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Tunnel buildability in ophiolitic mélange: a case history

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ABSTRACT: The Dinaride Ophiolite Zone (DOZ) in Bosnia and Herzegovina is characterized by the presence of ophiolite mélange and ophiolitic crust sheet formations, which outcrop at various locations. This rock mass formation resulted from the obduction of ophiolites onto the Adriatic margin, a process completed by the Late Jurassic, during which deep crustal levels of both the oceanic plate and the Adriatic margin underwent metamorphic transformations. DOZ mélange is tectonic in origin, exhibiting weakened planes, while the block inclusions range in size from several meters to several tens of meters, forming a distinct Block-in-Matrix (BIM) structure. The DOZ matrix in its fully metamorphosed and tectonically altered state behaves mechanically like hard soil - soft rock type of ground, characterized by very low permeability comparable to that of overconsolidated clays. The construction of the Putnikovo Brdo 1 twin motorway tunnel in central Bosnia, using the New Austrian Tunneling Method (NATM), was halted due to excessive deformations, including invert heave, which compromised the integrity of the tunnel lining. Additionally, significant water losses were observed during the installation of rock anchors. To address these issues, a 12-meter-long testing field was carried out in a section of the left tunnel tube to assess the efficiency of water-mist technology as an alternative drilling method. The testing field also served as a stress test to gather critical geotechnical, geological, and hydrogeological data, including an assessment of the left tube's influence on the right tube. The study examined the impact of boundary conditions on the feasibility and constructability of the Putnikovo Brdo tunnel, considering the prevailing geomechanical and hydrogeological characteristics of the site. The findings of the field-testing program, with particular emphasis on the interpretation of data related to the influence of groundwater on tunnel buildability, are presented in the paper.

KEYWORDS: tunnelling, hard soils - soft rocks, ophiolite mélange, groundwater

1 INTRODUCTION

In recent years, several highway tunnels along the corridor 5C in Bosnia and Herzegovina were planned for construction in geological formation containing ophiolitic mélange, which is a part of Dinaride Ophiolite Zone (DOZ). The construction of Golubinja tunnel near Žepče was carried out in extremely difficult ground conditions (Jovičić et al. 2024) often causing excavation works to stop due to local instabilities, partial collapses and excessive deformations.

The wider Dinaride Ophiolite Zone spans from Greece to Austria along Dinaric belt. The rock mass formation in question is the product of a complex geological process involving the obduction of ophiolitic sequences onto the Adriatic continental margin. This tectonic event, completed by the Late Jurassic period, led to placement of oceanic lithosphere onto continental crust. During this process, both the deeper levels of the oceanic plate and the Adriatic margin experienced significant metamorphic transformations, exposing the high-pressure and temperature conditions associated with obduction-related tectonics. Areas where ophiolite complexes were mapped in Bosnia and Herzegovina are shown in Figure 1.

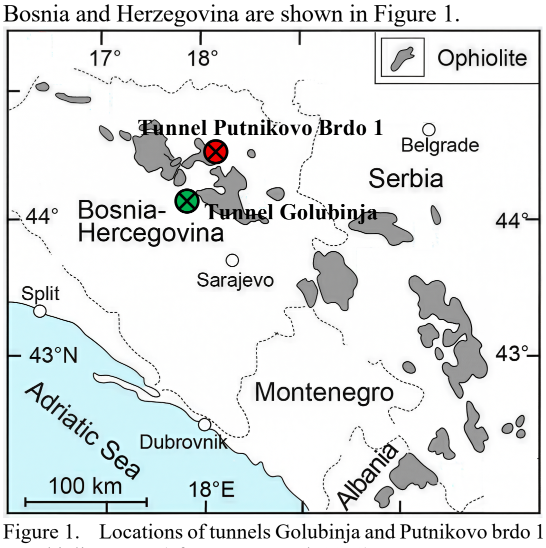

Figure 1. Locations of tunnels Golubinja and Putnikovo brdo 1 related to ophiolite zones (after Furnes et al. 2020).

The matrix of DOZ mélange is characterized by a disrupted fabric featuring numerous mechanically weakened planes, indicative of intense deformation and shearing. Within this matrix, isolated blocks of relatively more competent rock are embedded, varying in size from several meters up to several tens of meters. The result is a distinct Block-in-Matrix (BIM) fabric, a typical form of tectonic mélanges, which has significant implications on the mechanical behaviour and stability of the rock mass in engineering and geological context (Medley, 1994).

Putnikovo Brdo 1 is a 1,2 km long twin tube highway tunnel on the corridor 5C near the city of Doboj in central Bosnia. The excavation of the tunnel started in July 2023 but early in 2024 the construction of the tunnel from the southern portal has been halted due to the high recorded deformations and numerous local collapses and some surface instabilities. At several sections, the continuous tunnel deformation was achieving a cumulative value of almost 1 m and was prevailing despite several rounds of remedial works on re-profiling, during which the primary lining was fully reconstructed. Due to increasing costs and obvious inadequacy of technological procedure the work was stopped until further notice.

A broad monitoring plan on the state of the tunnel area was applied to understand the main causes of instabilities, which were occurring both internally in the tunnel and externally at the surface. The large movements, which were observed on the surface, were particularly worrying as some signs of sliding were observed above the tunnel. To examine the possibility of an activation of a deep landslide, sets of inclinometers and piezometers were installed along with the new geodetic surface measurement points, as shown in Figure 2.

During tunnel construction, significant water losses occurred during the water-assisted installation of rock anchors, caused by groundwater ingress into the surrounding rock mass. In response to these issues, a 12 meter long testing field was carried out at the continuation of the top heading in the left tube. The primary objective of the test field was to evaluate the effectiveness of water-mist drilling technology as an alternative drilling method aimed at minimizing water losses during the installation of the rock bolts.

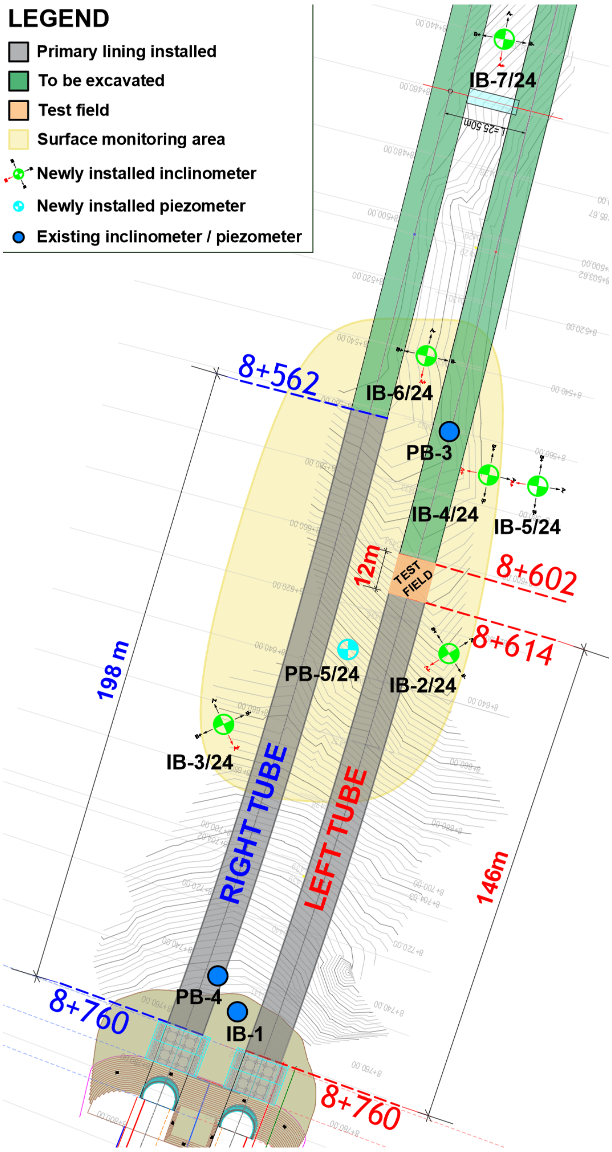

Figure 2. Location of additional boreholes for monitoring the state of the tunnel and possible landslide at southern portal of Putnikovo brdo 1 tunnel including the position of the test field.

In addition to testing the alternative drilling method, the testing field was regarded as a controlled ″stress″ test designed to collect critical multidisciplinary data. These included detailed geotechnical, geological, and hydrogeological observations essential for characterizing rock mass mechanical behavior within the tunnel zone of influence. This was also seen as an opportunity to assess the influence of construction activities carried out in the left tunnel tube on the adjacent right tunnel tube. As will be explained later, the short distance of only 25 meters between the tunnel tube axes proved to be an insurmountable obstacle to the feasibility of the tunnel construction.

2 GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

The geological profile along the Putnikovo Brdo 1 tunnel alignment exposes two contrasting formations. At the northern section of nearly half of the tunnel length the alignment intersects Upper Cretaceous sedimentary rocks: marls, marlstones, and sandstones. The layers are characterized by regular bedding with a predominant dip toward the north. Along this section the tunnel has been fully constructed without difficulties, with primary support installed using New Austrian Tunneling Method - NATM (Rabcevicz, 1964) principles and both tunnel tubes exhibiting stable conditions.

In contrast, the southern tunnel section traverses a Jurassic ophiolitic mélange formation of DOZ origin. This mélange formation consists of a fine-grained matrix of clays, silts, and sandy silts, within which lithological diverse olistoliths (primarily diabase, greywacke sandstones, and occasionally limestones) are embedded. These blocks vary in size from centimeters to over ten meters, randomly scattered to form a block-in-matrix (BIM) structure. Mechanically, the matrix of the DOZ mélange behaves as a transitional material between hard soils and soft rocks, exhibiting very low permeability and low shear strength, further reduced by weak schistosity foliation planes within it.

In terms of water transmissivity, ophiolitic mélange at the location of the tunnel effectively acts as an aquiclude, featuring a very low permeability. Due to the extremely low permeability of mélange matrix, localized groundwater seepage occurs within the Cretaceous marlstones and limestones, creating perennial springs near their contact with the ophiolitic mélange. The ophiolitic mélange itself exhibits minimal groundwater flow, except at interfaces with permeable diluvial layers, which are located above it. Once detected, this phenomenon was considered responsible for the abundance of shallow sliding above the tunnel southern portal, involving diluvial slides along the contact planes, thereby ruling out the hypothesis of a deep-seated landslide. Upon inspection of the tunnel, no water seepage was observed except for a few isolated locations in the right tunnel tube at the portal area.

Putnikovo Brdo 2 tunnel, separated by short open section of the route from the Putnikovo Brdo 1, will be built entirely in ophiolitic mélange. Using the borehole and laboratory data available for both tunnels, mechanical parameters derived from laboratory and field investigation are presented in Table 1:

Table 1. Geomechanical parameters in the execution design of Putnikovo Brdo 1 for ophiolitic mélange

Parameter	Symbol	Value	Unit
Unit weight	γ	21,7	kN/m^3
Friction angle	φ	19,5	°
Cohesion	c	15,0	kPa
Volume compressibility modulus (depth < 25 m)	$Mv_{<25}$	12,5	MPa
Volume compressibility modulus (depth > 25 m)	$Mv_{>25}$	19,6	MPa

3 TUNNEL STABILITY CONDITIONS

There is contractual obligation for tunnel Putnikovo Brdo 1 to be built using NATM (Rabcevicz, 1964). This methodology relies on several key assumptions, among them that primary support system, which consists mainly of radial rock bolts and reinforced shotcrete lining, carries part of the load caused by tunnel excavation while the other part is taken by the surrounding rock mass. This interaction between the primary lining, radial rock bolts, and the rock mass should achieve equilibrium during excavation, so that the secondary lining does not need to participate in load bearing. The NATM method enables flexible, economically viable and quick construction methodology, in which primary lining installation sequence does not interfere with casting of secondary lining and vice versa. As will be discussed later, the NATM method could not be applied in this form in the case of the Putnikovo Brdo 1 tunnel, as equilibrium could not be achieved solely through the interaction of the primary support and the rock mass.

The works on the excavation of the tunnel from the south portal started in July 2023 and were immediately born out with difficulties. At critical sections in the right tube, which was excavated prior to the left, the deformations in the tunnel were excessive. They were up to 1 m in vertical direction, up to 0,4 m in horizontal and around 0,2 m in longitudinal direction. First round of remedial works, which included the installation of additional anchors and the replacement of the invert, were carried out in January 2024 along some 50 m long critical section. However, a follow-up observation revealed additional damage and deformations so that further stabilization measures were implemented, including another reconstruction and the use of a stronger support system, including the installation of new pipe roofs. The unstable conditions in the right tube were further aggravated by the excavation of the left tube, which also suffered excessive displacements of the same order of magnitude. Since no remedial works provided equilibrium conditions in the critical section in any of the tubes and as further deterioration of the conditions continued, decision was taken by the contractor to stop the works in March 2024.

Inspection of the tunnel after the stoppage of the works carried out in May 2024 revealed highly damaged primary lining, manifested as cracks ranging up to several centimeters in both perpendicular and longitudinal direction. Besides cracks, deformations in the primary lining were evidenced by flaking of the shotcrete layers indicating spalling failure. Deformations were most common at the tunnel shoulder walls (the ceiling was protected using pipe roof in much of the tunnel) and between the bench and the floor indicating the invert uplift. Deformations related to the invert uplift were also visible along the tunnel floor.

Most anchors showed no sign of damage (no bent plates or similar sign of overloading) despite measured excess deformation in the tunnel. Conversely, several other anchors, sometimes located near non-deformed anchors, showed significant damage, with broken nuts and plates. The reason for this significant variation in anchor damage is probably caused by the possibility that some anchors were installed directly into inclusion blocks. Anchors installed exclusively in the matrix were reportedly grouted with up to 10 times more cement mass than usual, indicating substantial water intake during water-assisted drilling. Based on the understanding of mineralogy of matrix (presences of mica minerals, which will be discussed later) it was foreseen that anchors did not create a proper bond with the rock mass, allowing them to move relatively freely with the primary lining during deformation of surrounding rock mass.

During the inspection, particular attention was paid to the occurrence of water within the tunnel. Visible water seepage into the tunnel was observed only in the portal areas, where the sources were attributed to inflows at the contact between the diluvial cover and the rock. Further along the tunnel tubes, point water occurrences were absent presumably due to the very low permeability of the matrix. However, indications, particularly in the right tube, suggested the presence of groundwater in the rock mass, as moisture was readily detected within the tunnel.

Groundwater level measurements were initially carried out in piezometer PB-3 which was installed before the start of the works in May 2022. As can be seen in Figure 3, the recorded groundwater level ranges between 234,9 and 237,6 MSL, which is between 21 m and 18,3 m below the surface and some 6 m above the top of tunnel roof. Discrete measurements indicated that groundwater naturally responds to changes in the recharge area. The graph below shown in Figure 5 shows the groundwater level measurements in borehole PB-3 and rainfall data from the nearest weather station.

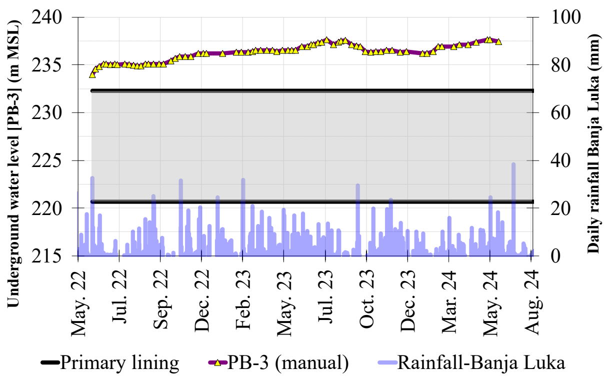

Figure 3. Tunnel profile, fluctuations in groundwater levels in piezometer PB-3 and daily rainfall levels in Banja Luka weather station

Due to low permeability of matrix, piezometer response was damped, and gradual rises in levels represent delayed response to prolonged periods of heavier rainfall. Since the tunnel invert at the location of the piezometer PB3 is at 221,5 MSL, it can be concluded that the level of groundwater is some 17 m above it. This fact will be discussed further and compared with the measurements from the piezometer PB-5/24, which was additionally installed to check the reliability of the piezometer PB3.

In order to understand the current state of the stability of the tunnel and to examine several key issues that were encountered during the inspection of the tunnel (low anchor capacity, large deformations, invert heave, influence of one tube to another, influence of groundwater, etc.), a trial excavation was proposed in the form of a test field in the left tunnel tube. The test field was conducted during the continuation of the top heading excavation in the left tunnel tube along a 12 meter section, as shown in Figure 2. The implementation of the test field has the following objectives:

1. To determine the suitability of the dry installation process for anchors (i.e. using water-mist drilling) instead of water assisted drilling.
2. To determine the load-bearing capacity of rock bolts installed using dry drilling, through pull-out tests.
3. To use the trial tunnel excavation as a "stress test" to obtain additional geotechnical, geodetic and other data to evaluate the impact of construction of one tube on the other.

To augment the assessment of the pore pressure and the possible effect on groundwater on tunnel behaviour and additional piezometer PB-5/24 was installed and continuously monitored (location also shown in Figure 2). The results of the test field and the interpretation of the results of the measurement of additional piezometer will be presented and discussed in continuation.

4 TEST FIELD LAYOUT AND THE RESULTS

4.1 The layout

Since the excavation of the right tube had advanced approximately 50 m in front of the left tube, the test field was established in the left tube to assess the influence of one tube on the other. The top heading section with a temporary invert was constructed in 1 m steps, while the primary support system consisted of a 30 cm shotcrete lining reinforced with two layers of Q257wire mesh and lattice girders 115/20/30. Passive IBO R38 anchors were installed using water-mist drilling, spaced radially at 1 m, with a length of 6 m and a capacity of 250 kN. For face stabilization of the top heading, a 5 cm shotcrete layer with one layer of wire mesh Q188 was applied, along with six IBO R38 face anchors, each 12 m long.

During the construction works, geodetic monitoring (convergence measurements in both tubes and surface measurements), geological mapping, and inclinometer and piezometer measurements were carried out. Pull-out tests of the installed anchors were conducted four weeks after the completion of the test field. In total, four additional geodetic measurement profiles were installed inside the tunnel within the testing field, and another in the right tube, positioned parallel to the excavation face in the left tube. All geodetic profiles, both new and existing, in both tunnel tubes were measured at daily intervals. The entire rock bolt installation process was documented to record drilling speed, grout volume intake, and installation time resulting in ""birth certificate" document produced for each anchor. Over the four-week period, monitoring data from the test field, including surface movements, groundwater levels, and inclinometer measurements, were collected and analyzed.

4.2 Mineralogical analyses and measurement of swelling potential

During the drilling of the inclinometers IB-2 and IB-3, as well as the piezometer PB-5, additional samples of the ophiolitic mélange matrix were taken for the laboratory and mineralogical testing. The laboratory tests were carried out to examine the swelling potentials while selected samples were sent for mineralogical analyses. The swelling potential of the samples taken from borehole IB-2/24 ranged from 4 to 14 %, with swelling pressures ranging between 50 and 237 kPa. The swelling potential of the samples taken from borehole IB-3/24 ranged from 6 to 13 %, with swelling pressures between 112 and 262 kPa while similar results were obtained from the samples taken from PB-5/24. Although these measurements indicated some potential for swelling, they were considered significant but not decisive. Their role in the recorded tunnel instabilities will be discussed later.

Among the samples with the highest swelling potential, three were selected for X-ray mineralogical analysis. One sample from each borehole at the elevation of the tunnel (i.e. at 36 m depth on average) was included in the analysis. Additional mineralogical analysis was carried out on the fraction larger than 2 μm to ensure that all fractions were properly examined. The mass fractions and types of minerals present in the two samples are shown in Table 2. The results of two samples were closely matched so that quartz (37 – 43 %) predominates in all three samples, followed by micas (mainly muscovite and illite 30 – 36 %) while plagioclase (11 – 12 %) and chlorite (2 – 13 %) were also present in significant amounts. Smaller amounts of hematite, magnetite, and anatase (1 – 3 %) were also found in the samples.

Table 2. The results of mineralogical tests for fractions larger (Sample 1) and smaller (Sample 2) than 2 μm.

Identified mineral	Relative mass percentage (%)	
	Sample 1	Sample 2
Quartz	50	30
Hematite	6	0
Plagioclase	11	12
Kaolinite	0	9
Mica (Illite, Muscovite)	30	36
Chlorite	2	13
Pyroxene	1	0

Mica silicate minerals are known for their quality in which individual crystals are easily split into fragile plates forming perfect basal cleavage. Here, presence of illite, a clay mica mineral, and muscovite, known for cleavage, were considered responsible for water losses during installation of the anchors. When exposed to pressurized water the cleavage texture of mica minerals can form preferential seepage paths forming slurry-like suspensions, as was observed in the field. The moderate swelling potential is attributed to the presence of illite as no other typical swelling minerals were found.

4.3 Convergence and inclinometer measurements

Test field deformations have mostly stabilized within a month of excavation works carried out in the testing field. Vertical deformations in the left tunnel tube showed trend to converge at around 8 cm and the whole top heading of the left tube has translated towards the right tube. As for the right tube, a noticeable horizontal movement of around 6 cm towards the left tube was evident, with vertical settlement of around 5 cm in the section located in parallel with the test field. Excavation influence was transferred also longitudinally, along both tubes, as much as 50 meters, as will be shown in the next section. Vertical settlements of both tubes were transferred to the surface of up to 3 cm, as shown in inclinometer measurements. Deflections in inclinometer IB-2/24, shown in Figure 4 provide insight into the deformation field zone around the tunnel. Excavation of the test field caused movement to 25 m depth below and above the tunnel, while the most excessive movements were observed some 5 m to 10 m the surface being probably related to shallow sliding of diluvium which occurred in parallel.

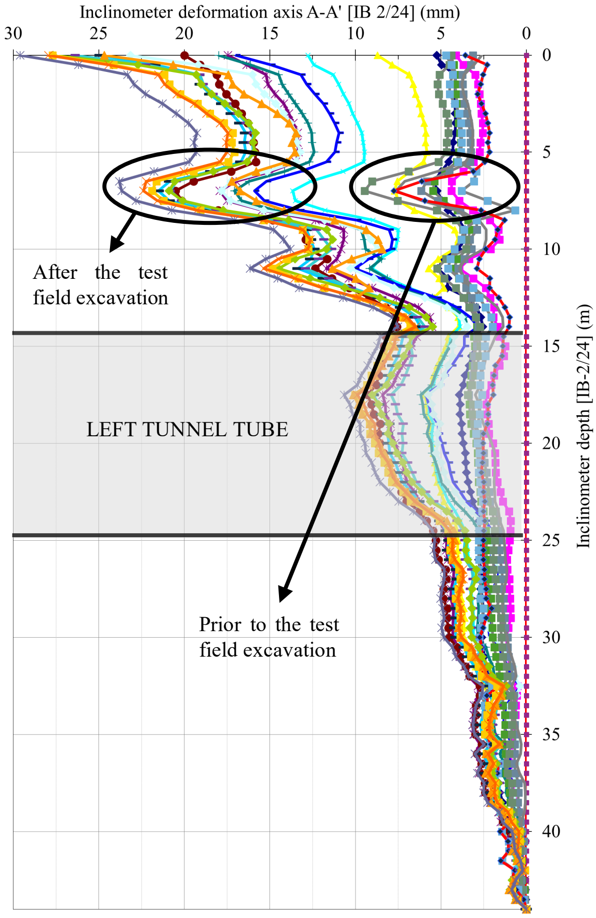

Figure 4. Deflections in inclinometer IB-2/24 and elevation of the left tube.

4.4 Anchors pull-out tests

The anchor pull-out tests were carried out covering samples from the entire 12-meter section of the test field. The anchor installations were already 34 days old at the time of testing. The criteria for selecting the anchors for testing were based on the data collected from the anchors "birth certificates". The selection of testing anchors included those "not problematic", as well as ″problematic″ and ″suboptimal″. The testing was conducted in accordance with the standard DIN (DIN 21521-2:1993-02, 1993), following the protocol for the approval test. The maximum force Fp (test load) was set at 320 kN. A total of 14 anchor tests were carried out and none of the tested anchors met the required standards. Twelve out of 14 anchors did not reach test load force Fp while the remaining two did not satisfy the creep criterion defined by the standard. The summary of anchor pull-out tests is shown in Table 3.

Table 3. Anchors pull out test results in the left tube test field.

Right Side Wall Anchor Capacity (kN)	Left Side Wall Anchor Capacity (kN)
240	223
157	320
187	170
320	38
241	159
191	38
37	-
35	-
292	-

4.5 *Piezometric measurements*

During the time between two manual measurements in piezometer PB-3 in September 2024, there was an unintended opening of the borehole, which caused the inflow of rainwater into the borehole (see detail in Figure 5). This event somehow distorts the groundwater dynamics picture during this crucial period but indirectly allows for the estimation of the permeability coefficient of the aquifer. This event enabled piezometric equalization, which was used to estimate a permeability coefficient to be approximately $k = 2{,}2 \times 10^{-10}$ m/s from back calculation.

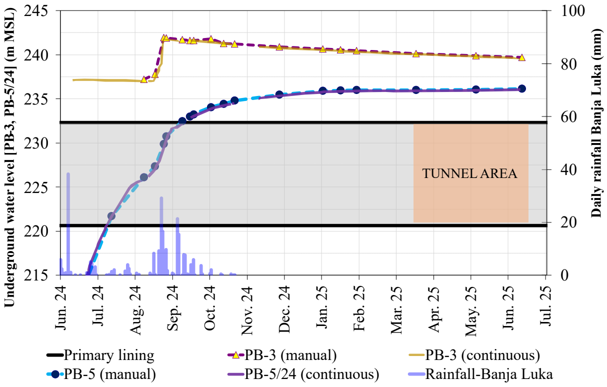

Figure 5. The hydrograph of groundwater levels in piezometers PB-3 and PB-5/24 for the period before and during the test field excavation.

The results of continuous groundwater level measurements in newly installed piezometer PB-5/24 also confirmed that a matrix of ophiolitic mélange acts as an aquiclude and contain significant pore water pressures. The actual groundwater level at the location of piezometer PB-5/24, which is also the closest to the test field area has not stabilized almost 18 months after the installation and activation. As shown in the graph in Figure 5, the level is still rising and, despite the proximity of both tunnel tubes, has already surpassed the level of some 5 m above the tunnel crown, converging towards the elevation of 237 MSL.

During the excavation of the test field, frequent heavy rainfall occurred in autumn 2024, which was partially reflected in the water levels in piezometer PB-5/24. The graph in Figure 5 shows both annual measurements and subsequent continuous groundwater level measurements from both piezometers which converge towards similar levels of around +238 MSL, which is currently some 18 m above the invert of the tunnel.

5 DEFORMATION FIELD AROUND THE TUNNEL

Excavation works in the test field started on 11.09.2024, while convergence measurement in the left tube started 3 days later. Excavation works in the test field were completed within 3 weeks, while the convergence activity could be seen almost until four weeks afterwards, when stabilization trend started. Convergence measurements profile P16 in the left tube and a layout of geodetic points are shown in Figure 6 (only points 1 through 5 were installed in test field since bench was not excavated). Positions of newly added measurement profiles (P16) in the left tube test field and (P27) in the right tube can be seen in Figure 1.

The highest vertical deformations reached 8 cm, while horizontal deformations were below 4 cm, and longitudinal deformations in the direction of the portal are approximately 2 cm. Similar behavior was observed in all measurement profiles within the test field in the left tube: large settlement coupled with the translation towards the right tube and longitudinal drift towards the southern portal. This behavior indicates that the middle pillar between the two tubes was heavily plasticized. Longitudinal movement towards the exit portal can be explained by the presence of the weak material in front of the face (Schubert & Moritz 2011), which was a consequence of the six months long stoppage of the works prior to the test field excavation.

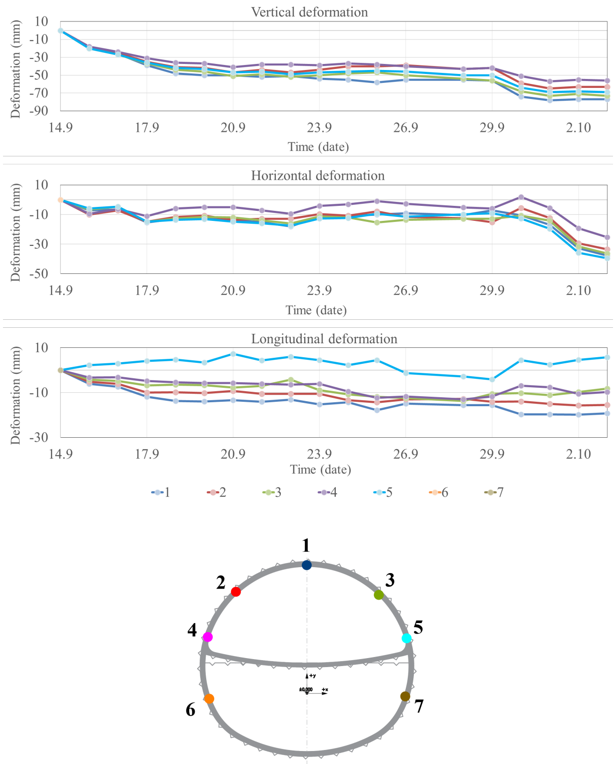

Figure 6. Convergence measurement profile P16 in the left tube within the test excavation (km 8+612) and a layout of geodetic points.

Profile P27 in the right tube was installed prior to the start of the test field excavation. The development of vertical, horizontal and longitudinal deformation component is shown in Figure 7. Right tube was nearly stabilized prior to the test field excavation (the orange dashed line marks start of test field work). After the excavation of the test field, the deformation in the right tube can be seen immediately so that the right tube has settled between 2 and 3 cm. Additionally, translation toward the left tube reached approximately 4 cm in the top heading and 6 cm in the bench area. These findings confirmed the assumption that the 25 m axis distance between the two tubes was too short, and that addressing this issue would be critical for the successful completion of the project. Deformations approximately 20 m behind the excavation face of the test field in the left tunnel tube, which was already reconstructed, settled further around 6 cm and translated towards the right tunnel tube approximately 2 cm.

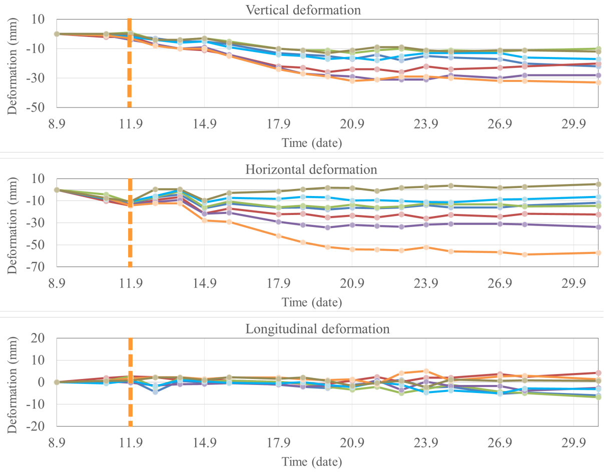

Figure 7. Convergence measurement profile P27 in the right tube parallel to the test excavation at km 8+607 (the orange dashed line marks start of test field work).

6 CONCLUSIONS

The unstable conditions persisted despite multiple reprofiling and reconstruction interventions within the initial 200 m of excavation of the Putnikovo Brdo 1 tunnel. To address these issues, a comprehensive monitoring and testing program was implemented, including additional site investigations and the installation of a testing field in the left tube.

Laboratory analyses indicated a moderate swelling potential of the ophiolitic mélange matrix and revealed a high content of mica minerals (illite and muscovite comprising approximately 30 % of the mass). These minerals were identified as the primary cause of the moderate swelling potential and of the water losses observed during water-assisted anchor installation, which hindered the formation of a proper bond between the anchors and the rock mass.

Inclinometer data and the surface geodetic monitoring showed that displacements were found to a shallow layer of diluvium approximately 5 to 10 m thick showing some large movements indication shallow landsliding and thus ruling out deep-seated landslide as a cause of tunnel instabilities. Piezometric observations indicated high water table in saturated ground, with groundwater levels approximately 6 m above the tunnel crown, that is some 17 meters above the tunnel invert. The estimate from piezometer equalization showed that matrix of ophiolitic mélange has extremely low permeability ($k=2{,}2 \times 10^{-10}$ m/s), while able to sustain high pore pressures.

The results of the test field revealed that, although water-mist drilling reduced water intake during anchor installation, pull-out tests demonstrated that the target anchor capacities were not achieved in any instance. Excavation of the test field caused vertical deformations of up to 8 cm in both tubes, accompanied by 6 cm of horizontal displacement as the tubes converged toward each other. Observations of the surrounding deformation field confirmed a clear mutual influence between the two tunnel tubes, with movements directed toward one another. The test field also induced measurable deformations extending up to approximately 40 m behind the tunnel face.

The combination of low stiffness, a high water table, and low permeability of the ophiolitic mélange matrix imposes significant constraints on the construction of the Putnikovo Brdo 1 tunnel. Buildability is further compromised by the short axis spacing between the tunnel tubes, which results in overlapping plastic zones and reduces the load-bearing capacity of the central pillar, as confirmed by test field convergence data showing mutual tube displacement. Additionally, insufficient rock bolt capacity prevents effective interaction between the already weak rock mass and the primary lining. Based on these findings, it can be concluded that the key postulates of the NATM method cannot be fulfilled for this tunnel construction.

It is highly likely that excavation of the Putnikovo Brdo 1 tunnel was initially performed under undrained conditions, with a gradual transition to a drained state through consolidation. Given the low strength of the ophiolitic mélange matrix, this process imposes excessive loads on the primary lining, exceeding its design capacity. Swelling of the invert was probably caused partly by the moderate swelling potential of ophiolite matrix but mostly due to hydraulic failure at the bottom of the excavation.

To complete the tunnel construction, modifications to the construction procedure are required, whereby the secondary lining must be engaged to carry part of the load resulting from stress relief during excavation. Further research is needed to quantify consolidation effects, assess secondary lining requirements, and determine the optimal timing of its installation relative to the construction sequence.

7 REFERENCES

DIN (Deutsches Institut für Normung), 1993. DIN 21521-2:1993-02, Rock bolts for mining and tunnel support — General specifications for steel bolts; tests, testing methods. Berlin: Deutsches Institut für Normung e.V.

Furnes, H., Dilek, Y., Zhao, G., Safonova, I. and Santosh, M., 2020. Geochemical characterization of ophiolites in the Alpine-Himalayan orogenic belt: Magmatically and tectonically diverse evolution of the Mesozoic Neotethyan oceanic crust. Earth-Science Reviews, 208, p.103258. Available at: https://doi.org/10.1016/j.earscirev.2020.103258.

Jovičić, V., Kucuk, B. and Kordić, S., 2024. Some aspects of tunnel construction in bimrocks: Golubinja tunnel case example. In: International Society for Rock Mechanics and Rock Engineering, New Challenges in Rock Mechanics and Rock Engineering - EUROCK2024. Alicante, Spain, 15-19 July 2024. Boca Raton: CRC Press, pp.290–296.

Medley, E., 1994. The engineering characterization of melanges and similar block-in-matrix rocks (Bimrocks). Ph.D. Thesis. University of California, Berkeley.

Rabcevicz, L.V., 1964. The new Austrian tunnelling method (Part 1 and Part 2). Water Power, November, pp.511–515, 19–24.

Schubert, W. and Moritz, B., 2011. State of the art in evaluation and interpretation of displacement monitoring data in tunnels. Geomechanics and Tunnelling, 4(5), pp.371–380. Available at: https://doi.org/10.1002/geot.201100033.