SHAPING THE FUTURE OF TUNNELLING
Innovation, Sustainability and Safety

PROCEEDINGS OF THE SOUTHEASTERN EUROPE TUNNELLING CONFERENCE (SETC-2025)

Papers on Technical Subjects Related to Tunnelling and Underground Space Planning and Engineering

EDITED BY
DEJAN DIVAC, SANJA ZLATANIĆ, VESNA TRIPKOVIĆ,
SLOBODAN RADOVANOVIĆ AND NIKOLA MILIVOJEVIĆ

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Tunnels and Underground Structures

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Edited by

Dejan Divac
ITA Serbia President, Serbia
Jaroslav Černi Water institute

Sanja Zlatanić
ITA-AITES Vice President, USA

Vesna Tripković
Jaroslav Černi Water Institute

Slobodan Radovanović
Jaroslav Černi Water Institute

Nikola Milivojević
Jaroslav Černi Water Institute

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Jaroslav Černi Water Institute
office@jcerni.rs

Editors:

Prof. Dr Dejan Divac
Ms Sanja Zlatanić
Dr Vesna Tripković
Dr Slobodan Radovanović
Dr Nikola Milivojević

Graphic design:

Miloš Djoković

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SHAPING THE FUTURE OF TUNNELLING

Innovation, Sustainability and Safety

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety contains the contributions presented at the ITA Awards & SETC-2025, held in Belgrade, Serbia, from 1 to 3 October 2025.

The papers cover a wide range of topics in the fields of tunnelling and underground engineering, including:

1. Advanced construction techniques
2. Use of new materials and machinery
3. Geological investigation and prediction
4. Numerical modelling
5. Instrumentation and monitoring/testing and inspection
6. Digital and information technology in design and construction
7. Strategic planning
8. Operational safety
9. Impact of climate change on tunnel infrastructure

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety aims to provide a useful resource for everyone engaged in tunnelling and underground engineering, from students and young researchers to experienced professionals and engineers.

PREFACE

The ITA Tunnelling Awards and the Southeastern Europe Tunnelling Conference (SETC-2025) were held from the 1st to the 3rd of October 2025 in Belgrade, Serbia.

The Serbian Association for Tunnels and Underground Structures (ITA Serbia) was honoured and proud to host this outstanding event of the international tunnelling community. Bringing together hundreds of distinguished experts, researchers, and industry leaders from across the globe, the event served as a dynamic platform for sharing knowledge, presenting innovations, and advancing scientific and technical excellence in the field of tunnelling and underground construction.

Serbia, with Belgrade as its dynamic capital, is experiencing a period of intensive infrastructure development, particularly in the domain of underground construction and sustainable urban mobility. Landmark projects such as the Belgrade Metro, tunnel connections, and urban underground infrastructure systems are transforming the city's transport network and enhancing its connectivity and sustainability. These projects demonstrate Serbia's growing expertise in modern tunnelling technologies, geotechnical engineering, and integrated urban planning, positioning Belgrade as a regional hub for innovation and progress in underground construction.

The conference proceedings encompass a diverse range of nine thematic areas, reflecting the multidisciplinary nature and technological depth of modern tunnelling. Topics include advanced construction techniques, the use of new materials and machinery, geological investigation and prediction, numerical modelling, instrumentation, monitoring, testing and inspection, the application of digital and information technologies in design and construction, strategic planning, operational safety, and the impact of climate change on tunnel infrastructure. Together, these themes highlight the conference's focus on innovation, sustainability, and resilience in underground construction.

It is our sincere expectation that these proceedings will contribute meaningfully to the professional and scientific community, providing valuable insights for engineers, researchers, and decision-makers engaged in the development of underground infrastructure. The knowledge and experiences shared during SETC-2025 aim to foster innovation, collaboration, and sustainable practices, encouraging the continued advancement of tunnelling and underground construction in the years ahead.

Belgrade, October 2025

Prof. Dr Dejan Divac

Chair of the ITA Awards & SETC-2025 Organising and Scientific Committee
President of the ITA Serbia

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The SETC-2025 Organizing Committee, Scientific Committee, and Editors wish to express their sincere gratitude to the conference sponsors and exhibitors for their generous support and valuable contribution to the success of this Event.

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Advanced methods for assessment of the interaction dynamics of the hydrogeological environment and pressurized tunnel: A case study of HPP Pirot

Dušan Mikavica[a], Maja Todorović[b], Marina Ćuk Đurović[b] and Igor Jemcov[b]*

[a] Jaroslav Černi Water Institute Belgrade, Serbia; dusan.mikavica@jcerni.rs
[b] University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia; maja.todorovic@rgf.bg.ac.rs, marina.cuk@rgf.bg.ac.rs, igor.jemcov@rgf.bg.ac.rs

Abstract: This study presents a methodological framework for assessing the hydraulic behavior and hydrogeological sensitivity to pressure regimes induced by the operation of a pressurized tunnel at the Hydroelectric Power Plant Pirot. By integrating total-loss tests, structural assessments, and high-frequency monitoring of pore pressure, temperature, and electrical conductivity, along with hydrochemical analyses, a comprehensive understanding of flow mechanisms between the tunnel and surrounding rock mass, hydraulic connectivity, and water origins across different lithological zones has been provided. Total-loss tests quantified cumulative leakage, while sensors in the surge tank tracked key parameters, facilitating analysis of solute and thermal transport. Internal piezometers monitored transient pore pressures, revealing the hydraulic connections between the tunnel and its surrounding environment. Results show varying reactivity among hydrogeological units; highly fractured systems exhibited rapid pressure fluctuations in sync with tunnel operations, indicating direct connectivity, whereas others showed minimal response due to low permeability or isolation. Notably, significant lining cracks did not consistently correlate with leakage, suggesting that lining conditions alone are insufficient for evaluating hydraulic performance. Hydrochemical analyses confirmed interactions between the tunnel and groundwater, particularly in sensitive areas. Findings indicate that the hydraulic reactivity of the rock mass is primarily influenced by the geometry of pore spaces and proximity to the surge tank, with tunnel lining condition having a minor role in overall sensitivity. This methodological approach enhances understanding of the interplay between the performance of the concrete lining-grout-rock interface and the surrounding hydrogeological environment under different pressure loads, underscoring the importance of high-resolution hydrogeological monitoring in assessing the hydraulic response of the rock mass, detecting potential leakage, and identifying hydraulically critical zones along the tunnel and defining priorities for rehabilitation works.

Keywords: hydraulic tunnel; concrete lining; cracks; hydrogeological monitoring; hydrochemical indicators; tunnel-groundwater interaction

1. Introduction

Hydraulic tunnels are essential components of hydroelectric power plants (HPPs), enabling the conveyance of pressurized water across geologically diverse terrains. However, their construction and operational integrity are challenged by intersecting zones of heterogeneous lithology and structural complexity, resulting in spatially variable hydraulic behavior along the tunnel alignment. Different types of linings, such as cast-in-place concrete, precast segmental lining, or shotcrete, are often used to address ground conditions, but also introduce complexity in pressure transfer and inflow–leakage behavior. Concrete linings combined with grouting are designed to reduce permeability (Schleiss, 1997); however, operational pressure fluctuations often induce tensile stresses that can lead to cracking, particularly under transient flow conditions (Karami et al., 2019). In faulted or fractured rock, such cracks may create leakage paths that undermine the hydraulic isolation of the lining, making the achievement of complete watertightness challenging. The reduced water resistance of the tunnel,

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*Corresponding author: dusan.mikavica@jcerni.rs (D. Mikavica).

combined with the initiation and propagation of cracks in the lining caused by operational pressure cycles, creates interconnected flow paths that alter the surrounding hydrogeological regime.

Considering the sustained influence of tunnel operation over time, the interaction between internal hydraulic loads and the surrounding rock environment becomes increasingly important. Water ingress and leakage through the lining–rock interface can alter local pore pressure regimes and cause mechanical-hydraulic coupling, which impacts the overall stability and function of the hydrogeological system (Liu and Li, 2022). These processes are strongly influenced by the type of tunnel lining. Segmentally lined tunnels tend to exhibit increased permeability through joints and connections, which elevates seepage velocities and affects stress distributions (Shin et al., 2012). In contrast, cast-in-place concrete linings are more prone to progressive crack development and connectivity, resulting in increased permeability over time (Yi et al., 2011; Gao et al., 2019).

Conventional monitoring methods, such as structural assessments and cumulative water loss measurements, provide valuable insights into performance and watertightness (Andjelković et al., 2013), but offer limited information on lining leakage points and transient behavior. In contrast, visual inspections can identify localized damage and quantify zones of water leakage but frequently fail to detect dynamic processes under actual conditions and are limited by low frequency and high costs. Recent studies have highlighted the benefits of high-frequency pore-pressure monitoring using internal piezometers in detecting transient hydraulic events and enhancing the characterization of aquifer response (Neupane, 2021; Jemcov et al., 2024). Additionally, hydrochemical indicators offer complementary insights into groundwater–tunnel interactions, particularly under variable pressure regimes (Ćuk et al., 2020).

This study presents advanced methods for investigating the pressurized headrace tunnel of the HPP Pirot in Serbia, situated in a complex hydrogeological environment with variable permeability. By integrating tunnel lining condition mapping data, high-frequency measurements of pore pressure, temperature, and electrical conductivity with hydrochemical analyses and total water loss testing, the study aims to identify zones prone to leakage and evaluate the hydraulic sensitivity of the rock mass. The primary objective is to develop a comprehensive methodological framework that elucidates flow mechanisms across different geological units, detects hydraulically weakened zones in tunnels, and evaluates the mutual interactions between the tunnel lining, the grout–rock contact zone, and the surrounding hydrogeological environment under variable pressure regimes.

1.1. Case study

The studied tunnel is part of a hydroelectric power plant (HPP) in southeastern Serbia. It conveys water from the Zavoj Reservoir (568–615 m a.s.l.) to a surge tank and penstock before discharging into the compensation basin. The pressurized tunnel is 8672 m long, circular in cross-section (4.5 m diameter), with a longitudinal slope of 3‰. Surge suppression is managed through a side surge tank, with measured transient levels reaching up to 630.4 m a.s.l. (Ilić et al., 2019). The tunnel lining is predominantly cast-in-place unreinforced concrete (CIP), except between stations 3+156 and 7+061, where precast segmental lining (PSL) was installed using a tunnel boring machine. The surrounding rock mass was treated with pressure and consolidation grouting to enhance structural stability and reduce permeability under internal pressure.

Geologically, the alignment crosses two major tectonic units of the Carpatho-Balkan system, the Getic and Danubian, separated by the east-vergent Vidlič thrust (Kräutner and Krstić, 2002). The Getic unit comprises Permo-Devonian clastics and Triassic–Jurassic carbonates, while the Danubian unit includes Triassic clastics and massive Jurassic–Cretaceous platform limestones (Fig. 1). Structurally, the tunnel alignment intersects a regional sub-vertical strike-slip fault and numerous secondary oblique faults (Krstekanić et al., 2022), which strongly control groundwater flow. Five hydrogeological systems were identified through earlier investigations, ranging from shallow karstic and fissured aquifers to deeper fault-controlled systems with thermal water discharge, reflecting the litho-structural heterogeneity of the terrain (Ćuk et al., 2020).

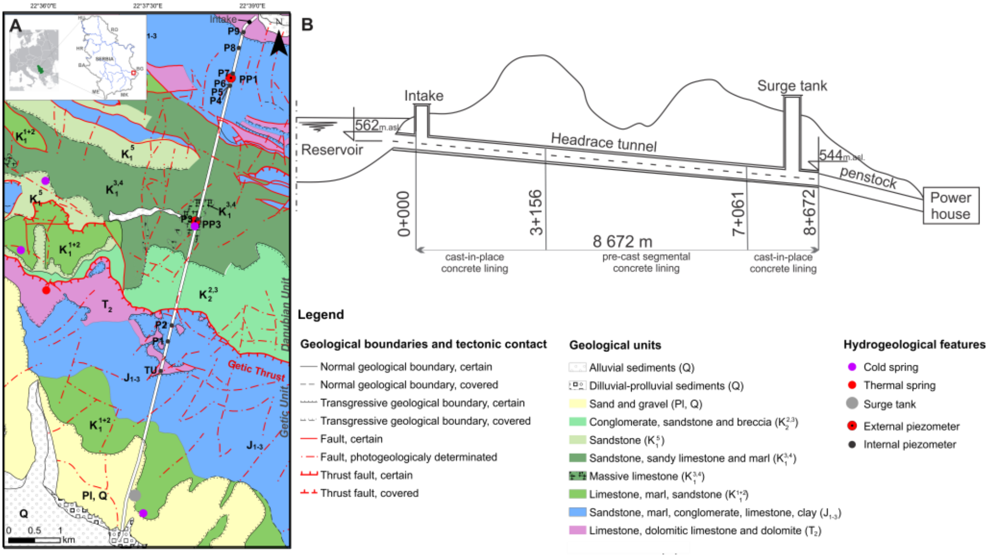

Fig. 1. (A) Geological sketch map of the study area (Anđelković et al., 1975); (B) Schematic representation of the Pirot HPP tunnel.

2. Applied methods

2.1. Measurements of the tunnel total water loss

To evaluate the watertightness of the concrete-lined tunnel and detect cumulative leakage, a multi-step total-loss measurement has been implemented as a standard procedure. The methodology was adapted from established hydraulic loss assessment protocols (Andjelković et al., 2013, Radovanović et al., 2022) and tailored to the site's geometry and operational conditions. Total-loss testing has been conducted by isolating the tunnel and monitoring water-level decline in the vertical inlet shaft (IN) with a five-step drawdown procedure. Each step consisted of a controlled discharge period followed by stabilization and an observation interval. The total leakage has been quantified by calculating volume loss over time. The test mentioned above provides a general evaluation of the hydraulic tightness of the tunnels. Therefore, the pressure lowering in the tunnel with each step results in a reduction in the total loss. A significant limitation of the implemented approach is the inability to detect water inflow from the surrounding geological environment, resulting from the induced reduction in water pressure within the tunnel. To overcome this problem, high-frequency multi-probes (measuring pressure, temperature, and electrical conductivity) have been installed in the water intake and surge tank to characterize water ingress when external groundwater pressure prevailed.

2.2. High-frequency pore pressure monitoring in the tunnel and internal piezometers

To examine the hydraulic interaction between the surrounding hydrogeological environment and tunnel pressure, an advanced monitoring system has been implemented. This system includes internal piezometers, which are situated within the tunnel and extend into the surrounding rock mass, ensuring they are completely isolated from the tunnel's water pressure. High-frequency probes have been installed in these internal piezometers to investigate the transient pressure propagation from the tunnel into the hydrogeological environment during HPP operations. While probes equipped with data loggers are effective for monitoring transient pressure, regardless of their distance from the tunnel access, they have a limited storage capacity for temporal data and require access to the tunnel for data retrieval.

Nine internal piezometers (up to 3 m deep into the rock mass) with probes, with minute logging intervals, were installed within the tunnel at points chosen based on seepage, lining damage, geological structures, and hydrochemical anomalies (Fig. 1). Additionally, internal hydraulic conditions in the tunnel and pressure fluctuations within the karst system connected directly to the tunnel were monitored by installing a pressure sensor (TU) at the open end of a karst conduit encased in a pipe within the tunnel. Furthermore, identical probes were installed in external piezometers, situated approximately 15 m from the tunnel line.

2.3. Evaluating tunnel lining damage and water leakage

To evaluate the structural condition and hydraulic performance of the tunnel lining, a combination of detailed tunnel mapping and flow assessment methods was applied to identify structural damage and spatially characterize water ingress in the depressurized tunnel. Detailed mapping of the tunnel lining is carried out on a base that incorporates the results of the previous phases. During mapping, the positions and characteristics of all fractures and water leakage events are recorded, which involves assessing or measuring their abundance. This method of collecting data on the condition of the tunnel lining provides a good database for analyzing the development of cracking over time, in relation to the geological and hydrogeological framework. A crack index (CI) was calculated and spatially correlated with inflow intensity and lithological features. Leakage was categorized into four classes (dry, wetting, dripping/seepage, leakage). To support the assessment of leakage through the lining, inflow measurements were taken at four measuring points within the tunnel: at the beginning (near the entrance structure), at two locations where the lining type changes, and finally at the tunnel exit (representing the cumulative inflow). To focus on sections of significant leakage through the tunnel, supplemental flow measurements are needed through a dense network of gauging sectors at zones where there is a considerable flow difference. Based on this approach, it is possible to detect hydraulically weakened zones, regardless of the tunnel lining. Starting from the need to perform measurements on a larger number of profiles, one possible rapid technique is the use of a flow meter that employs the tracer (salt) dilution method, which measures water flow based on the tracer concentration as a function of flow rate. The advantage of this technique lies in its simplicity and the ability to perform quick calculations, but a drawback is the potential variability in water conductivity within the measured section.

2.4. Hydrochemical analysis

A comprehensive hydrochemical monitoring campaign has been carried out, covering sampling sites within and surrounding the tunnel structure (key leakage points in the tunnel, internal and external piezometers, karst springs, and the reservoir) under different HPP operational statuses. Within an empty tunnel, successive in situ measurements of physicochemical parameters, pH, electrical conductivity (EC), redox potential (ORP), temperature, and dissolved oxygen (DO), were conducted at each leakage point to indicate possible changes in water chemistry and to select samples for chemical analyses. Water samples were analyzed for major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (HCO_3^-, SO_4^{2-}, Cl^-, NO_3^-). In addition to standard hydrochemical parameters, special attention was given to the determination of Sr, Li, and H_2S, to identify the presence of deep hydrogeological systems, and better understand their hydraulic interaction with the tunnel. Although carefully planned, sampling was limited to discrete points, preventing continuous tracking of hydrochemical changes during transient events. To address this, the sampling network needs to expand to under-monitored areas.

3. Results and Discussion

3.1. Total-loss measurements and pore pressure reactions

Total water loss measurements were conducted under pressurized conditions at a reservoir level, involving incremental reductions of the water level within the inlet shaft with stabilization periods maintained between steps. Losses were quantified at five distinct water levels (Fig.2A). Initially, at the first step, losses reached 13.10 L·s^{-1}, followed by 12.63 L·s^{-1}at the next step, and a further reduction to 5.18 L·s^{-1}. At the fourth step, the measured loss was 0.84 L·s^{-1}, indicating minimal leakage. At the final measurement (the fifth step), a slight inflow of –0.40 L·s^{-1} was observed, indicating a reversal in the hydraulic gradient. Contrary to the detected inflow into the tunnel in only the fifth step, the changes in electrical conductivity indicated that water was inflowing from a specific part much earlier, thereby reducing the total losses from the tunnel (Fig. 2A). The measured total losses demonstrated that the tunnel's water retention capacity remained within long-term safe thresholds, with stepwise-measured losses maintained within controlled limits, indicating that no concerning hydraulic changes occurred within the system. The descending trend with decreasing water level confirms that the high pressure contributes most to leakage. Considering that highly mineralized waters have been identified in Zone 3 (Table 1), increased electrical conductivity suggests potential inflow in the zone of incomplete sealing of the segmental lining related to the anticline structure.

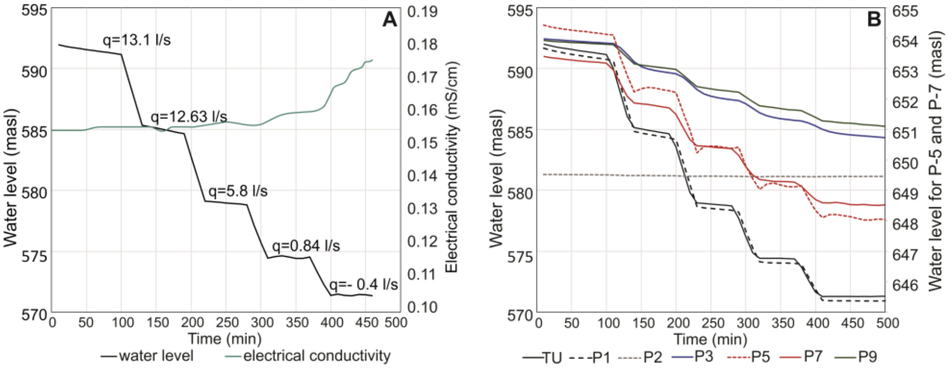

Fig. 2. (A) The results of total loss measurements (B), Pore pressures in the internal piezometers during total loss measurements.

Piezometric responses to controlled depressurization provided insights into the hydraulic conductivity of distinct hydrogeological sections along the tunnel, particularly in the vicinity of the surge tank, where important tunnel–rock mass interaction was observed (Fig. 2B). Pressure declines patterns reflected the influence of lithology, indicating zones of reduced impermeability and compromised sealing within the tunnel lining. A comparative analysis of internal pore pressure data and water level fluctuations in the inlet shaft during total loss measurements emphasized the heterogeneous connectivity and influence of natural groundwater conditions along the tunnel alignment.

High-frequency monitoring of tunnel pressure during HPP operation cycles revealed notable pore pressure responses to unsteady hydraulic phenomena (significant pressure variations caused by hydraulic transients during turbine operation changes). These fluctuations exhibited clear spatial patterns, with pronounced pressure oscillations observed due to the surge tanks' influence, which further attenuate toward the reservoir, indicating variations in pressure magnitude and transmission. Analysis of piezometric data identified four characteristic types of hydrogeological response shown on Fig. 3: (1) non-responsive zones, such as piezometeres P8 and P2, where stable pressures without oscillations indicated hydraulically isolated conditions; (2) attenuated responses, as seen in P5, P7, and P9, where small to moderate oscillations suggested limited but synchronous pressure transmission within the rock mass; (3) highly responsive zones, embodied by P1 and TU, which recorded large, rapid pressure fluctuations (15–20 m) that closely mirrored tunnel pressure variations, confirming direct hydraulic connectivity with the karst aquifer conduits and open fault zone; and (4) a unique response at P3, which displayed moderate pressure variations (~3 m), manifested by gradual pore pressure changes, without a sharp drops caused turbine-start events, implying a well-structured karst aquifer acting over a broader scale as indicated with groundwater level response of external piezometer PP3.

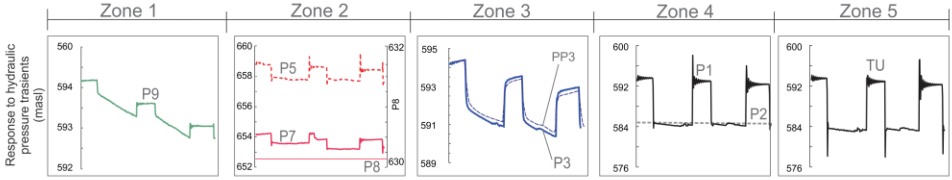

Fig. 3. Pore pressure transient during operational regimes of HPPP.

3.2. Qualitative evaluation of tunnel lining integrity and hydraulic behavior under depressurized conditions

The results of the structural and hydraulic integrity assessment of the tunnel lining under depressurized conditions identified five distinct zones (Jemcov et al. 2024.), which were further interpreted in relation to the geological and hydrogeological context (Table 1, Fig. 4).

Table 1. Summary of zonal classification based on field observations of structural and hydraulic integrity of tunnel lining across geological zones.

Zone Station (m)	Dominant lithology and structural features	Lining type	Groundwater inflow, crack pattern, and leakage	Piezometer
Zone 1 0+000 – 0+650	Triassic limestone, dolostone, and shale; thin-layered. Fault zone near 0+240–0+330. Low karstified – partially fissured	CIP	Relatively uniform moderate cracking lining (CI 0.13). Leakage has a diffuse distribution, with the highest rates near the fault intersection.	P9 0+370
Zone 2 0+650 – 2+775	Lower and Middle Jurassic conglomerate, shale, marl, and sandstone, tectonized with reverse faults (faulted interval 1+357–1+440). High-pressure aquifer system.	CIP	Cracking related to the fault zone (CI 0.19). Low-intensity, diffuse seepage from a high-pressure aquifer. Hydraulically low permeable.	P8 0+840 P7 1+360 PP1 1+400 P6 1+480 P5 1+500 P4 1+540
Zone 3 2+775 – 5+200	Cretaceous marl, marly limestone, and limestone, with a prominent anticline (4+230–4+280). Divided from the 2nd zone by reverse faults	CIP PSL	CIP-type of lining (CI 0.26) with diffuse seepage along the fractures. The PSL-type lining had a low crack index (mean CI = 0.01) and exhibited good hydraulic performance, only localized joint leakage connected to the karstified anticline core (4+230).	PP3 4+210 P3 4+230
Zone 4 5+200 – 7+031	Autochthon in the vicinity of the Getic thrust: marl, shale, silicified limestone, and sandstone intersected by multiple faults.	PSL	Segmental lining had a low crack index (mean CI 0.01). Leakage increased in several zones, particularly around station 6+100 and 6+700, where the expansion of preferential pathways within the faulted fracture zone facilitated drainage from a deep karst aquifer with subthermal waters, notably higher diffuse inflow.	P2 6+390 P1 6+715
Zone 5 7+031 – 8+900	Getic allochthonous limestone and sandstone, intensively folded.	CIP	Increased cracking (mean CI 0.19) and significant pressurized leakage occurred near the Getic thrust zone, especially around chainage 7+355. Karst conduit flow (5–10 $L \cdot s^{-1}$) through the tube directly into the tunnel (7+355).	TU 7+350

The comprehensive leakage assessment identified that 353 m (4%) of the tunnel displays intense leakage, 2.7 km of diffuse seepage, 2.1 km of low-permeability sections with wetting, and 3.7 km of effectively impermeable sections. Cast-in-place lining is more prone to cracking and leakage, exhibits a higher crack index (mean CI 0.19), and diffuse seepage concentrated in faulted zones. Segmental precast lining exhibits very low cracking (mean CI 0.01) and improved watertightness, with elevated hydraulic sensitivity attributed to compromised gasket performance at segmental joints, resulting in localized zones of high inflow.

Inflow measurements in the dewatered tunnel were carried out in two phases: the first was conducted immediately after the tunnel was emptied, and the second measurement was carried out immediately before the tunnel was closed and placed into operational use. The temporal measurement design captures two distinct hydrogeological conditions of surrounding rock mass: one with residual pressurized tunnel water and another reflecting sustained leakage after drainage. The difference between measurements is commonly observed, and when analyzed alongside groundwater level data and results from tunnel mapping allowed identification of leakage characteristics in sections of the tunnel that have different types of lining between the measurement profiles.

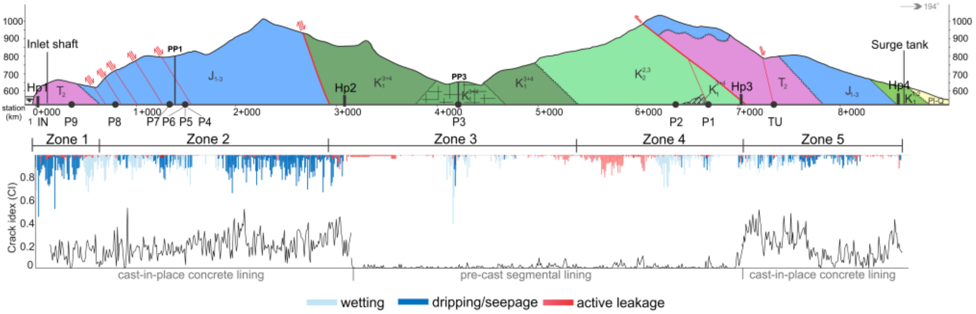

Fig. 4. Spatial distribution of quantified crack index and corresponding qualitative assessment of water leakage through the lining (legend as in Fig. 1). Hp1-4 hydraulic profiles for inflow measurements.

A more straightforward interpretation of the hydraulic responses in the hydrogeological environment and a deeper understanding of hydraulic sensitivity were achieved by correlating the results with the qualitative assessment of tunnel leakage. The structurally complex zones with significant cracking within Triassic and Jurassic limestones (Zones 4 and 5) acted as preferential pathways for the most persistent inflows of pressurized groundwater and subthermal karst water, with discharge rates reaching up to 10 $L{\cdot}s^{-1}$. In contrast, sections that traversed fine-grained marl and shale units, such as those of the Danubian formations, showed localized cracking but low leakage. This reveals an important insight: structural damage, as observed visually, is not a reliable indicator of hydraulic behavior. A quantitative assessment using the crack index highlighted these differences, with values ranging from 0.01 in segmental lining sections to 0.52 in cast-in-place concrete segments located in the fault zones. While segmental linings generally showed lower crack densities and surface damage, localized leakage was still observed at joints installed in transmissive formations, particularly in structurally significant areas like the anticline at station 4+230.

3.3. Hydrochemical analysis of groundwater–tunnel interaction

Spring and surface water samples remained hydrochemically stable over time, suggesting minimal impact from tunnel operations, likely due to their shallow occurrence and limited hydraulic connection with the deeper groundwater systems. In contrast, hydrochemical analysis confirms that the pressurized tunnel has a significant impact on the surrounding hydrogeological environment, as evidenced by notable changes in the tunnel's water chemistry. During the depressurization phase, significant hydrochemical variability occurred across different zones, indicating active interactions between the tunnel and the aquifer. Zone 3 (Station 4+230 m) exhibited the highest electrical conductivity (up to 10,200 μS/cm) with noticeable dilution due to the influence of the tunnel. External piezometer PP3 located near Zone 3, recorded increases in chloride and sulfate concentrations during depressurization, pointing to rapid hydraulic response and showing that the tunnel influence extends beyond its immediate vicinity. This zone also displayed elevated strontium and lithium levels, consistent with inflow from deep karst aquifers. Zone 2 showed increased pH and bicarbonate levels, alongside the presence of hydrogen sulfide, suggesting active sulfate reduction processes. In Zones 4 and 5, characterized by tectonic activity, hydrochemical fluctuations were more pronounced, with higher temperatures and complex compositions indicative of mixing between thermal and tunnel waters. Hydrochemical fingerprints provided validation of inferred flow paths and revealed permeability contrasts that were undetectable using hydraulic data alone.

4. Conclusion

An integrated methodological approach to pressurized tunnel hydrogeology in complex geological settings is crucial, as the interaction between the tunnel, lining, and rock mass is inherently geologically dependent and requires multi-parameter monitoring. Effective evaluation of tunnel-groundwater interaction were achieved through the integration of multiple complementary methods: (1) total-loss measurements quantified cumulative tunnel water losses; (2) pore pressure data captured pressure redistribution and revealed tunnel–rock mass hydraulic conductivity; (3) transient hydraulic analysis characterized connectivity; (4) structural surveys indicated lining damage and hydraulic behavior in depressurized conditions; and (5) hydrochemical data traced flow origins and mixing processes. Significant spatial variability in pore pressure responses was noted, influenced by geological conditions and lining types, with lining cracks producing varied leakage patterns. Monitoring demonstrated that hydroelectric power plant operations can rapidly redistribute pressure within the tunnel system, especially in zones under strong influence of the surge tank, with structurally complex or hydraulically sensitive conditions. Hydrochemical methods helped identify zones of interaction between groundwater and tunnel water, aligning observed changes with hydraulic signals, and highlighting the importance of a multidisciplinary approach to tunnel monitoring in geologically sensitive areas. Findings derived within this study indicate that pressure transmission to the hydrogeological environment and its behavior are primarily governed by the geological and structural features of the rock mass, rather than by the visible integrity of the concrete lining. A comprehensive approach is recommended for future tunnel surveillance and maintenance, especially in zones affected by faulting, karstification, or dynamic transient pressure changes, all of which necessitate continuous monitoring. This framework facilitates the early identification of hydrogeological risks and can help define priority zones for effective grouting interventions, thereby promoting the long-term safety and operational efficiency of tunnel infrastructure in complex geological and hydraulic settings.

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