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TUNNEL DESIGN CHALLENGES AT THE EXAMPLE OF DIVAČA KOPER RAILWAY LINE

Abstract:

New Divača-Koper railway runs through the karst area associated with the major thrust fault, which divides limestone and flysch strata known as the Karst Edge. Due to some 400m high difference in altitude between Divača and Koper most of the railway line runs underground, featuring two six to seven kilometers long tunnels. Two types of tunneling methods were considered: TBM and drill and blast method based on NATM. The advantages and shortcomings of each method are discussed and the set of reasons is given why TBM was not selected as a preferred solution. The main design challenges encompassing the overcoming of the karst phenomena and protection of the water resources are presented in the paper.

Keywords: tunnel design, karst phenomena, TBM, NATM, protection of water resources

ИЗАЗОВИ ПРИ ПРОЈЕКТОВАЊУ ТУНЕЛА НА ПРИМЕРУ ЖЕЛЕЗНИЧКЕ ПРУГЕ ДИВАЧА КОПЕР

Абстрацт:

Нова железничка пруга Дивача-Копер пролази кроз подручје краса кога карактеризира повратни расед који дели кречњачке и флишне слојеве, познат као Крашки руб. С обзиром на висинску разлику од 400 m између Диваче и Копра, највећи део железничке пруге пролази испод површине терена. Два тунела дужине шест и седам километара ће пролазити кроз високо карстифицирану стенску масу. Разматране су две методе тунелоградње: TBM и конвенционална метода NATM. Расправљене су предности и недостаци ових метода са приказом разлога због којих ТБМ није одабран. У чланку су представљени главни изазови при пројектовању тунела укључујући савлађивање карстних појава и заштиту водних ресурса.

Кључне ријечи: пројектовање тунела, карстне појаве, TBM, NATM, заштита водних ресурса

1. INTRODUCTION

The new Divača–Koper railway line connects the port of Koper with major logistic railway junction of Divača. The 27.1 km long route overcomes 400 m high difference in altitude between karst plateau and sea level in difficult ground conditions. The required maximum inclination of the railway track of 1.7% dictates that almost 75% of the railway line runs underground. The main challenge is the construction of the two tunnels T1 and T2, which are six to seven kilometres long and run through heavily karstified rock mass. The exemplary design solutions for tunnelling in karst are presented for tunnel T1. Similar design solutions were applied for tunnel T2 6.[1]. Tunnel T1 is the twin tunnel comprising the 6727 m long main tube and 6683 m service tube while tunnel T2 is also the twin tunnel comprising the 6017 m long main tube and 6028 m service tube.

Service tube will be used as a rescue facility and is equipped to provide access of the vehicles and to aid the ventilation in the case of fire. However, both tubes are of the same shape so that the service tube can host the railway track in the future. The size of the excavation profile for both tubes is some 75 m2, the operational bright width and height are 6,86 m and 7,00 m, respectively. There are 13 passages along the tunnel T1 and 12 along the tunnel T2, which are distributed at approximate distances of 500 m. The passages are designed to allow access to rescue vehicles and to host power supply stations.

2. GEOLOGICAL FEATURES ALONG THE ROUTE

Between Kozina and Koper there is the border area between Istria, belonging to Dinaric foreland, and Kras (Slovene word for Karst) that belong to the External Dinarides. This imbricate geological structure, formed between Eocene and Oligocene, is known as Karst Edge or Karst Rim. The main feature of Karst Edge is the sequence of thrust faults overlapping Cretaceous, Paleocene, Lower and Middle Eocene carbonate beds with transition to marl and flysch rocks of Eocene age. The faults were active in post-Miocene times due to under-thrusting of Istrian peninsula under the mainland External Dinarides 6.[9].

This sub-thrusting belt is a geomorphologic phenomenon that is intermittently exposed from Gulf of Kvarner to Gulf of Trieste (see Figure 1) in the form of high limestone cliffs overlying fertile flysch terraces. The overlap of thrust faults formed ideal conditions for the formation of karst features in the Slovenian Karst plateau, which extends east of Karst Edge.

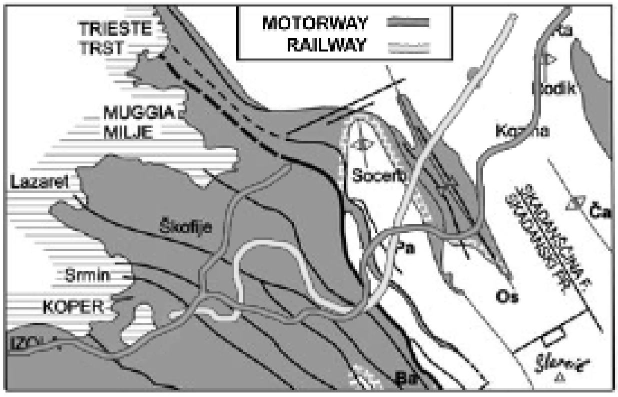

Figure 1 *Simplified scheme of Karst Edge (heavy black line), separating in parts flysch rock formations (in grey) from carbonate rocks (in white) 6.[9].*

In the typical sequence, the underlying flysch acts as an aquitard, holding the significant water retention to water bearing limestone above. As a result, a substantial karstification of the limestone is present at Karst plateau featuring the well-known Postojna and Škocjan caves, which are among the biggest cave systems in Europe. Additional karstification is occurring along sub-vertical faults and fractures giving way to vertical run-off of the almost entire net rainfall 6.[3].

As shown in Figure 1, the new Divača-Koper railway line is crossing Karst Edge in the close proximity to the existing motorway. The construction of the motorway was instrumental in obtaining the geological and hydrogeological information of this complex geological sequence. However, the motorway layout is spatially placed much higher than that of the railway. Additional site investigations, which were carried out at larger depths, revealed zones of different levels of karstification along the railway route. This is schematically shown in Figure 2 on the example of tunnels T1 and T2. It can be seen in the figure that most of the tunnel T2 runs through the highly karstified limestone with the expecting cavities of maximum diameters of up to 10 m. Tunnel T1 features three different levels of the expected karstification in terms of the cavity diameter (up to 5 m, 5-10 m and up to 10 m), as indicated in the figure. At the same time, both tunnels have transition fault zone to and sections in flysch geological sequence, which are some 0.7 km and 1.5 km long in T1 and T2 respectively.

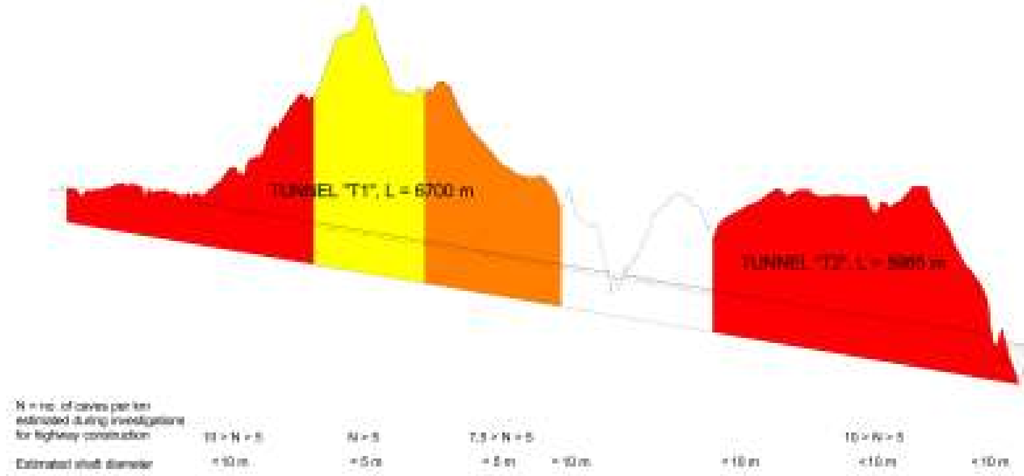

Figure 2 *Distribution of karstification along tunnels T1 and T2 (flysch sections in white).*

3. THE CHOICE OF TUNNELLING METHOD

The two types of tunnelling methods were considered: TBM (Tunnel Boring Machine) and drill and blast method based on the NATM (New Austrian Tunnelling Method) concept. The use of TBM method looked plausible, given that the lengths of the two main tunnels T1 and T2 were more than 6 km.

It is generally accepted that TBM method can be appropriate for tunnels, which are at least 3 to 4 km long. This condition is based on the assessment of the length of the drive needed to compensate the high mobilisation costs. In general, the TBM method is considered the most efficient in homogeneous rock mass or soil in which large lengths of sequence drives can be achieved using the same excavation tools and techniques. The success of TBM technology is dependent on the adequate preparation of the portal areas, resilience of the power supply, maintenance capability, competence of the crew, and above all the appropriate selection of TBM machine for the given variety of the geological conditions 6.[5]. As it will be explained further, not all of these circumstances could have been successfully met for the construction of the Divača-Koper railway.

The first consideration is that both tunnels have a sequence of considerable length in flysch geological sequence and there is a major fault transition from flysch into karstified limestone along the route, which is water bearing 6.[2]. For these difficult conditions an open type TBM, which will be otherwise fully appropriate for the limestone conditions, could not be used. A ″mixed shield″ machine would be needed, to offer appropriate alternations of the working regime 6.[5]. Additionally, in the conditions of the water-bearing fault, in which high inflow of water is expected an EPB type of the machine would be the most suitable to maintain the stability of the head of the excavation.

A further and decisive difficulty for using TBM in karst is the high probability of the total loss of the machine. This might occur due to a partial fall into the karst cave causing derailment and damage of the machine. The total loss can be caused also by a sudden flooding of the cavity. Both events are highly realistic scenarios for the given geological and hydrological conditions. Further on, along the full length of the both tunnels there would be sections, in which the karst features clash with the tunnel route. For these cases unique design solutions must be devised and implemented. Under these circumstances, the TBM method would not be useful, as it does not offer possibility of an easy access to the clash area needed for the immediate remedial action. There was no doubt that all these obstacles would significantly hamper the progress of TBM drive and slow it down, up to the point of no usability. For the reasons given above the TBM method was ruled out as a possible construction method.

It was considered that for the given geological and hydrogeological conditions the classic drill and blast method carries more flexibility and less risk for the tunnelling construction works. This method is easily adapted to any geological conditions and offers different solutions to overcome severe hydrological conditions (e.g. pre-drilling, pre-drainage and embracing drainage boreholes, use of pilot tunnels and others). Most importantly, the method enables direct access to the area of the cavity in the case of a clash. This allows for the immediate development of appropriate remedial and reconstruction measures 6.[6],6.[7].

4. PROTECTION OF WATER RESOURCES

Design solution considered mutual interference of ground water and tunnel construction. Hydrogeological investigation, that involved installation and long term monitoring of piezometers at significant locations, showed that most of the tunnel construction would be below the water table, with the maximum head of some 100 m 6.[3]. The design solution was governed by the necessity to release the water pressures so that majority of the tunnel was designed as ″drained″, featuring the drainage system comprising the watertight membrane and the longitudinal drainage pipes. Given that the water pressures will be released by the drainage system there was no need to reinforce the inner lining of the tunnel.

Certain sections of the tunnel were designed to be ″undrained″ so that they retain the hydrostatical water pressures. There were two reasons for this necessity: a) the water in the given karst conditions flows through the network of connected vessels so the oscillations in the water table can be quite rapid making the tunnel drainage capacity temporarily inadequate, and b) if the tunnel drainage takes too much water it can deplete water resources in the long term. The importance of the second argument was further amplified by the fact that part of tunnel T2 runs through the protected water-supply zone for the two major cities Koper and Trieste. For the ″undrained″ section, the tunnel was shaped to be almost circular and the lining was dimensioned to take 100 m of the water column pressures.

Given that the in the ″undrained″ variant the inner lining of the tunnel has to take the pressures of up to 10 bars, the necessary amount of reinforcement was significant. Consequently, the expense of the construction of the undrained variant of the tunnel is significantly higher (up to 30%) than for the drained variant. The decision on which part of the tunnel would be constructed in either of the variants was based on the consideration how much water will be permanently taken from the aquifer by the drained version of tunnel. If the estimate was that this amount will be unacceptably high (more than 20 l/minute per 100 m of tunnel length) at particular section the ″undrained″ variant will be considered. However, if at this section the limiting water pressure was expected to be higher than 10 bars, the drained version was still the only option. In that case the rock mass in the vicinity of the tunnel excavation will be grouted using cement grouting, with an aim to reduce the permeability of the rock mass up to the required level.

The issue of permanent water intake is defined by the amount of rock mass transmissivity along the certain section of the tunnel. The transmissivity is dependent on the thickness of the aquifer and on the type and magnitude of the conductivity of the rock mass. At this particular project the presence of karstic features added a considerable complexity to this consideration. In karstic aquifer, there is an interplay of matrix, fracture and channel (e.g. through karstic phenomena) porosity, which defines the magnitude of rock mass conductivity, as indicated in Figure 3 6.[4].

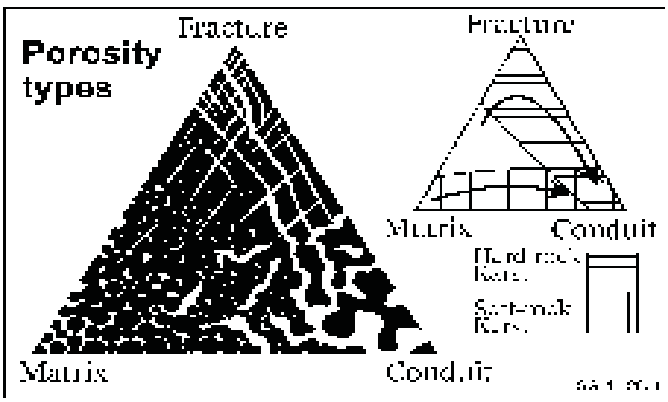

Figure 3 *Interplay between matrix, fracture and conduit porosity within karstified rock mass*

As it can be seen from the diagram of the piezometric measurement in real time, shown in Figure 4, as a result of channel permeability within karstic phenomena, certain water levels were oscillating up to 140 m in several hours following precipitation. On the other hand, other piezometers showed low sensitivity to precipitation indicating dominating impact of matrix or fracture porosity.

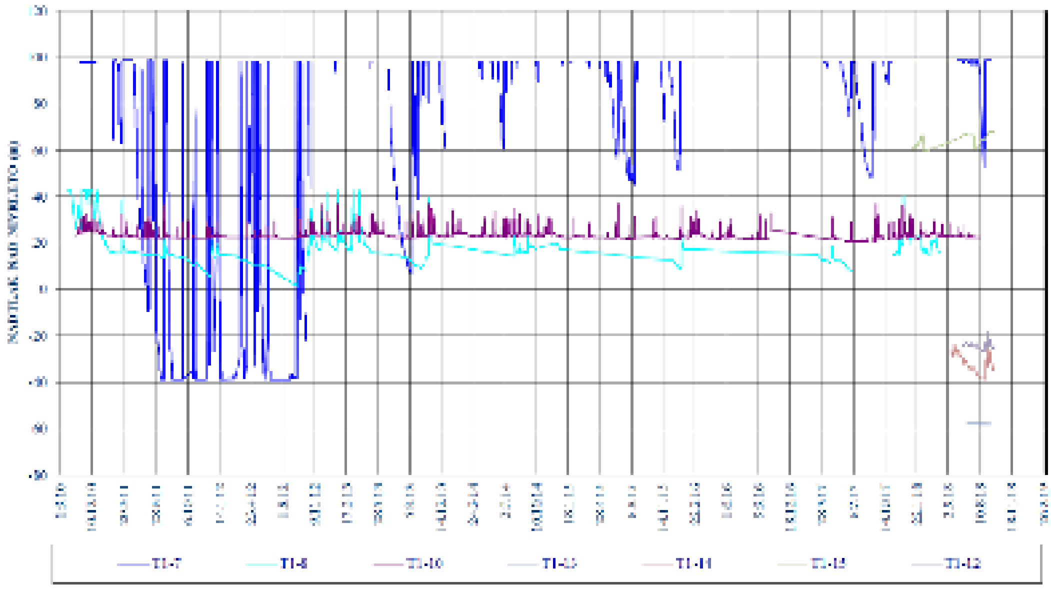

Figure 4 *Measurement of different piezometers in real time indicating the dominant type of porosity at particular location.*

In this case, it was necessary to develop a precise system of decision making by considering all the necessary information, which can be acquired using geological and geotechnical monitoring during the excavation of the tunnel. The geotechnical and hydrogeological monitoring was designed to provide with the following information: water pressures, immediate water inflow, pressures drop, the results of lugeon tests in the case of the absence of the water and the long-term water inflow along the critical section of the tunnel.

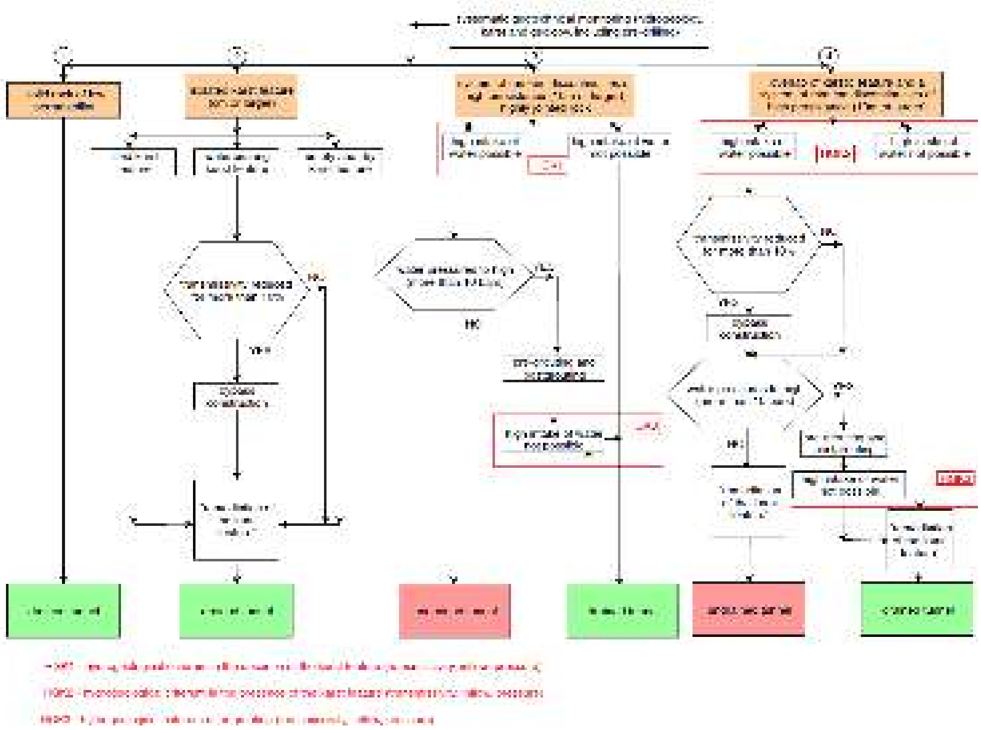

Figure 5 *A decision-making chart for the undrained and drained section of the tunnel*

A decision making chart on construction of drained or undrained variant of the tunnel at a certain section is presented in Figure 5. The decision making process considers three different types of porosities: a) matrix, b) conduit (isolated karst phenomena) and c) fracture, by dealing with four different activity scenarios: 1) use of cement grouting to lower the matrix or rock joint porosity, 2) diverting the water flow of isolated karst features, with an aim not to restrain conduit transmissivity, 3) construct the undrained tunnel to prevent the water intake overall and 4) a combinations of measures 1), 2) and 3) if there is an overlap of conduit and fracture porosity. As indicated in the figure, if the water pressures are too high for the undrained variant (e.g. higher than 10 bars) the grouting and the use of drained variant will be considered. The most complicated case is the interplay between fracture and conduit porosity, in which the measure of grouting might not be fully efficient. In this case a post-grouting will be carried out until the required water intake criteria is not satisfied.

The influence of the water inflow was also considered for the temporary conditions of the tunnel excavation. The protective ″water doors″ are designed to be installed along the tunnel at the frequency of the tube passages. In the case of the rapid water inflow the ″water doors″ are closed so that working force and machinery can be removed from the endangered zones into the safe tube and out.

As a last measure to prevent depletion of water resources, a design solution was developed to return the water collected in the ″drained″ sections of the tunnel into the aquifer in the areas of the karst caves. The discharge system is located in the ″undrained″ section so that the water collected along the ″drained″ section can be released back into the environment. The one-way system is closed so that allows the movement of water only in the direction of the discharge. The discharge equipment is planned to be installed in the separate niche so that it can be easily maintained.

5. TYPICAL DESIGN SOLUTIONS TO OVERCOME CLASHES WITH KARST FEATURES

The support measures in tunnel T1 were designed according to the principles of NATM method 6.[8] using Austrian standard ÖNORM B 2203-1. The tunnel route passes mainly through limestone and some 8% through flysch including a major fault zone in between the two rock formations.

For this geotechnical environment and for the given height of overburden (max. value of 400 m) some 5 different behavioural types (BTs) were devised, with a dominant type BT2, which is associated with deep continuous cracks and possible shear failure. There were 6 different matrix types to define 29 support types for ″drained″ and 9 for ″undrained″ type of profile. However, the sole application of the standards is not appropriate for the support measures in the clashing positions with the karst features, so the entirely different approach was needed to resolve this design challenge.

In order to develop a systematic approach in devising actions in the case of a clash, the karst features were divided into different categories by: a) position relative to the tunnel layout (middle, side, above and below), b) size (up to 5 m^3, 5 – 10 m^3, up to 50 m^3), c) filling (empty or filled with clayey material), and d) presence of water (dry or water bearing).

For each of the possible combination of the conditions a) to d) a matrix of actions was devised and remedial measures were defined in principle, so that karst obstacles can to be addressed on the basis of their significance. The key significant issues were isolated as: a) stability of the tunnel, both temporary and in the long run, b) sustainability of the maintenance and c) preservation of the encountered hydrogeological conditions and existing waterways. A set of actions was predicted to detect the type and the size of the clashing karst features including afore and radial pre-drilling and use of geophysical investigation methods. Remedial and reconstruction measures were further divided into several different categories relative to the impact they have on the progress of the works; a) not postponing the main excavation (e.g. 10 m^3 karst feature out of the main axis) b) delaying the main excavation and requiring immediate action (e.g. 50 m^3 karst feature with water inflow) and c) halting the main excavation (e.g. 100 m^3 karst feature with water inflow). These events were also categorised in terms of the risk of appearance and appropriate allowances for the delays were taken into account in the programme of the works and in the bill of quantities.

The remedial and reconstruction measures encompassed the following activities: filling, ground improvement, grouting, compaction, water-proofing, enforcement of the secondary lining and provisions of the drainage paths for the existing underground waterways. Some typical design solutions for the remedial and reconstruction measures are described in Figure 6.

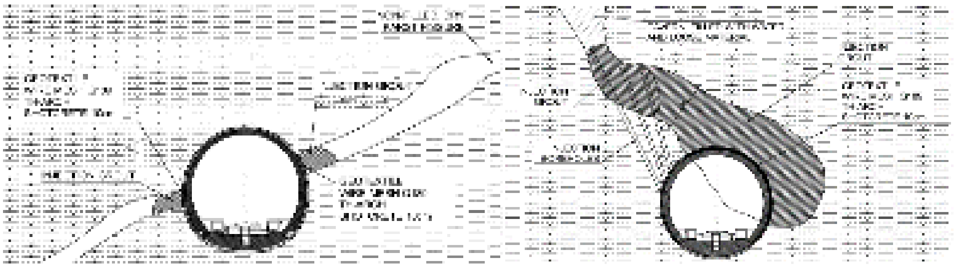

Figure 6 *Examples of remediation of the karst channels intersecting the tunnel.*

6. CONCLUSIONS

The paper presents demanding geological and hydrogeological conditions facing the construction of Divača- Koper railway line. A set of arguments is presented explaining why TBM technology was regarded not suitable for heavily karstifed rock at this location. The main governing principles for tunnel design are presented including the influence of ground water on tunnelling as well as clash of the tunnel layout with the karst features. Challenges in tunnel design were highlighted and design solutions were presented emphasizing the importance of geological and geotechnical monitoring during the tunnel excavation to aid the decision-making process in terms of selection of the type of tunnel construction.

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