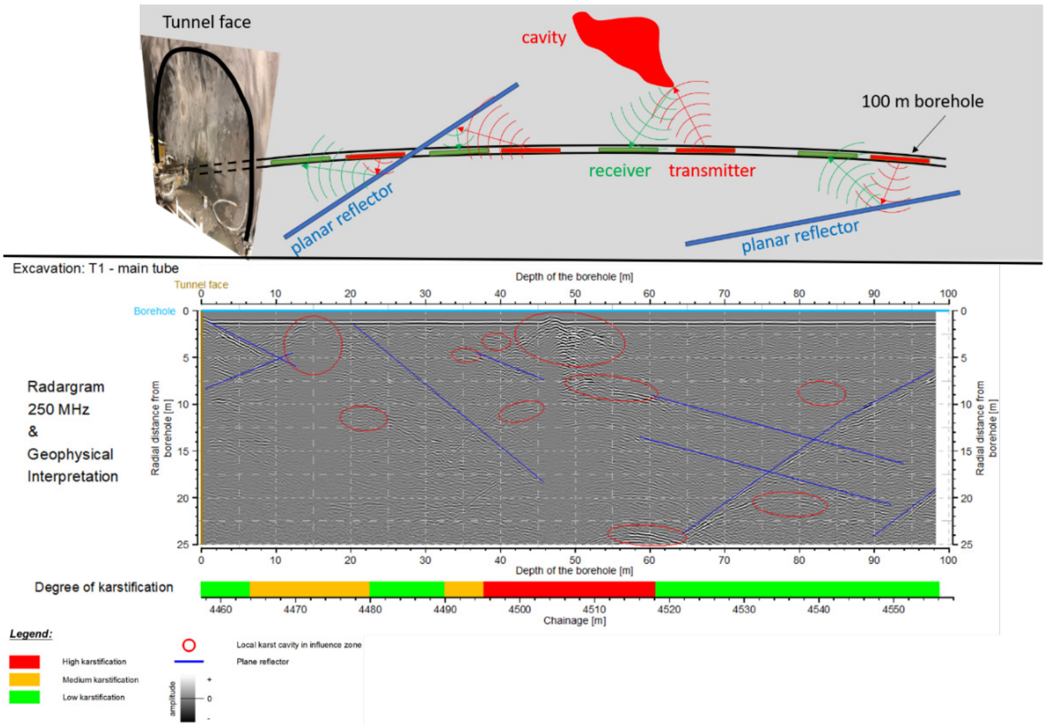

Figure 2. Radargram showing typical resulting signals of borehole radar in tunnel T1.

The Borehole-Radar-Method is pulse-reflection method in which transmitter antenna transmits short omnidirectional electromagnetic pulses into the rock mass. Transmitter and receiver antennas are lowered in the borehole and moved continuously along the run of the borehole. Discontinuities in the rock including contacts between layers, karstic voids, fractures, partly reflect the impulse back to the receiver. By correlating the measured travel time between the transmitted and reflected electromagnetic pulse with the known propagation velocity of the radar waves, the information about the distance and the run of a karst features relative to a measured borehole are determined. The typical resulting signals of a measurement along a 100 m long borehole in tunnel T1 starting at chainage km 4+457,00 are displayed in the form of radargram, shown in Figure 2. The radargram shows radar reflections in the measured section and their distance to the borehole so that the chainage and the distance and the length of a karstic feature relative to the borehole can be determined, but not the direction in space.

Figure 3. Photographs of tunnel face of the T1 main tube at chainages: a) km 4+473 local karstic feature in solid limestone; b) km 4+508 entrance to air filled cave; c) km 4+525 solid limestone.

In this specific case a zone of radar attenuation with hyperbolic reflections was detected at chainages km 4+468 to km 4+476, indicating a local karstic feature, as shown in Figure 3. The excavation confirmed this estimation at chainage km 4+473. A strong radar reflection was detected between chainages km 4+498 and km 4+514 indicating a partly air-filled cavity which was then later hit by the excavation around chainage km 4+508. The last part of the radargram from chainage km 4+518 onwards indicates low karstification and solid limestones at chainage km 4+525.

Second stage for detection of karstic features is carried out with the fan form pre-drilling pattern. Drilling pattern, comprising 7 boreholes and length of 20 m covers tunnel face and 5 m influence area around tunnel perimeter. Aim of pre-drilling is to micro locate and determine approximate size of karstic feature. If necessary, a complementary method for detecting karstic features bellow invert GPR (ground penetrating radar) is used.

3 REMEDIATION MEASURES

3.1 Temporary and final remediation

For larger karst phenomena (caves more than 10 m long and wide enough for a person to pass through), speleologist carries out cave registration, inspection, measurements and provides with description (hydrological, meteorological, nature conservation, and geotechnical) and spatial location of the cave. These directions and the karstological report serve the designer in the preparation of the temporary and final remediation measures for the particular karst phenomenon.

The useful work of speleologist is demonstrated on the example of the karstic phenomena 2TDK-009 shown in Figure 4. The cave was examined and surveyed using a 3D laser scan and the entrance was referenced relatively to the tunnel BIM model. It can be seen that karstic phenomena 2TDK-009 represents a combination of sinkhole and a cave, the entrance of which was found shallowly under the top heading floor. The shortest distance between the ceiling of the cave and the tunnel invert was about 5.0 m, while the cave stretches across the entire width and length of the tunnel, dropping steeply in the south direction for some 50 m meters.

Remediation measures in tunnel T1 are divided into two categories: a) temporary, which is referred to the top heading, and b) permanent, which is referred to the entire profile of the tunnel and/or the entire karst phenomenon.

The purpose of the temporary remediation is to enable safe conditions for the continuation of work while the purpose of the permanent remediation is to ensure the safe utilization of the tunnel in the long-term. The permanent remediation becomes possible only after the excavation of the invert, once the karst conditions are fully exposed and evaluated. Example of temporary remediation is shown in Figure 5, in which the primary lining of the right bench and invert (karstic phenomena 2TDK-018) was reinforced after the backfilling using reinforcing meshes and 50 cm thick shotcrete. The karst feature was further backfilled up using loose rip-rap obtained by the excavation of the tunnel with a grain size of approx. 5-50 cm.

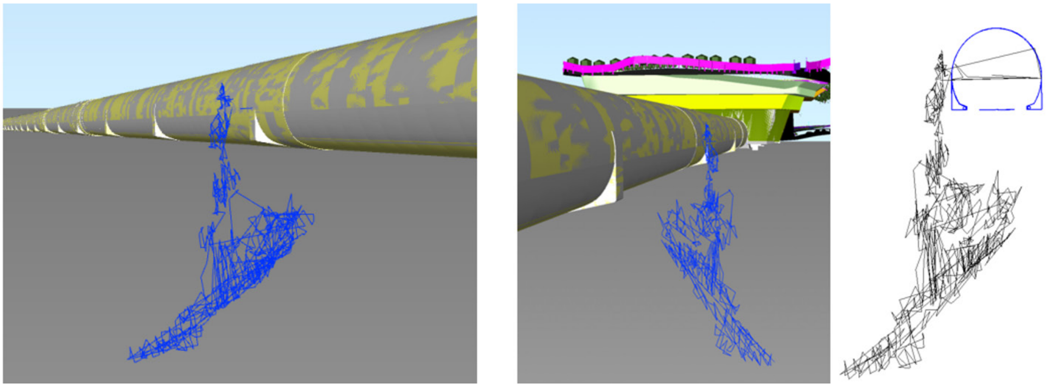

Figure 4. Three-dimensional and cross-sectional view of karstic phenomena 2TDK-009 and its position in relation to the route of the service pipe.

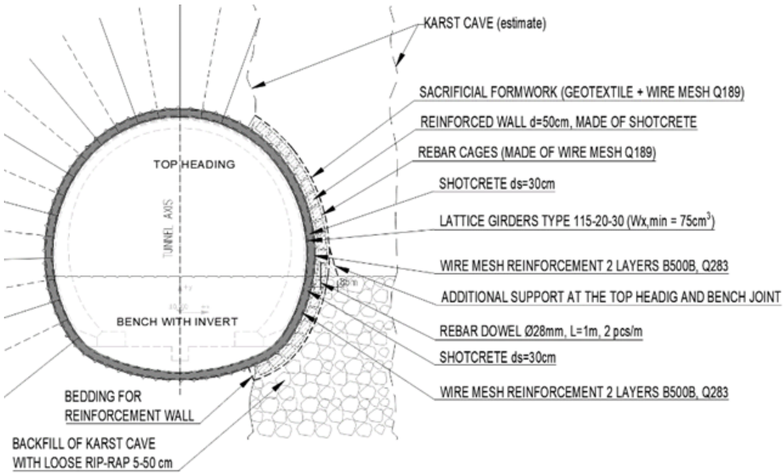

Figure 5. Schematic of temporary remediation of the abyss formed by the karstic phenomena 2TDK-018.

The permanent remediation measures must not affect the critical path of tunnel construction. Those comprise filling of empty caverns and other cave spaces with concrete or cement mass, consolidation of the cave sediment by injection, and replacement of low-bearing foundation floor with a concrete slab (Neukomm et al., 2019).

4 SUSTAINABILITY MEASURES FOR THE PRESERVATION OF WATER RESOURCES

Considering that within the karst caverns there are possible occurrences of groundwater of variable inflow, which can reach pressures greater than 10 bars, the tunnel design solution was based on the need to release the water pressures so that they are not transferred to the inner lining. For this reason, most of the tunnel was designed as drained. In the areas of high expected water intake certain sections of the tunnel were designed as undrained. There were two reasons for this: a) the fluctuations in the water level can be very fast, which makes the drainage capacity of the tunnel temporarily inadequate, and b) if the drainage of the tunnel captures too much water, it can deplete water resources in the long term. The expected division between drained, undrained and transitional sections of the tunnel T1 is also presented in Figure 1. It can be seen in the figure that certain sections have a different status notified ″karst channels″, which must be dealt with individually by using by-pass channels to re-direct the underground water inflow (Milanovic, 1981).

In the undrained section, the tunnel was designed in such a way that secondary lining can retain hydrostatic water pressures of up to 10 bars. In the zones, in which higher water pressures are expected (and in the zones of the tunnel intersection with cross passages) the tunnel was unconditionally designed as drained. The eventual possibility of high intake of ground water at those sections was to be counteracted by rock grouting, which has an aim to reduce rock mass transmissivity to the allowable levels (Stille, 2012). Rock grouting is considered as a key technical measure that can deliver both sustainability of water resources and feasibility of tunnel construction. The characteristic undrained cross-section of the tunnel is almost circular in shape so that hydrostatic water pressures cause only compressive forces, while the inner lining is made of 50 cm thick reinforced concrete.

To sustain water resources, the downstream return of the water is predicted for the groundwater collected in the drained parts of the tunnel in places where the groundwater level is below the level of the tunnel. The water return valve, allowing the movement of the water only in the direction of the outlet, is installed in a separate niche so that it can be easily maintained. A comprehensive explanation of the measures to achieve sustainability of water resources in Slovenian karst undermined by tunnelling, given for a case example of tunnel T1, is presented by Dvanajščak et al. 2021.

5 CONCLUSIONS

The experience of overcoming karst phenomena during the construction of the first 2.2 km of the approximately 7 km long T1 tunnel is outlined in the paper. General geological and hydrogeological conditions for tunnel construction determined on the basis of the extensive site investigations and long-term monitoring of the variation of the water table, are summarized. It was observed that the frequency and size of the karstic phenomena was higher than expected but no major karstic feature, which would significantly hamper tunnel construction was exposed so far.

Detection of the karstic features was carried out using 100 m long predrilling and borehole radar. Borehole radar measurements provided an overview of the level of karstification along the projected tunnel route. It was demonstrated that the karstification can be reliably estimated within the tunnel construction influence zone (radius of approximately 15 m from the tunnel axis). Experience in date collection and the interpretation of the results are summarized in the paper.

The remediation measures, divided into temporary and permanent, were readily used to overcome karstic features along the tunnel route. The examples of temporary remediation measures, used to enable safe conditions for the continuation of work on the excavation of the tunnel, and permanent measures used to ensure the safe utilization of the tunnel in the long-term, are presented in the paper. Finally, the rationale of division of tunnel T1 into drained and undrained variants, with an aim of preservation of water resources in the long-term is explained in the paper. Rock grouting is seen as a key technical operation which should be used to reduce the transmissivity of the rock mass in the vicinity of the tunnel and thus prevent depletion of water resources at the sections where groundwater pressures exceed 10 bars.

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