

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,
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Tunnels and Underground Structures

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

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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

ACKNOWLEDGEMENT

The Editors would like to thank and express their sincere gratitude to all members of the Scientific Committee for their effort and the valuable time devoted to reviewing the abstracts and manuscripts.

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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Rehabilitation of the Pressurized Hydraulic Tunnel: A Case Study of the Pumped-Storage Hydropower Plant “Bajina Bašta“

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Abstract: The “Bajina Bašta” pumped-storage hydropower plant was commissioned in September 1982. The facility is located in the Drina River valley, immediately downstream from the existing Bajina Bašta hydropower plant dam, whose reservoir serves as the lower basin. The “Beli Rzav” pumped reservoir, located in the valley of the river of the same name in the Zaovine region, functions as the upper basin.

In addition to the upper and lower reservoirs, the power plant complex comprises a powerhouse and a headrace–tailrace system, which consists of several interconnected components: upper and lower intake/outlet structures, the headrace–tailrace tunnel, the tunnel bifurcation, a surge shaft, an inclined penstock, and a horizontal penstock with a bifurcation.

Based on the monitoring and maintenance performed during the operational period of the tunnel, as well as on the condition of the structure observed in 2005, the scope of rehabilitation works was defined.

This paper initially presents a description of the facility and its condition immediately prior to the rehabilitation, with particular emphasis on the hydraulic tunnel. The core focus is on the presentation of the rehabilitation technology and execution, which involved pressure grouting, the installation of prestressed rock anchors and chemical grouting. The paper discusses the results and challenges encountered during the rehabilitation process, offering a critical analysis aimed at emphasizing the significance of rehabilitation works and encouraging the exchange of experience in the restoration of capital infrastructure with extended service life.

Keywords: hydraulic tunnel; concrete lining rehabilitation; grouting; “Bajina Bašta” hydropower plant; pumped-storage hydropower plant; case study

1. Introduction

The Bajina Bašta pumped-storage hydropower plant was commissioned in September 1982. The facility is located between the “Perućac” reservoir, created by damming the Drina River, and the upper pumping reservoir “Beli Rzav,” situated in the valley of the river bearing the same name, in the Zaovine region. In addition to these reservoirs, the PSHPP Bajina Bašta includes the powerhouse and a complex water conveyance system. This system consists of several key structures: the upper and lower intake/outlet structures, a bifurcation with associated components, a surge shaft, an inclined penstock, and a headrace/tailrace tunnel. Under operational conditions, the PSHPP Bajina Bašta enables efficient utilization of hydraulic energy for electricity generation (Radovanović et al., 2022).

According to the literature Savić (2009) and Zabuski (2019) hydrotechnical tunnels are generally categorized as either pressurized tunnels or free-surface (non-pressurized) tunnels. Pressurized tunnels, which enable water intake regardless of the reservoir water level, are the most common solution for hydropower intake systems (Savić, 2009). These tunnels may be a part of complex hydroelectric systems – as is the case in this facility – but can also be integral components of large industrial plants

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or irrigation networks. Regardless of their operational context, after decades of use, such tunnels require well-defined and properly implemented rehabilitation projects, based on detailed investigations and inspections (Krukovskyi et al., 2024).



(a)



(b)



(c)

Fig.1. (a) Map of Serbia showing the River Drina and the position of the PSHP Bajina Bašta (Radovanović et al., 2022), (b), (c) Hydrotechnical Tunnel of the Reversible Hydroelectric Power Plant “Bajina Bašta”.

The importance of inspection planning as a key aspect of tunnel maintenance has been emphasized in the study by Ai et al. (2020), which also outlines the influence of inspection frequency on both total maintenance costs and the risk of structural failure over the service life of the tunnel. The paper highlights the limitations of traditional periodic inspection regimes and proposes degradation modes (accelerated, decelerated, and stationary). These modes are intended to both describe structural deterioration trends and serve as reference models for the planning of tunnel inspection strategies on real-world projects. In the study by Strauss et al. (2020), an overview is provided of various inspection methods and the classification of monitoring strategies and tools, with a focus on both international

technical literature and contemporary engineering practice in Austria. Current research trends emphasize a shift toward automation and 3D reconstruction, as opposed to manual tunnel inspections and conventional data management approaches (Sanfilippo et al., 2025). Technologies such as point cloud data (PCD) and advanced modeling techniques have significantly improved tunnel inspection and model generation processes (Machado et al., 2025).

In discussing recent innovations in visual inspection methods, it is essential to highlight the trend described by Montero et al., (2015) regarding the application of robotic technologies in tunnel inspection. Hazards encountered during tunnel lining mapping and construction work – including dust, poor lighting, and, in some cases, exposure to toxic substances – underscore the necessity for automation in tunnel inspection processes (Montero et al., 2015). Further contributions from the literature (Attard et al., 2018) focus on capturing the tunnel environment conditions using photogrammetry, computer vision, and image processing techniques.

A detailed description of pressure grouting applied in pressurized hydrotechnical tunnels is provided in Anđelković et al. (2013). The same study presents an experimental method for measuring water leakage along the entire length of the tunnel. This leakage measurement was also conducted during the most recent tunnel rehabilitation campaign. In this paper, we present only the results recorded following tunnel dewatering – i.e., at the beginning of the rehabilitation works – and after the completion of the remedial interventions.

The tunnel in question has a circular cross-section with a diameter of 6.30 meters. Its total length is 8030 meters, with a longitudinal slope of 4.5‰. This tunnel belongs to the category of pressurized hydrotechnical tunnels, in which, under operational conditions, a maximum hydrostatic pressure of 1.3 MPa occurs (Ai et al., 2020).

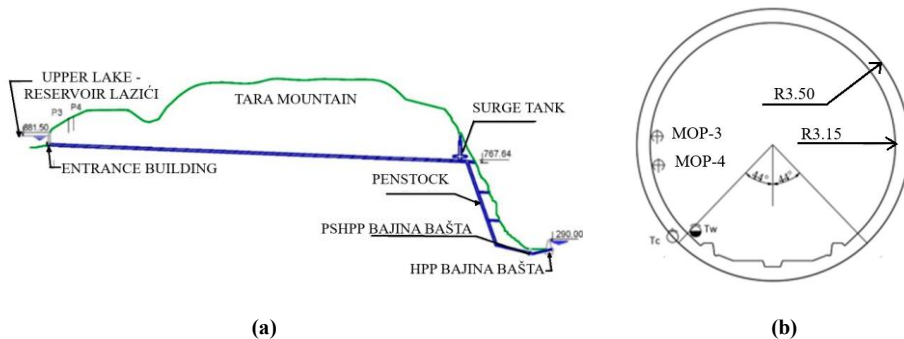


Fig. 2. (a) Longitudinal tunnel profile with a schematic view of the upper lake, pipeline, PSHPP and HPP “Bajina Bašta”, (b) Cross-section of tunnel (Radovanović et al., 2022).

2. Tunnel Rehabilitation – Technologies and Construction Techniques

The repair works on the hydrotechnical tunnel were executed in accordance with the rehabilitation project, developed based on observations, previous maintenance activities on the headrace–tailrace tunnel (HTT), and experience gained during the last rehabilitation conducted in 2005, as well as from monitoring of the HTT throughout the subsequent years of operation. Selection of intervention zones was based on visual inspections and testing of the HTT, aiming to identify sections with moderately to severely cracked concrete lining. Under operational conditions, such locations represent a potential risk of significant water seepage, which could in turn affect the structural stability of the tunnel lining.

Due to the scale and complexity of the planned activities, the rehabilitation works were carried out across four designated work zones:

1. Work Zone 1 included the access tunnel leading to the bifurcation, and the HTT section from chainage 0+010 to 0+600.
2. Work Zone 2 covered the lower surge chamber areas, including parts of the shaft body and the tunnel crown (kalotte).
3. Work Zone 3 encompassed the main HTT section from chainage 0+600 to 7+000.
4. Work Zone 4 involved the final kilometer of the tunnel, located directly adjacent to the “Beli Rzav” pumping reservoir (HTT section from chainage 7+000 to 8+000).

2.1. Scope of Rehabilitation Works Defined in the Project Documentation

2.1.1 Inspection of the Headrace–Tailrace System of the PSHPP “Bajina Bašta” During the Reconstruction Phase

During the reconstruction of the headrace–tailrace system (HTT), the following investigations were carried out: Visual inspection of the hydrotechnical tunnel, surge shaft, and inclined penstock, Chemical and physico-chemical testing of water and sediment in the tunnel, Terrestrial laser scanning (TLS) of the concrete lining in both the tunnel and the surge shaft, Geophysical surveys using ground-penetrating radar (GPR) and electrical resistivity imaging (ERI). In accordance with the Updated Technical Monitoring Project, the existing monitoring system was revitalized by replacing damaged and malfunctioning instruments, expanding the system with new, primarily electronic, instruments, and automating the data acquisition process through their integration into an automatic data logging and archiving system.

The updated system includes the following types of monitoring: Mechanical displacement measurements along neotectonic faults, Telemetric temperature monitoring of water and concrete in the surge shaft, Telemetric monitoring of hydrostatic pressure exerted on the tunnel lining, Telemetric monitoring of displacements along cracks and joints in the tunnel, Telemetric piezometric readings in the access tunnel and gate shaft.

Following dewatering of the tunnel, the initial activity conducted in the hydrotechnical tunnel was a visual inspection, which, as similarly described in Krukovskiy et al., (2024), included the preparation of graphical documentation for mapping cracks in the concrete lining. The main objective of the visual inspection was to either confirm or adjust the proposed rehabilitation design, in case certain areas – originally not included in the project – were found to be in a critical condition. As part of project implementation, two visual inspections were performed: the first prior to the commencement of reconstruction works, the second upon completion of all works, to assess the effectiveness of the interventions with respect to the project specifications.



Fig. 3. Visual Inspection – Mapping of Changes in Concrete Lining.

The visual inspection of the surge shaft, unlike the tunnel inspection, required the application of speleological industrial alpinist techniques. The process was carried out in several phases, beginning with a trial descent, which involved the inspection and technical outfitting of the structure. In the subsequent phases of the visual inspection of this system section, markers were installed for laser scanning, marking the start of the phases for scanning the concrete lining and mapping cracks and damages.

The geophysical investigations of the concrete lining of the HTT were performed using ground penetrating radar (GPR) and electrical resistivity imaging (ERI) methods. The objective of these investigations was to assess the condition of the tunnel lining and the surrounding rock mass in direct contact with the concrete lining, focusing on crack patterns, water flow paths in both vertical and horizontal planes, and the presence of cavities and voids behind the concrete lining.

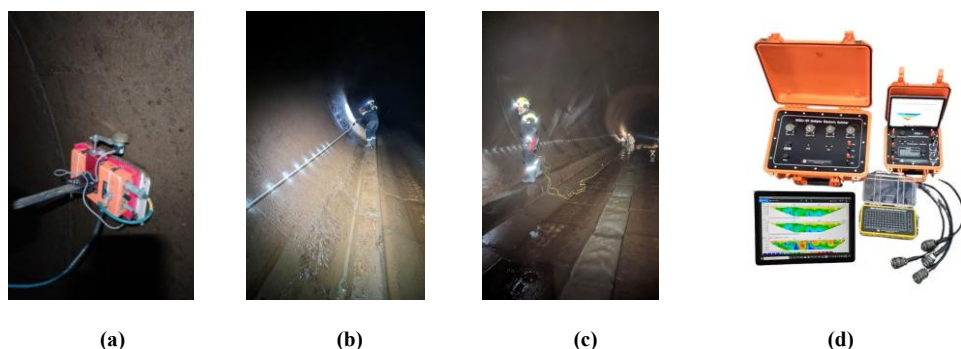


Fig. 4. Geoelectric Testing: (a) Ground Penetrating Radar (GPR); (b), (c) Preparation for Geoelectric Measurements – Placement of Metal Electrodes; (d) Geoelectric Measurement System – VS-1 Resistivity Meter, Electrode Selector, External Power Module and Cables with Metal Electrodes.

Following the completion of the rehabilitation works, the application of this type of investigation enabled verification and quality control of the implemented remedial measures. In the case of this specific project, a total of 7,000 m³ of ground penetrating radar (GPR) surveys and 175 m³ of electrical resistivity imaging (ERI) surveys were performed.

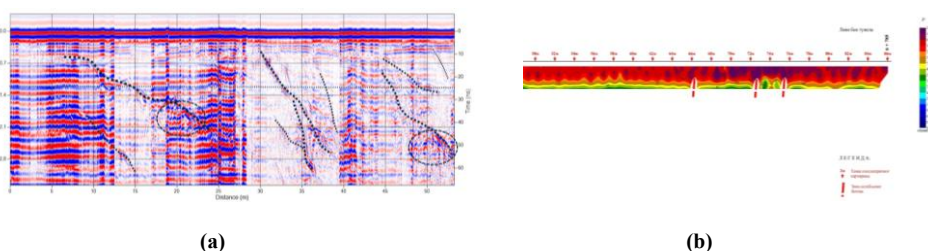


Fig.5. Geoelectric Testing: (a) Results of Ground Penetrating Radar (GPR) Surveys; (b) Results of Geoelectric Measurements.

2.1.2. Stress Grouting Technique

Stress grouting is a specific type of pressure grouting applied in engineering practice when it is necessary to induce pre-stressing of the tunnel lining, i.e., to increase tangential stresses within the lining. This grouting method is most commonly used in pressurized hydrotechnical tunnels, where the effect of prestressing is intended to counteract the internal water pressure acting on the tunnel lining during the operational phase.

The works were carried out at predefined locations along nearly the entire alignment of the tunnel, starting with machine drilling using rotary-percussive drilling with water cooling. The equipment used included the Hydra Joy 2P drill rig, equipped with a hydraulic hammer.

The drilling procedure differed only in two areas: within the surge shaft and at the very beginning of the tunnel, in the bifurcation zone. In the surge shaft, drilling was performed manually using pneumatic hand drills, while in the bifurcation zone and the initial tunnel stations, a Hydra SL200 hydraulic hammer mounted on a JCB 3CX skip loader was used to ensure better mobility and maneuverability.

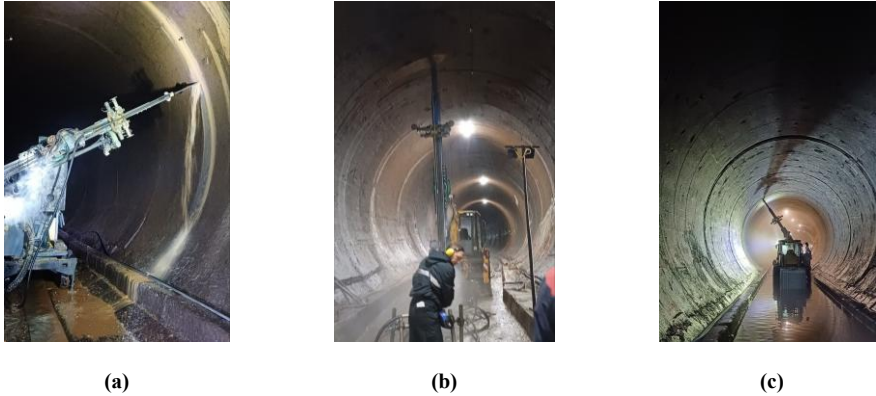


Fig. 6. (a) Hydra Joy 2P equipped with a hydraulic hammer; (b), (c) Hydraulic hammer Hydra SL200 mounted on the JCB 3CX skip carrier.

Drilling was executed in a radial pattern, as specified by the design, with 5-meter spacing between boreholes, a drilling depth of 4 meters, and a borehole diameter of $\text{Ø}56$ mm. The design also included a provision for modifying the technical solution in the event of increased grout consumption – specifically, by reducing the radial spacing between boreholes to 2.5 meters.

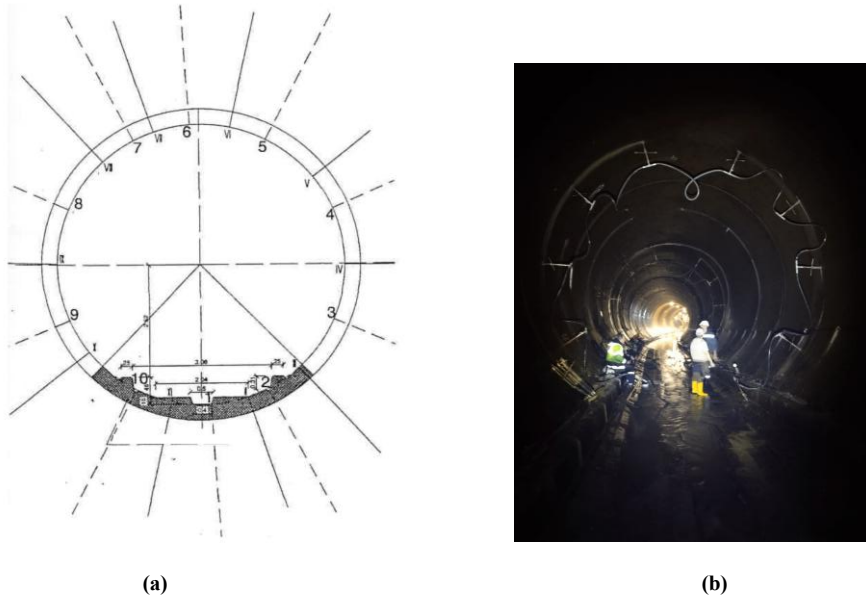


Fig. 7. (a) Detail of stress grouting according to the rehabilitation project; (b) Drilling execution inside the tunnel.

2.1.3. Installation of Self-Drilling Anchors (SDAs)

The rehabilitation project specified the installation of self-drilling anchors (SDAs). The maximum designed anchor length was $L = 6$ m (Type 3), while in certain locations, shorter anchors were prescribed: $L = 3$ m (Type 1) and $L = 4$ m (Type 2).

The installation procedure was the same for all SDA types. Prior to installation, $\varnothing 56$ mm boreholes were drilled to the required depth, using the same equipment as for the stress grouting works.

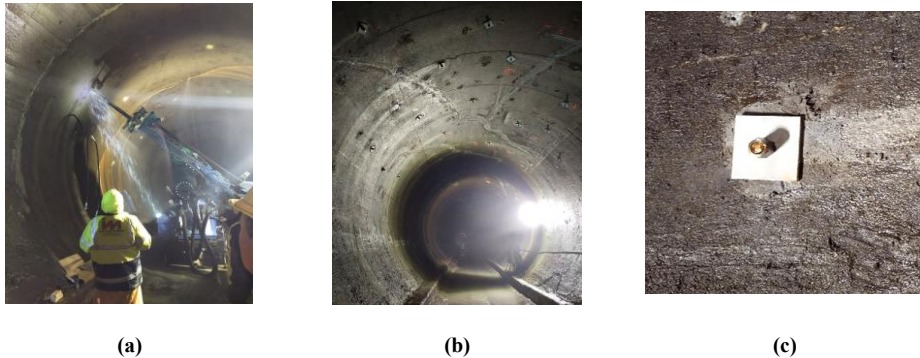


Fig. 8. (a) Drilling of tunnel lining, (b) Appearance of tunnel lining after installation of anchors, (c) Anchor type “SDA”.

The grouting process begins after the anchor and the grouting tubes are inserted into the borehole. One tube is used to deliver the grout, while the other serves to release excess air during injection. The completion of the injection process is marked by the moment when grout begins to exit through the air-release tube, indicating that the borehole is fully filled. After grouting and removal of the excess tubing, anchor bearing plates and nuts are installed. Once the grout has fully cured, the plate is tightened against the rock surface by tensioning the nut.

2.1.4. Chemical grouting

Chemical grouting was performed using polyurethane-based injection materials. To prevent leakage of the injection grout, the cracks were prepared by cutting triangular grooves along their length. These grooves measured $3\text{ cm} \times 3\text{ cm}$ and were filled with fast-setting mortar prior to injection.

Drill holes were made at an angle of 45° , diagonally across the crack, with spacing between 25 and 35 cm, resulting in borehole lengths ranging from 45 to 55 cm, placed alternately on both sides of the crack (left and right). Drilling was performed mechanically, using electric drills with a borehole diameter of $\varnothing 10$ mm. Upon completion of the chemical grouting process – i.e., after the polyurethane material had cured – the packer was removed and the borehole was sealed with mortar.

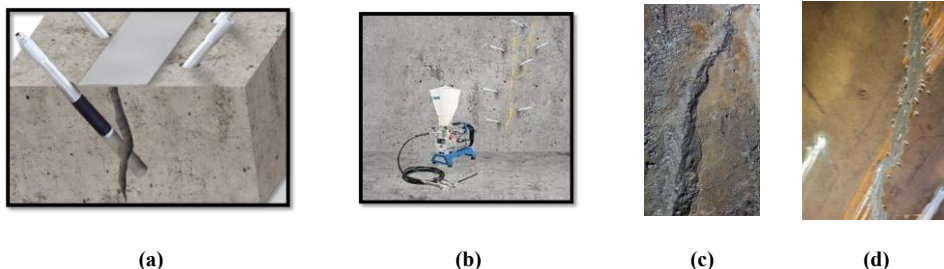


Fig. 9. (a) Placement of packer; (b) Overview of complete chemical injection; (c) Saw-cutting of crack; (d) Completed chemical injection

2.2. Adapting the Technical Solution to Actual Tunnel Conditions

2.2.1. Adapting the Technical Solution to Actual Tunnel Conditions during Works at Work Site 1

Based on the results of the visual inspection of the headrace–tailrace tunnel (HTT), mapping of the concrete tunnel lining, and preliminary analyses, certain adaptations of the designed solution were made to the actual tunnel conditions in the section between chainage km 0+010 and 0+100. These adaptations primarily concerned the locations for carrying out rehabilitation works – drilling and grouting, as well as anchor installation.

The condition of the lining with the positions of the newly designed works is illustratively shown in Figure 10. For better understanding of the illustrated executed works, square symbols indicate the positions of the self-drilling anchors (SDAs), with color differentiation depending on their length (SDAs of $L = 6$ m or $L = 4$ m). Injection boreholes are represented by circular symbols, varying according to the diameter and length of the borehole. Green lines in Figure 10 denote locations of chemical grouting, while brown rectangles with green borders indicate positions of segregation remediation.

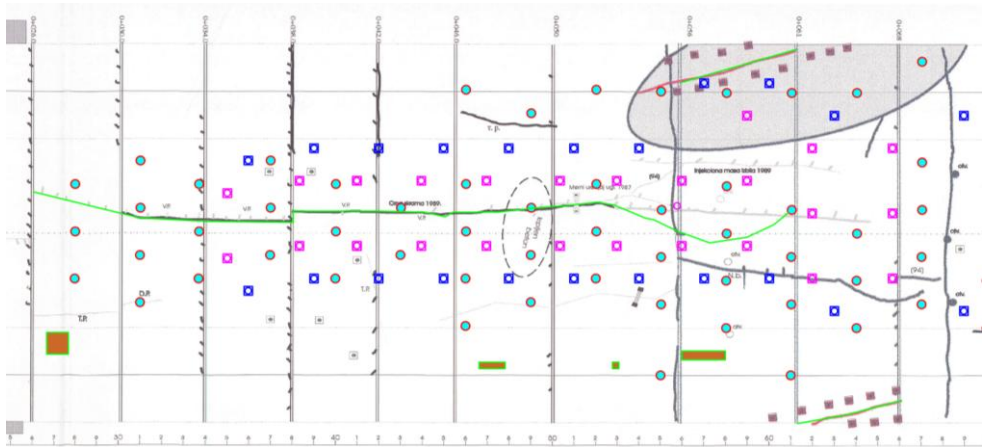


Fig. 10. Condition of the concrete lining with locations of newly designed works on the section between st. km 0+026 and 0+070 (illustrative representation).

After the initial assessment of the condition, it was decided to adapt the execution of the rehabilitation works at work site 1 by correcting the locations of the injection boreholes and their grouting. The borehole layout was revised based on the damage mapping analysis, taking into account the history of works on this section. The arrangement of injection boreholes was defined so that grouting could be performed for all newly detected damages as well as for several existing defects assessed as potential water leakage points in the tunnel. In addition to the layout, the drilling depth was also adjusted according to the revised borehole arrangement, with the most common drilling depth being 3 m. These changes during the rehabilitation works also necessitated adjustments in injection pressures, which were generally applied at 12 bar. It is important to note that on this section, the total planned drilling length of 352 m exceeds that of the original Rehabilitation Project, but based on the conducted investigations this proved to be necessary.

On the section between chainage km 0+502 and 0+580, the condition of the concrete lining has not significantly changed compared to the mapping performed during the 2005 reconstruction. A short crack with minor opening and leakage was identified at chainage 0+541, another short crack with minor opening and leakage at chainage 0+575, several short dry fissures, and several wet spots related to old

injection boreholes. Accordingly, no significant changes in the positions were made during the works on this section.

To improve the tunnel's operational conditions, the previously planned pre-stressing grouting at Work Site 1, originally designated for the section from chainage 0+500 to 0+580, was shifted to the section between chainage km 0+100 and 0+180. This created a unified rehabilitation zone from chainage 0+010 to 0+180 to reduce tensile stresses in the concrete caused by water pressure, which will also decrease water losses in the downstream slope area, thus enhancing its stability (Figure 11).

Considering the pressure values during grouting in the empty tunnel, the pressure-induced stresses in the concrete lining depend on the pressure intensity, tunnel diameter, and lining thickness. The project assessment concluded that the maximum grouting pressure should not exceed 20 bar to keep the concrete stresses within allowable limits.

On the left side of Figure 11, the odd-numbered profiles (cross-sections 1 to 15) are shown, while the right side displays the even-numbered profiles (cross-sections 2 to 16). The rehabilitation works were carried out so that the borehole layout within all even profiles is identical, as well as within all odd profiles. However, the borehole arrangements in even profiles differ from those in odd profiles, with boreholes in consecutive profiles offset by an angle of 18°. The spacing between injection profiles is 5 meters.

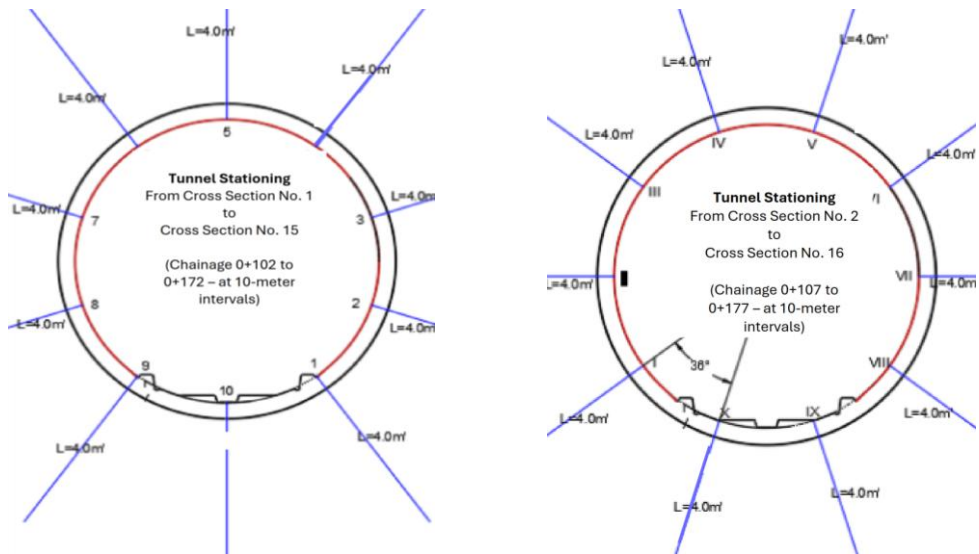


Fig. 11. Layout of tension grouting injection boreholes (profiles at Work Site 1).

2.2.2. Adapting the Technical Solution to Actual Tunnel Conditions during Works at Work Site 2

The investment maintenance project for the headrace-tailrace system of the PSHP "Bajina Bašta" defined rehabilitation works for work site 2, which includes the hydropower surge chamber structure. The planned works on the lower vault of the surge chamber included the installation of SN anchors, tension grouting, and chemical grouting.

The maximum pressure defined by the project is 25.0 bar. According to the concluding considerations of the project "Tension-Deformation Analysis of the Surge Chamber and Steel Pipelines," conducted by the Institute for Water Management "Jaroslav Černí" in 2024, it was stated that, given the cracking of the concrete lining combined with the high pressures of tension grouting, which could lead to damage of the concrete lining, it is necessary to reduce the maximum tension grouting pressures to 15 bar.

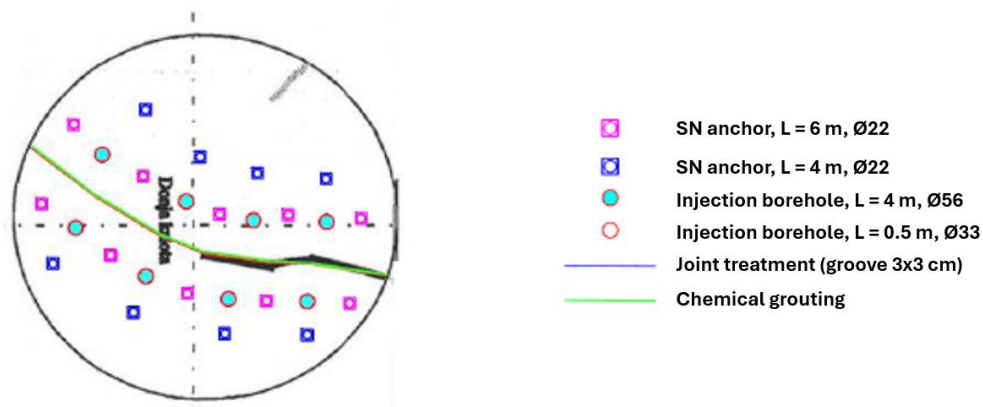
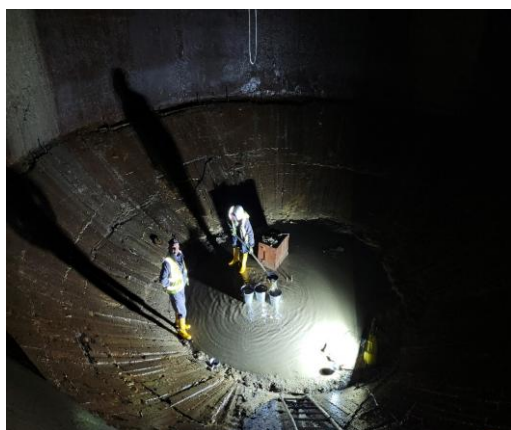
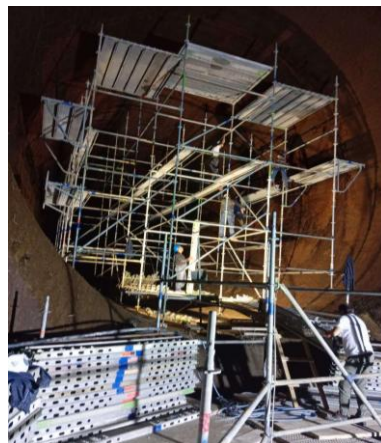


Fig. 12. Repair works on the lower crown of the water reservoir.

During the execution of the works, monitoring of cracks in the surrounding concrete lining of the lower vault of the surge chamber was conducted, and no changes indicating deficiencies in the execution of the rehabilitation works were observed.



(a)



(b)

Fig. 13. (a) Mapping of cracks in the concrete lining of the lower crown of the water reservoir, (b) Assembly of scaffolding in the water reservoir chamber

2.2.3. Adapting the Technical Solution to Actual Tunnel Conditions during Works at Work Site 4

Rehabilitation works at Work Site 4 represented the greatest challenge in the implementation of this project. Work Site 4 is located in the zone of significant influence of the “Beli Rzav” reservoir, which was at operating level during the project execution. There were risks of excessive water leakage through the boreholes, so the work had to be carried out carefully and sequentially.

The rehabilitation works began according to the project design by drilling holes and installing SDA anchors shown in Figure 14, marked as B4 and An2. During the drilling for the installation of anchor A2 at a depth of 4 m, water inflow was registered in the borehole with slight leakage. The anchor was installed, but injection grouting could not be performed.

During the drilling for the installation of the anchor marked B4 at a depth of 4.2 m, significant water leakage was registered from the borehole, which, unlike the previous situation, prevented the installation of the anchor. At this position, a packer was installed with a valve at its end, and on the other side, a pressure gauge was mounted, which recorded a pressure of 7.5 bar.

In accordance with the condition of the lining at the location, the project design, and the observed phenomena, an additional 5 injection boreholes were drilled at the site to reliably locate water-filled cracks behind the concrete lining, determine pressures, and collect data for the successful execution of further rehabilitation works.

Drilling started at the location marked B0, but after drilling through the concrete lining at a depth of 0.65 m, metal (from reinforcement or straps) was encountered, so further drilling was abandoned and drilling continued below the initial borehole B4. In the zone of borehole B4 at chainage 7+942 on the vertical profile, 5 boreholes of various depths were drilled, as shown in Figure 14. They were drilled at mutual distances of about 1.1 m. Drilling was carried out sequentially, starting with drilling to a depth of 0.6 m. At this depth, the drill string was withdrawn to check for water inflows from the surrounding rock. This procedure was then repeated every 0.3 – 0.5 m until the final depths were reached. The relevant criterion for completion was to drill until water appeared indicating the presence of a discontinuity that needed to be injected. The decision was made not to drill deeper than 2.2 m to avoid entering the zone of reduced effectiveness of previous injections, where larger water inflows under a pressure of 7.5 bar were observed in the cracks.

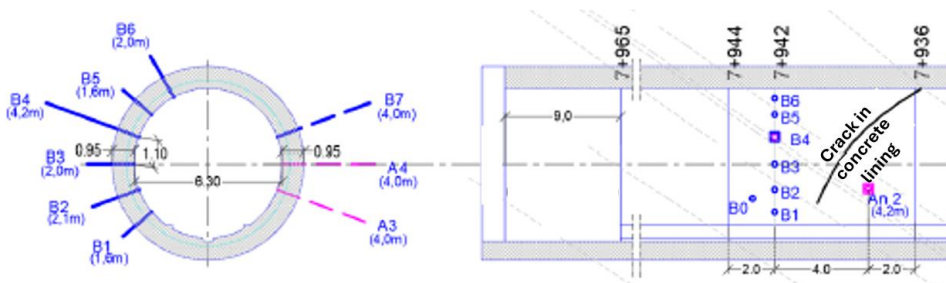


Fig. 14. Overview of initial anchor installation and grouting works in the section from chainage km 7+944 to 7+936.

From boreholes B1-B5, after the first meter of drilling, water carried out finely ground samples of grey marl, unlike in anchor borehole A2 where the water expelled many pieces of limestone. After drilling, water from B1 and B2 flowed gently, from B3 and B5 more significantly in a jet, while B6 only slightly moistened. After drilling and a brief analysis of the observed phenomena and results, injection of the boreholes commenced.

Due to site conditions, which involved significant risks of water leakage under full pressure from the “Beli Rzav” reservoir, on-site decisions were made that required corrections to the project. The holes for installing 6 m long anchors, as originally planned for this section, were replaced with the installation of 4 m long anchors. At positions where installation of 4 m anchors was not possible due to large water inflows from the borehole, borehole grouting was performed. The proximity of the reservoir and the objective conditions during the work execution meant that, out of the total 177 planned SDA anchors, only 8 were installed at the specified work site (Work Site 4).

The Jaroslav Černi Water Institute pointed out to the other project participants the importance of future repair works in the zone of Work Site 4, which is located upstream of the closure structure. This zone needs to be approached under conditions of reduced water pressure on the lining, which can be achieved by lowering the water level in the “Beli Rzav” reservoir, so that the planned works can be carried out in full scope in order to have a significant impact on the safety and security of the headrace–tailrace tunnel system and the operation of the hydroelectric power plant itself.



Fig. 15. Installed packers in the right side of the tunnel cross-section at chainage km 7+942.

3. Discussion on the Effects of Rehabilitation and Guidelines for Further Work

The rehabilitation works described in the previous chapter significantly improved the condition of the concrete lining at the work sites in the access tunnel to the bifurcation, as well as in the initial chainages of the hydrotechnical tunnel, in the lower chamber of the surge tank, and parts of the cylinder and vault. The most demanding location for the rehabilitation works was at the final chainages of Work Site 4 near the fixed wheel gate, i.e., the upper reservoir. Considering the overall picture during the project execution, the section of the tunnel adjacent to the upper reservoir represents an area that will receive great attention in the next rehabilitation project, while in the meantime its behavior will be monitored through the proposed tunnel monitoring measures.

Because of all the above, one of the most important guidelines for the upcoming operational period is continued monitoring with the existing and newly installed monitoring equipment, as well as planning for future maintenance of the fixed wheel gate, which will require carrying out works differently, given that such maintenance requires draining the upper reservoir. When the upper reservoir is drained, it will also be possible to undertake maintenance of the maintenance gate and other elements that could not be performed under current conditions. Furthermore, draining the reservoir can have a highly positive effect on the rehabilitation outcomes on the last section, about 1500 m long, through the application of prestressed grouting and anchor installation. If the investor decides that it is unacceptable to drain the upper reservoir during the works, lowering the reservoir level by 15-20 m can significantly improve the quality and speed of the works, thus avoiding potential problems during concrete lining drilling in the indicated zone.

Regardless of the tunnel's purpose, regular inspections are necessary throughout the operational life to prevent potential incidents caused by structural failure and to contribute to extending the service life of the structure. Carrying out rehabilitation works on such types of structures involves working in a potentially hazardous environment. Inspections of this kind rely heavily on the subjectivity of the project team, especially during concrete lining mapping. Considering all challenges, various systems have been developed to automate certain procedures for tunnel inspection and monitoring (Attard et al., 2018).

To ensure quality control after the completed works, the use of modern technologies such as artificial intelligence (AI), photogrammetry, BIM, and GIS in tunnel construction and monitoring is becoming increasingly common. The application of these technologies in infrastructure management brings numerous benefits, with automated data collection, structural condition assessment, and digital data management being particularly emphasized (Sanfilippo et al., 2025). The use of technologies like laser

scanning and photogrammetry allows for faster data acquisition about the tunnel structure's geometry and condition. Utilizing such technologies and improving automation in data collection ensures a higher degree of objectivity, repeatability, and data quality compared to manual data collection methods. The management and use of collected data in modern trends aim toward BIM technology, which allows BIM models of such hydrotechnical structures to be integrated with GIS, which remains the primary tool for managing large sets of geospatial databases (Sanfilippo et al., 2025).

One of the challenges in modern tunnel monitoring trends focuses on digital twin technology (Ai et al., 2020). This technology, applied in monitoring hydrotechnical structures, provides the possibility of continuous and efficient object condition monitoring. Continuous monitoring and early-stage change detection contribute to effective maintenance during the operational phase, timely planning of rehabilitation projects, and elimination of potential undesirable scenarios regarding structural failure. Developing advanced information models improves the understanding of tunnel behavior throughout its operational life and enables faster damage detection (Machado et al., 2025). The main challenges highlighted by the authors concern the development of digital twins, particularly in integrating heterogeneous data sources. Implementing such modern approaches requires anticipating challenges and potential limitations at the project's outset, as digital twin models demand highly detailed models based on realistic data from the actual structure to minimize approximations (Machado et al., 2025). After overcoming initial challenges, it should be noted that applying such technologies can greatly enhance the monitoring process of demanding tunnels, where digital inspection is supported by an integrated tunnel model database. This type of result enables an automated model linked to the actual structure, facilitating management, identification of specific damages, and optimization of maintenance plans (Machado et al., 2025).

4. Conclusion

The rehabilitation works on the hydrotechnical tunnel project presented in this paper were carried out with quality, expertise, and within the planned budget. Accurately forecasting the budget for rehabilitation works on complex structures, such as the headrace–tailrace system of the reversible hydroelectric power plant “Bajina Bašta,” is an exceptionally challenging endeavor. The fact that most of the rehabilitation works foreseen in the project were completed, with modifications necessitated by site conditions and still fitting within the budget limits, speaks to the good practice and professionalism of all team members involved in the project's implementation.

The execution of such projects highlights the necessity of adjusting project designs during works to adapt to field conditions. System investigations immediately prior to the commencement of works are of utmost importance. Thoroughness in this phase of project execution largely focuses the project team on current problems that cannot be ignored and that, due to objective circumstances, may not always be fully covered by the project design.

Attention was also drawn to the section that posed the greatest challenge during the execution of works. Work site 4, located just before the gate near the “Beli Rzav” reservoir, is in a zone heavily influenced by the reservoir, which was at operating level during the works. Since the high water presence prevented the installation of the full length of anchors specified in the design and significantly reduced the number of installed anchors in this section, a discussion arises regarding the necessity of reservoir draining during similar rehabilitation projects.

The importance of modern methods for monitoring structural behavior was emphasized. The development of advanced monitoring systems allows for real-time assessment of structural condition and timely interventions that can greatly affect the operational life of the tunnel. The methods presented in this paper, which reflect the research focus of various authors in this field, clearly highlight the importance of quality systems for monitoring the condition and safety of such structures, which are components of complex hydrotechnical systems.

Based on all the above, the authors emphasize the importance of automation systems that reduce subjective assessments of tunnel structural conditions and thus enhance the safety of project

participants. Developing systems for continuous condition monitoring would enable active surveillance and assessment of the optimal timing for rehabilitation projects, as well as detection of sensitive tunnel sections. Draining the reservoir and potential modifications in future project designs at specific locations would yield better results during execution, thereby contributing to a certain extent to reducing losses during the operation of the headrace–tailrace system of the “Bajina Bašta” hydroelectric plant.

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