

FEDRO'S TUNNEL RENOVATION METHOD FOR MOTORWAY TUNNELS UNDER LIVE TRAFFIC

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ABSTRACT: To address the ageing of motorway tunnels under increasing traffic demand, the Swiss Federal Roads Office developed an innovative renovation methodology that allows major rehabilitation works to be carried out while maintaining daytime traffic. The method is based on the partial removal of the existing lining, followed by the installation of drainage and waterproofing systems and the casting of a new inner lining during nighttime closures. Pilot applications demonstrated the feasibility of the approach under demanding operational conditions, while also highlighting its limitations. Overall, the methodology offers a sustainable alternative to conventional tunnel rehabilitation strategies by reducing demolition, material consumption and traffic disruption.

1. INTRODUCTION

The Federal Roads Office (FEDRO) is Switzerland's federal authority responsible for road infrastructure and private road transport. To ensure the long-term availability and usability of the national road network, FEDRO regularly assesses the condition of road assets and plans maintenance works over 5 to 15 km sections so that no further interventions are required on the same stretch for at least 15 years.

Tunnels represent a major component of Switzerland's transport infrastructure due to the country's challenging topography. At least one quarter of road tunnels were constructed more than 40 years ago and are therefore increasingly in need of systematic maintenance, ranging from partial lining replacement to more extensive structural interventions where targeted measures are no longer sufficient to ensure economically viable long-term performance.

When carrying out maintenance works, it is essential to maintain full traffic capacity without restricting or interrupting traffic flow. In view of increasing traffic volumes and the progressive deterioration of infrastructure, particularly tunnels, this requirement poses a growing challenge. To address this, FEDRO has been developing innovative tunnel renovation solutions that allow works to be carried out while keeping tunnels open to traffic.

2. FEDRO'S TUNNEL RENOVATION METHOD

Many motorway tunnels in Switzerland and elsewhere in Europe have reached a critical age, and infrastructure owners must anticipate weaknesses in the substructure as well as problems related to sealing. Over the past years, FEDRO has carried out several tunnel renovation projects on different motorway sections, which have progressively contributed to the development of new renovation strategies. One of the first projects that highlighted the limitations of conventional approaches was the renovation of tunnels along the A16 motorway section in the Bernese Jura between La Heutte and Bözingenfeld. These tunnels, constructed between 1960 and 1970, provided valuable experience and clearly demonstrated the need to test and develop innovative methodologies capable of ensuring long term performance while maintaining traffic capacity.

Water ingress can severely disrupt traffic, particularly when it results in the formation of hazardous icicles in the tunnel arch or ice patches on the carriageway. The non reinforced concrete arch of these tunnels was cast in place directly against the rock, without any waterproofing system having been installed beforehand. In such situations, the conventional approach consists of removing the inner concrete ring, installing a waterproofing system and subsequently casting a new lining in place. Crack grouting or curtain grouting would not provide a durable solution, as the long-term performance of these measures has not been proven and the cost benefit ratio is not always favourable.

FEDRO's maintenance planning regulations stipulate that all traffic lanes in each direction must remain available during peak traffic periods. Completely replacing the primary lining could therefore not be considered a standard solution, as the secondary lining alone could not guarantee sufficient stability and the demolition work would pose a risk to road users. Owing to the reduced lateral clearance, the

installation of a new lining was also not feasible. Alternative solutions therefore had to be identified that could achieve performance comparable to that of a new structure while guaranteeing road user safety without impairing traffic flow.

The solution ultimately selected consisted of partially removing the primary lining, installing new drainage and sealing systems, and subsequently constructing a new final lining. The stability of the weakened arch was ensured by means of temporary rock bolts, while traffic diversions were limited to nighttime periods when construction activities were carried out inside the tunnel. The new arch, made of self-compacting concrete, was constructed in a single operation and was designed solely to provide the required structural stability. To maintain two lane traffic during daytime, a special tunnel formwork system had to be developed.

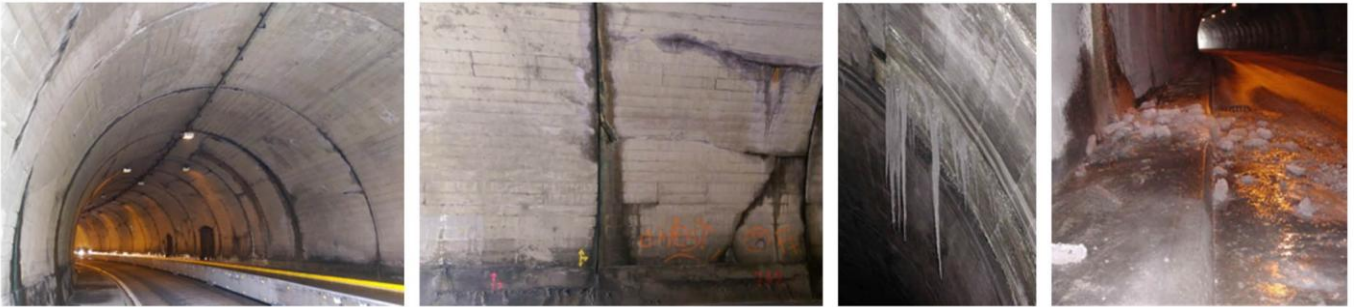


Figure 1: Deterioration of the existing tunnel lining leading to water ingress and ice formation in the traffic area

3. RENOVATION OF TUNNEL T3 ON THE A16 MOTORWAY

3.1 OVERVIEW

The renovation of the 196-metre-long tunnel T3 on the A16 motorway represented the first application of this renovation methodology and involved the use of an innovative approach under previously untested conditions, making this project a world first. The arch of tunnel T3 consisted of 5-metre-long non reinforced concrete rings that had been cast in situ directly against the rock, that is without any waterproofing system. Tunnel T3 crosses the Portland limestone segment of the Twannbach Formation. Stratigraphic discontinuities and tectonic cracks result in potentially unstable rock formations, which may impose additional loads on the tunnel arch. The estimated volume of unstable rock formed the basis for the structural analysis of the temporary reinforcement measures and for the dimensioning of the new lining.

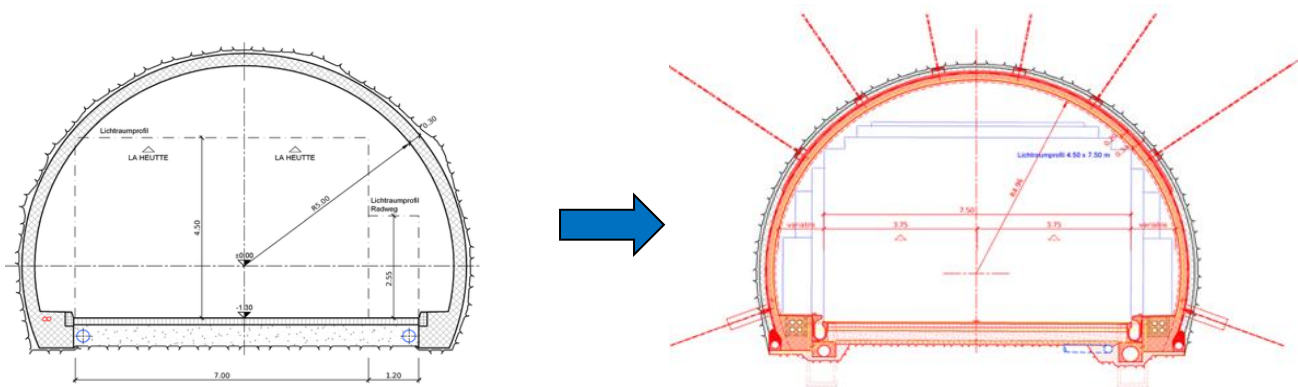


Figure 2: Cross-sections of tunnel T3 before and after renovation

The renovation procedure involved the following steps:

- Installing an anchoring system
- Milling the non-reinforced concrete arch
- Installing a drainage layer over the entire surface

Applying a new waterproofing system
Casting a new inner ring.

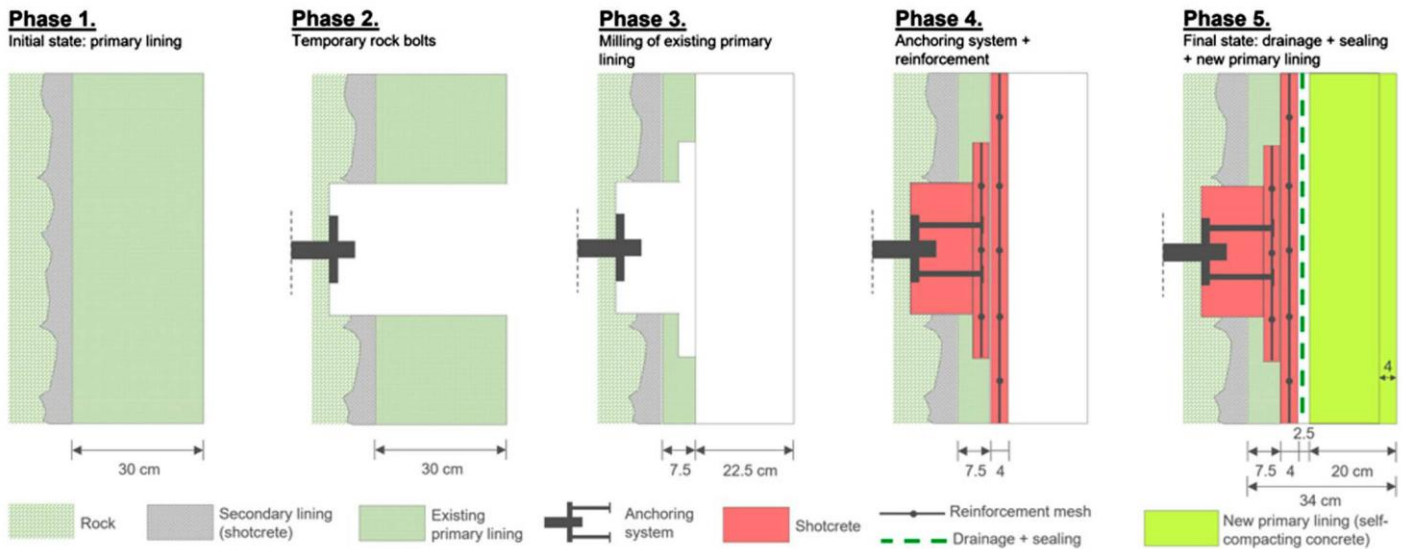


Figure 3: Sequential phases from existing lining to final inner shell

All construction works were carried out at nighttime between 8.30 pm and 5.00 am, five days per week. The works were completed in March 2020 after a total construction period of twelve months.

3.2 ANCHOR SYSTEM AND MILLING OPERATIONS

Milling operations on the tunnel arch inevitably weakened the existing lining and reduced its stability. However, the thickness and quality of the inner shell were well documented through extensive core sampling carried out prior to construction, allowing structural safety to be verified by numerical analyses.

Temporary passive rock bolts were first installed along the full length of the tunnel to stabilise the arch, thereby enabling the subsequent milling of the existing lining to be carried out safely. The bolt layout, including number, length and diameter, was adapted to the degree of fracturing of the limestone massif identified during the geological investigations. These measures reduced the load transferred from the surrounding rock mass to the milled arch.

The non-reinforced concrete lining was then removed in a controlled manner using specialised milling machines, ensuring precise execution and a uniform surface finish suitable for subsequent layers. The average advance rate was approximately 2 m per night. At tunnel portals, where the lining consisted of reinforced concrete, removal was carried out using hydro-jetting.

Following milling, the geometry of the remaining inner shell was surveyed, and periodic convergence measurements were performed, with automatic monitoring installed in the portal area only.



Figure 4: Installation of temporary rock bolts to stabilise the tunnel arch after milling



Figure 5: Controlled milling of the non-reinforced concrete tunnel lining

3.3 DRAINAGE AND WATERPROOFING SYSTEM

The main deficiencies of the existing structure of tunnel T3 were largely attributed to water ingress through numerous cracks in the lining. Consequently, the primary objective of the renovation works was to ensure effective drainage of the surrounding rock layers. For this tunnel, a conventional drainage system applied over the entire surface of the arch, combined with a full-face waterproofing system, was selected.

Two waterproofing technologies were tested: conventional synthetic waterproof sheeting installed over one half of the tunnel, and a spray-applied waterproofing system applied over the other half. The spray-applied system was initially favoured due to its advantages in installation speed and logistics. However, as the project progressed, it became apparent that conventional synthetic sheeting provided a better overall result as well as faster execution. This was mainly due to the difficulties associated with applying the liquid spray on waterproofing evenly to a rough surface while meeting the required quality standards.



Figure-6:-Drainage-System



Figure-7:-Conventional-synthetic-waterproofing-system



Figure-8:-Spray-on-waterproofing-system·
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3.4 INNER SHELL

Once the waterproofing system had been installed, a new 20 cm thick arch of self-compacting concrete was constructed to provide permanent structural support to the tunnel. The new arch was cast in place in a single operation during nighttime closures, using a mobile formwork system. Special anchors were installed at the base of the formwork to counteract the pressure exerted by the fresh self-compacting concrete during casting. These anchors made it possible to minimise the dimensions of the tunnel formwork, which would otherwise not have allowed two lanes of traffic to pass through the tunnel during daytime. The construction of the new inner shell required a total duration of seven weeks, with a production rate of one 5-metre-long block per night.

During the T3 pilot project, an alternative solution was also tested on three concrete sections to maintain traffic flow in both directions during daytime. This solution consisted of an ultra-fast, self-compacting concrete. During casting, temporary mobile horizontal supports could be used to counterbalance the horizontal pressure of the fresh concrete and were subsequently removed before the tunnel was reopened to traffic. At that time, the concrete of the inner ring had already developed sufficient mechanical properties, which occurred within approximately 2 to 3 hours for a concrete strength f_c greater than 20 N/mm². The tunnel formwork remained in place during this period and was only removed on the following day, allowing traffic to flow without restriction.

3.5 ROAD SAFETY, SUSTAINABILITY AND SAFETY RECORDS

To ensure a high level of safety during construction, the existing lining was first stabilised by installing a system of temporary rock bolts. This preliminary reinforcement allowed the subsequent milling of the inner shell to be carried out safely. A mobile crash deck was installed to protect the carriageway from falling debris. During the most critical phases of inner shell installation, the available clearance was temporarily reduced to 6.0 m × 4.2 m and the speed limit was lowered to 60 km/h.



Figure 13: Night-time works inside the tunnel during renovation



Figure 14: Completed inner lining after renovation



Figure 15: Fresh UHPFRC consistency during casting

4.2 OBSERVED BEHAVIOUR AND LIMITATIONS

During and after construction, the behaviour of the UHPFRC lining at tunnel T5 was closely monitored. A key initial concern was whether a complete and homogeneous filling of the tunnel arch could be achieved in a single casting operation, given that the material had to be pumped and placed against an overhead curved surface with variable thickness, unlike typical gravity-based UHPFRC applications. Despite these challenging conditions, the entire lining ring was successfully filled without voids or major execution-related difficulties.

However, the subsequent performance of the lining did not fully meet the initial expectations. Cracking was observed shortly after casting, in some cases extending through the full lining thickness and locally leading to water ingress. As a result, the intended waterproofing function was not fully achieved. Various corrective measures were implemented during construction, including adjustments to casting procedures and curing conditions, but these did not result in a satisfactory improvement. The observed cracking was therefore attributed to a combination of factors related to material behaviour, construction conditions and application-specific boundary conditions rather than to a single isolated cause.



Figure 16: Cracking of the UHPFRC inner lining after casting



Figure 17: Drilled UHPFRC cores extracted from the tunnel lining

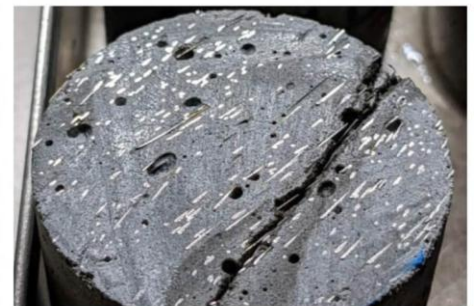


Figure 18: UHPFRC core with through-thickness crack and fibre distribution

4.3 IMPLICATIONS AND NEXT STEPS

The renovation of tunnel T5 revealed important limitations in the use of UHPFRC as a thin, structural and watertight tunnel lining. Although a fallback solution based on the proven T3 methodology was available, the project was deliberately pursued as a learning-oriented pilot case to better understand the limits of this innovative material under real construction conditions.

Targeted investigations were therefore carried out in collaboration with the Swiss Federal Laboratories for Materials Science and Technology (EMPA). Using X-ray computed tomography, the three-dimensional fibre distribution within drilled cores was analysed, revealing preferential fibre orientations related to casting and flow conditions. These investigations demonstrated that fibre orientation and local heterogeneity have a significant influence on crack initiation and propagation in UHPFRC linings. Building on these findings, a further research programme is planned for 2026 and 2027, including controlled prototype tests and casting trials. The investigations will focus on key parameters such as pumping method, mix design, formwork configuration and lining thickness, with the aim of improving fibre distribution and crack control.

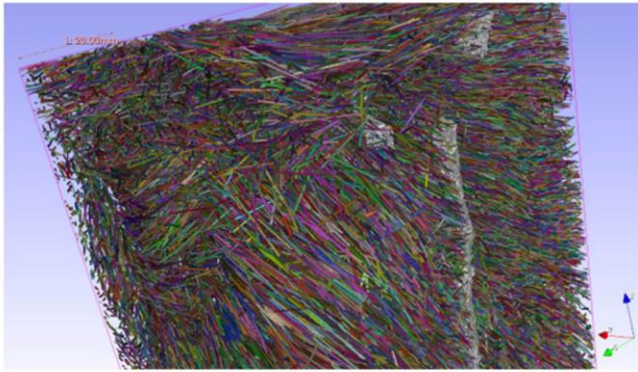


Figure 19: 3D rendering of fibres and a crack in a core sample. Individual fibres are randomly colour-coded, while the segmented crack is shown in grey

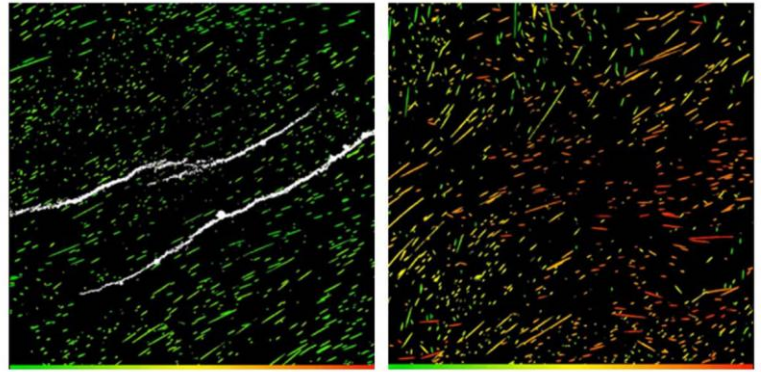


Figure 20: Fibre orientation in UHPFRC cores derived from X-ray CT analysis. Left: Core with a through-going crack, showing fibres predominantly oriented parallel to the crack plane (green), which is unfavourable for crack bridging. Right: Core without crack, exhibiting a heterogeneous colour distribution (green to orange/red) indicative of a largely random fibre orientation.

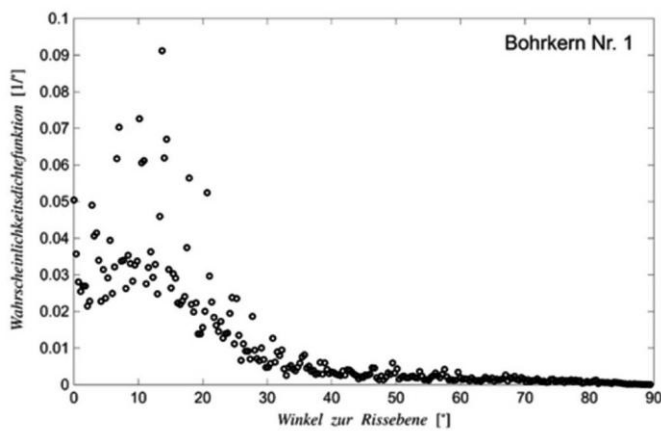


Figure 20: Probability density function as a function of the fibre orientation angle α relative to the crack plane for core 1 with a through-going crack

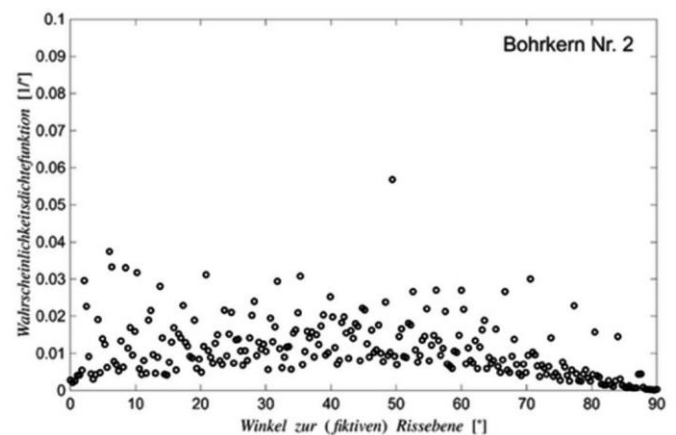


Figure 21: Probability density function as a function of the fibre orientation angle α relative to the crack plane for core 2 without crack

At present, the use of UHPFRC in this application is not considered suitable for direct implementation, and future developments will determine whether material adaptations or alternative high-performance solutions can provide viable options.

5. RENOVATION OF THE CRIBLETTE AND CHAUDERON TUNNELS ON THE A9 MOTORWAY

5.1 INTRODUCTION AND BACKGROUND

The renovation of the Criblette and Chauderon tunnels was carried out on the A9 motorway, one of Switzerland's most heavily trafficked road corridors. In both tunnels, the main deterioration concerned the existing waterproofing system, which exhibited cracking associated with localised water ingress.

Conventional rehabilitation approaches involving extensive demolition were deemed incompatible with the operational constraints of the A9, as they entailed a high risk of not being able to safely reopen the tunnels to traffic at the end of each night-time work shift.

The renovation strategy adopted for the A9 tunnels was therefore directly derived from the methodology previously developed and applied at tunnel T3 on the A16 motorway. The project primarily served to demonstrate the robustness and transferability of the T3 approach under demanding traffic and operational conditions, confirming that the methodology can be applied in highly constrained motorway environments when the identified boundary conditions are respected.



Figure 22: Project area of the Criblette and Chauderon tunnels



Figure 23: Traffic management layout on the A9 motorway during renovation works



Figure 24: Tunnel prior to renovation, showing waterproofing defects

5.2 KEY PROJECT DATA AND EXECUTION SEQUENCE

The Criblette and Chauderon tunnels are located on the N09 (A9) motorway section between Lausanne Vennes and Chexbres, in the Canton of Vaud, within the municipalities of Lutry and Bourg en Lavaux. The section was opened to traffic in 1974 and is currently undergoing a major maintenance and renewal programme scheduled from 2024 to 2028.

Both assets consist of two parallel twin lane tubes with a carriageway width of 7.75 m. The Criblette tunnel has tube lengths of 294 m (*Lac*) and 282 m (*Montagne*), while the Chauderon tunnel has tube lengths of 194 m (*Lac*) and 222 m (*Montagne*). In 2024, the tunnel vaults of the *Montagne* carriageway were renovated during nighttime closures with daily reopening to traffic, while additional works on sidewalks and other elements are planned for the subsequent phases of the programme.

The execution sequence followed the same high-level steps as the T3 methodology. Works were organised to ensure daily reopening, with the tube under intervention closed at night and the parallel tube operated with bidirectional traffic.

A key operational aspect was the formwork installation and fixing concept. The formwork carriage was designed to withstand the horizontal concreting pressure without intermediate struts that would conflict with the traffic clearance. Load transfer was ensured through prefabricated reinforced concrete running strips placed on the pavement, providing a stable load path and avoiding the need for additional temporary props or anchoring systems.



Figure 25: Drilling works inside the tunnel during night-time closures



Figure 26: Controlled removal of the existing lining



Figure 27: Installation of waterproofing system

5.3 OUTCOME AND TRANSFERABILITY

The renovation works carried out on the Criblette and Chauderon tunnels confirmed the applicability and robustness of the tunnel renovation methodology developed during the pilot projects on the A16 motorway. The approach proved to be compatible with very high traffic volumes and strict operational constraints, provided that the boundary conditions identified during the pilot phase are respected.

The experience gained on the A9 demonstrates that the methodology can be transferred to heavily trafficked motorway tunnels where conventional demolition-based rehabilitation is not feasible, offering a reliable solution for addressing waterproofing defects while maintaining daily traffic operations.

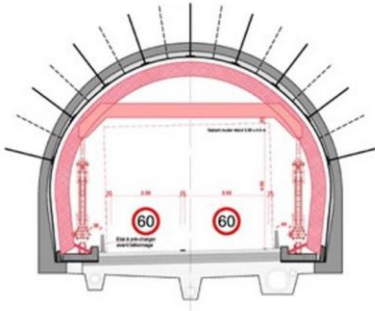


Figure 28: Cross-section showing the formwork system and its fixing concept (anchor lengths shown schematically)



Figure 29: Inner lining casting with mobile curing and formwork units



Figure 30: Traffic circulation with formwork in place during renovation works

6. CONCLUSIONS AND OUTLOOK

A significant portion of the existing motorway tunnel infrastructure in Switzerland is reaching an age at which structural and functional deterioration can no longer be addressed through minor maintenance measures alone. At the same time, steadily increasing traffic volumes severely limit the feasibility of traditional rehabilitation strategies based on long term closures or extensive demolition. In this context, developing renovation methods that extend the service life of existing tunnels while maintaining traffic operations has become a key challenge.

The tunnel renovation methodology developed by FEDRO addresses this challenge by adopting the principle of removing as little as possible and as much as necessary. By partially dismantling and upgrading the existing structure instead of fully demolishing it, the method reduces material consumption, limits construction waste and significantly lowers the associated CO₂ footprint compared to conventional reconstruction approaches. This sustainability driven strategy is particularly relevant for tunnel structures, where complete demolition and replacement would result in substantial environmental and operational impacts.

The pilot application at tunnel T3 demonstrated for the first time that a full structural lining replacement combined with a modern drainage and waterproofing system can be achieved without closing a tunnel tube to daytime traffic. Prior to this development, tunnel owners were often faced with two unsatisfactory alternatives: either closing one tube for extended periods, which is no longer acceptable on heavily trafficked motorways, or renouncing a cast in situ concrete lining and relying on sprayed concrete solutions. This second option, while suitable for certain applications, is generally not recommended as a permanent lining in road tunnels due to durability, waterproofing and long-term maintenance considerations.

The subsequent projects presented in this paper illustrate both the robustness and the limitations of the methodology. The advanced pilot application at tunnel T5 provided valuable insights into the use of innovative materials and highlighted the importance of clearly defining boundary conditions for their application. The successful transfer of the T3 methodology to the heavily trafficked A9 motorway confirmed that the approach is viable even under very restrictive operational conditions, provided that the lessons learned during the pilot phase are respected.

Overall, the projects demonstrate that innovative, stepwise renovation strategies can offer reliable alternatives to full tunnel reconstruction. The FEDRO tunnel renovation methodology, recognised with the ITA Tunnel Award in 2020, represents a key contribution in this direction. Ongoing research and future developments will focus on further improving materials and execution techniques, with the objective of extending the service life of existing tunnel infrastructure safely, sustainably and with minimal disruption to traffic.



Figure 31: Finished portal of tunnel T3 (©patriceschreyer.com)



CERTIFICATE OF APPRECIATION

Awarded to
FEDRO's Tunnel Renovation Method
 as **WINNER**
 of the ITA Tunnelling and Underground Space Awards in the Category
Project of the Year 2020 – Incl. Renovation (up to €50M)

Jenny Yan
 ITA President 2019-2022

Lars Babendererde
 ITA First Vice-President 2019-2022
 Chair of ITA Tunnelling Awards Committee 2020

04 December 2020

Figure 32: ITA Tunnelling Awards 2020 – Certificate awarded to FEDRO's Tunnel Renovation Method (Project of the Year 2020).

LITERATURE

BALBI, G. (2020) *FEDRO's tunnel renovation method – Renovation of a non-reinforced primary lining using night shifts while keeping all traffic lanes open during peak traffic periods*. Geomechanics and Tunnelling 13, No. 5, pp. 547–556. <https://doi.org/10.1002/geot.202000024>

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