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Original
Refurbishment of Existing Tunnels: Common Practice and Future Perspectives / De Feudis, S., Insana, A., Barla, M.. - In: BER. - ISSN 3065-0569. - ELETTRONICO. - 3:4(2026), pp. 1-21. [10.70465/ber.v3i4.100]

Availability:
This version is available at: 11583/3016489 since: 2026-10-10T08:51:55Z

Publisher:
FABRE Consortium

Published
DOI:10.70465/ber.v3i4.100

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22 October 2026

BER the international journal of bridge engineering management and research

Refurbishment of Existing Tunnels: Common Practice and Future Perspectives

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Submitted: 19 June 2026 **Accepted:** 17 September 2026 **Publication date:** 10 October 2026

DOI: 10.70465/ber.v3i4.100

Abstract: Tunnels are inherently resilient structures whose service life commonly extends well beyond the intended design period, resulting in a substantial number of tunnels that have been in operation for over five decades and more. From this perspective, addressing tunnel aging requires maintaining functionality and ensuring continued safe and reliable operation. This involves a series of coordinated efforts in maintenance, risk management, and refurbishment to guarantee consistent service over extended lifespans. This article has the aim to provide an up-to-date overview of the international framework for the management and refurbishment of existing tunnels. Relevant guidelines and standards adopted worldwide are examined and compared, highlighting common principles and distinctive features. Established techniques for maintenance, structural reinforcement, rehabilitation, and upgrading are then deeply reviewed, providing practical examples and illustrative images from construction sites. The article concludes by discussing selected innovative approaches and emerging technologies shaping the future of tunnel management and refurbishment.

Author keywords: Maintenance; tunnelling; tunnel engineering; tunnel refurbishment; asset management

Introduction

As inherently resilient geotechnical structures, tunnels often remain serviceable well beyond their intended design life. Therefore, an increasing proportion of the global tunnel network now consists of aging assets that have been in continuous operation for more than five decades.[1] The literature indeed abounds with case studies documenting operational tunnels that have surpassed one hundred years of service.

Among the European countries with the highest tunnel density per unit of national surface area (Fig. 1), Switzerland, Italy, and Austria stand out as remarkable examples. In Switzerland, *Rhaetian Railways AG* operates a railway network of 384 km. Because of the Alpine terrain, this tallies around 77 km of tunnels, 59 km of which, corresponding to 115 tunnels, were realized between 1901 and 1914.[2,3] Similarly, in Italy, *Rete Ferroviaria Italiana S.p.A*. manages about 24,500 km of railway lines, including 1,460 tunnels, two-thirds built before 1930.[4] Likewise, *Autostrade per l'Italia S.p.A*., operates over 2,900 km of motorways comprising 595 tunnels, corresponding to around 365 km, most realized during the 1960–1980 economic boom.[5,6] Regarding Austria, instead, *ÖBB-Infrastruktur AG* operates and maintains 246 tunnels, with an overall length of 250 km, nearly 150 of which are more than 100 years old and 35 are over 150 years old.[7] Additional evidence of aging underground infrastructure from the U.S.A., Taiwan, the U.K., Germany, and Canada can be found in Zeidler et al.,[8] Chiu et al.,[9] Burgess et al.,[10] Atkinson et al.,[11] Vetter et al.,[12] and Motallebi et al.,[13] respectively.

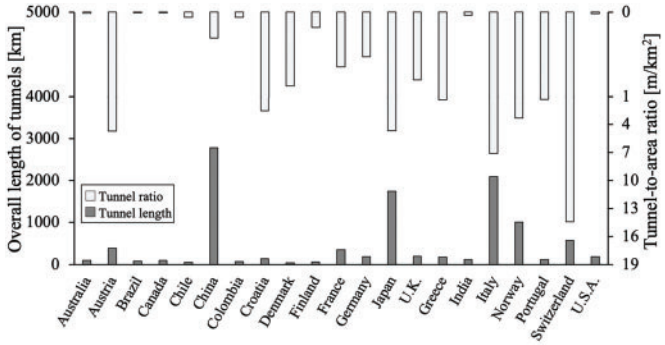

Figure 1. Motorway and railway tunnel length and tunnel-to-area ratio for some countries worldwide (modified from De Feudis et al.,[14])

An additional noteworthy aspect emerges when examining long-term trends: the expansion of motorway and railway networks appears to have undergone a pronounced deceleration over recent decades.[15] This is a symptom that attention is edging toward the refurbishment of the existing networks rather than expansion and development. As noted above, this shift is largely driven by the progressive aging of tunnel assets, which increasingly poses risks to owners, concessionaires, and users. For owners, aging infrastructure

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Discussion period open till six months from the publication date. Please submit separate discussion for each individual paper. This paper is a part of the Vol. 3 of the International Journal of Bridge Engineering, Management and Research (© BER), ISSN 3065-0569.

threatens long-term asset and investment value; for concessionaires, it affects revenue stability and growth; and for users, it compromises safety and operational efficiency.

As aging tunnels continue to experience cumulative degradation, increasingly stringent safety requirements, coupled with evolving performance demands, make their management ever more critical. This highlights the paramount importance of regular and systematic inspection routines, reliable condition assessments, and the prioritization of refurbishment interventions. In response, research and practice are progressively converging toward innovative and longer-lasting refurbishment methods, effective management strategies, and emerging technologies to support the long-term resilience of tunnel infrastructure.

In this framework, this article focuses on the management and refurbishment of existing tunnel infrastructure. It offers a state-of-the-art review of the most established strategies and solutions for addressing tunnel aging and deterioration, while highlighting recent methodological advances and technological innovations. Through a synthesis of current knowledge and emerging trends, the article aims to inform effective management and refurbishment practices to ensure the long-term functionality and safety of tunnel assets.

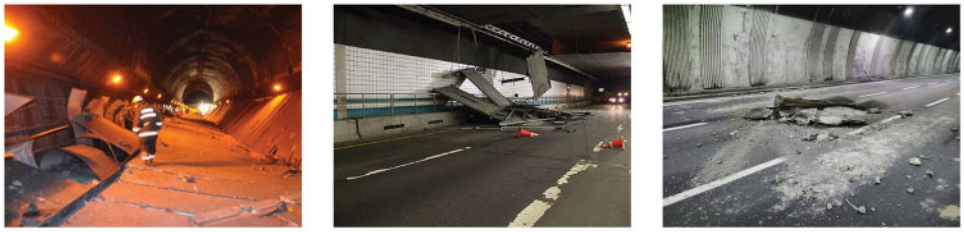
Risk Management and Safety Assessment

Tunnel management presents many operational, risk minimization, and refurbishment tasks whose fulfilment allows the infrastructure to serve safely and consistently. It includes time-scheduling and resource allocation for inspections and investigation campaigns aimed at verifying the state of preservation of the structure and planning refurbishment works that influence tunnel serviceability. Tunnel management also involves the pre-codification of effective responses to incidents and emergencies, ideally supported by early detection through monitoring systems. Therefore, several countries and international organizations have developed guidelines for tunnel management and risk assessment.

For instance, following the ceiling panel fall in the Sasago tunnel (Figs. 2a and 2b) in 2015, the Japanese *Ministry of Land, Infrastructure, Transport and Tourism* (MLIT) issued the "Guideline for Periodical Inspection of Road Tunnels",[16] instructing standardized close-visual inspections of all road tunnels at least every 5 years. The inspection outcomes, involving not only structural components but also portals, joints, and mechanical and electrical facilities, are used to classify tunnels on a uniform scale, with 4 distinct stages ranging from I to IV, that determine the need for monitoring and/or refurbishment. Tunnels receiving lower ratings have a shortened inspection interval, from 5 to 2 years.

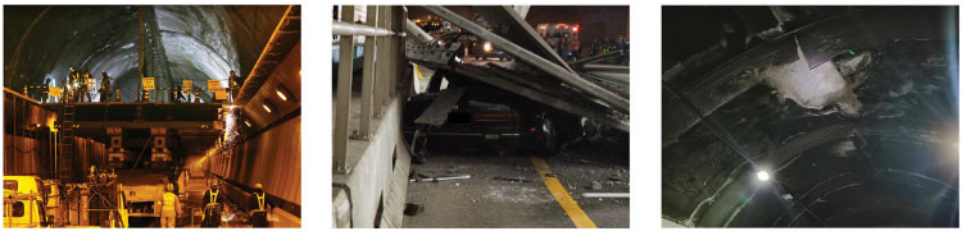
In 2015, the Chinese *Ministry of Transport* (MOT) published the "Technical Specifications for Maintenance of Highway Tunnels",[17] standardizing management practices according to tunnel class, defined by length, traffic volume, and strategic importance. Such a procedure evaluates tunnel safety through three components, i.e., structural condition, mechanical and electrical equipment, and additional facilities, each assessed via routine and periodic inspections or overhauls at frequencies determined by tunnel importance and state of preservation. Defects are graded from 1 to 4, and their severity and location contribute to a weighted overall technical condition score through which the tunnel can be classified into categories ranging from 1 to 5. This category determines the inspection frequencies, varying from 1 to 3 months for routine inspections and from 1 to 3 years for periodic inspections, and guides the choice of the refurbishment approach. In this regard, daily patrols to verify normal operating conditions are mandatory, and tunnel cleaning is considered ordinary maintenance activity with a prescribed frequency based on tunnel class and category. Emergency and special inspections are also envisaged, the former for structure, which suffered from natural disasters, traffic accidents, or other abnormalities and the latter when extensive degradation requires further investigation.

In the same year, a decade after the Ted Williams Tunnel accident (Figs. 2c and 2d), the U.S.A. *Federal Highway Administration* (FHWA) released the "Tunnel Operations, Maintenance, Inspection, and Evaluation (TOMIE) Manual"[18] to regulate road-tunnel management. The process starts with a review of as-built documents, previous testing procedures, refurbishment records, and incident histories, as required by the *Specifications for the National Tunnel Inventory*.[19] An initial inspection, to be carried out before opening to traffic or within 2 years from *National Tunnel Inspection Standards*[20] issuing, establishes baseline tunnel conditions and highlights areas needing attention during the 2-year (extendable to 4 years with proper justifications) routine inspection cycle. The TOMIE Manual also instructs about in-depth (with level and frequency to be established on purpose based on the needs of the tunnel facility and routine inspection findings), damage, and special inspections when safety concerns arise or extraordinary events occur. Inspection results are used to rate tunnel condition, guide



(a) (c) (e)

Figure 2. (Continued)



(b) (d) (f)

Figure 2. Tunnel local collapses that drove the development of modern tunnel guidelines: (a) Sasago tunnel ceiling panel fall and (b) subsequent refurbishment[16,20]; (c) Ted Williams tunnel ceiling panel fall and (d) vehicle with a fatally injured occupant beneath[22]; (e) Berté tunnel concrete vault collapse and (f) resulting cavity in the lining[23]

preventive or corrective maintenance, and, eventually, plan structural reinforcement or rehabilitation. The TOMIE manual recommends that 70–80% of maintenance activities be preventive, reserving corrective actions for unforeseen events.

Concerning Europe, the *European Parliament* and *Council of the European Union* issued the "Directive 2004/54/EC",[24] which establishes minimum safety requirements for tunnels in the Trans-European Road Network. Though it provides only limited guidance on inspection, whose interval should never exceed 6 years, and refurbishment, it sets general structural, equipment, and safety-system principles that newly built tunnels must satisfy and to which existing ones must be adapted within 10–15 years since its issuance. Safety measures must be supported by risk-assessment analyses carried out by qualified independent bodies, considering factors such as tunnel geometry, traffic volume and composition, and heavy vehicle proportion.

Following the fall of nearly 2000 kg of concrete from the Berté tunnel vault in December 2019 (Figs. 2e and 2f) and the approaching deadline for compliance with the "Directive 2004/54/EC," the Italian *Consiglio Superiore dei Lavori Pubblici* (CSLLPP) released the "Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio delle Gallerie Esistenti".[25] These establish a multilevel, preventive tunnel management procedure to anticipate damage that could compromise structural safety or network serviceability. The 6 analysis levels are structured hierarchically and progressively increase the degree of knowledge and analytical refinement, moving from inventory and condition assessment to quantitative safety verification and network-scale evaluation.

Level 0 — Census and data acquisition provides the knowledge baseline. It involves the systematic collection of geometric, structural, geotechnical, hydrogeological, traffic, and historical data, including past inspections, interventions, and significant events. Its objective is to identify potential risk factors and define critical areas requiring targeted investigation.

Level 1 — Defectiveness sheets completion translates the collected information into a standardized condition assessment. The tunnel is subdivided into inspectional sectors and observed defects are classified according to location, extent, magnitude, and gravity, the latter being a qualitative index to reflect the likelihood of present or future safety implications. The result is a structured representation of the state of preservation of the tunnel, forming the basis for risk classification.

Level 2 — Attention Class (AC) assessment provides an expeditious risk-based prioritization at the national scale. Based on hazard, vulnerability, and exposure factors derived from previous levels, diverse risk domains are evaluated: i) global stability of the structure, with emphasis on ground-tunnel interaction; ii) local stability of the structure against block detachments; iii) road pavement conditions; iv) landslide mechanisms; v) seismic events; and vi) flooding phenomena. For each inspectional sector, ACs (High, Mid-high, Mid-low, Low) are assigned and combined into an overall AC to determine inspection frequencies (ranging from 2 to 12 months and from 1 to 6 years for routine and in-depth inspections), AC update and maintenance activities.

Level 3 — Preliminary safety assessment consists of simplified analytical evaluations aimed at verifying the consistency of the assigned ACs and investigating possible global or local instabilities, landslide mechanisms, or flooding phenomena. It is mandatory for mid-high AC tunnels and recommended for lower classes.

Level 4 — Accurate safety assessment involves advanced investigations and 2D/3D numerical modelling to quantify safety margins and assist decision-making on management, monitoring, and refurbishment of tunnels. It is triggered when Level 3 indicates insufficient safety margins or when Level 2 assigns a high AC.

Level 5 — Network resilience assessment applies to tunnels and underground infrastructures of national and international strategic relevance and evaluates the socio-economic and traffic consequences of potential service disruptions, extending the analysis from structural safety to system-level functionality.

A flow chart illustrating the hierarchical structure, sequential progression, and interdependencies among the 6 analysis levels defined by the Italian guidelines is illustrated in Fig. 3. Collectively, these guidelines, whose logical framework is systematically compared in Table 1, illustrate the principles of tunnel management and risk assessment, providing the background upon which targeted refurbishment strategies can be developed. The following section focuses on the most widely employed refurbishment interventions for existing tunnels in the currently established practice.

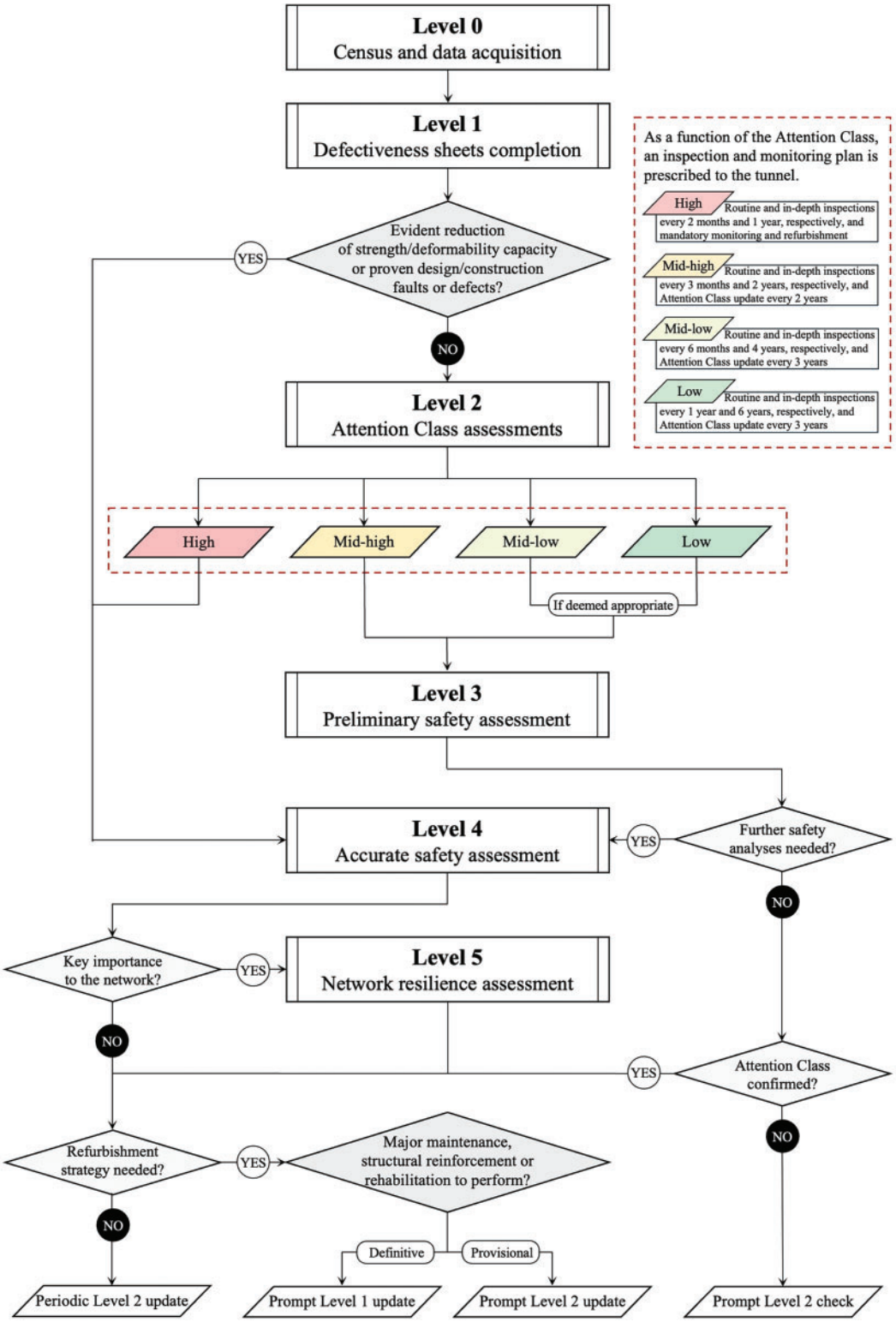


Figure 3. Multilevel procedure of the Italian guidelines and relationship between the different analysis levels (modified and implemented from CSLLPP[25])

Tunnel Refurbishment

Despite their resilience, tunnels unavoidably undergo performance degradation due to progressive aging and deterioration. Hence, refurbishment, intended as the set of actions undertaken to keep safety and serviceability above the minimum acceptable thresholds throughout operation, becomes vital. As schematically illustrated in Fig. 4, the performance level of a structure declines steadily if no interventions are undertaken, eventually dropping below acceptable limits. In contrast, timely maintenance, structural reinforcement, rehabilitation, or upgrading works introduce

Table 1. Comparison among international tunnel management guidelines

	Inspection frequency	Evaluation indicators	Classification systems	Notes
MLIT (JPN)	2–5 years based on tunnel preservation	Structural and nonstructural elements	I–IV, with IV denoting the best preservation	–
MOT (CHN)	1–3 months and 1–3 years for routine and periodic inspections based on tunnel importance and preservation	Structural, nonstructural elements, road pavement and traffic signs and marking	1–5, with 5 denoting the worst preservation	Emergency and special inspections are envisaged to deal with abnormalities
FHWA (USA)	2–4 years for routine inspections with in-depth inspections scheduled as required	Structural and nonstructural elements	No clear classification system, but prioritization of repair works	Damage and special inspections are envisaged to deal with abnormalities
CSLLPP (ITA)	3–12 months and 1–6 years for routine and in-depth inspections based on tunnel preservation	Structural, nonstructural elements, road pavement, and traffic signs and marking	ACs (High, Mid-high, Mid-low, Low), with High denoting the worst preservation	Special inspections are envisaged to deal with abnormalities

step-wise improvements that restore, enhance, or adapt the tunnel's performance to current or evolving functional requirements (De Feudis et al.,).[1,26,14]

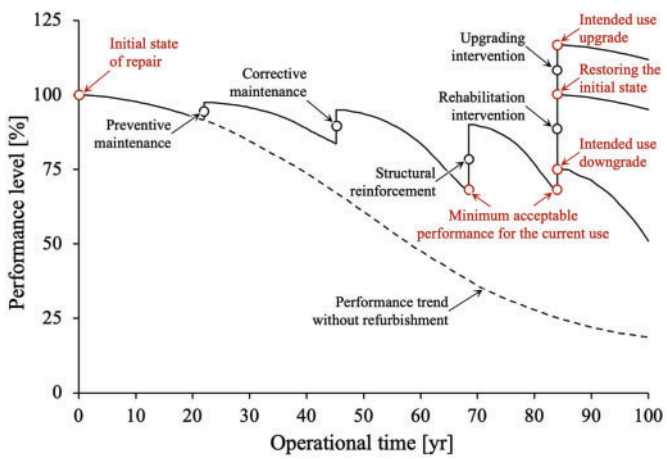


Figure 4. Life cycle performance of constructions (modified from ISO 15686-7:2006[27])

When refurbishment is not feasible or justified, repurposing may offer an alternative, whereby tunnels are reassigned to functions with lower performance demands, such as cultural or exhibition spaces,[28–30] underground storage and logistics facilities[31,32] or for more cutting-edge use.[33–36]

Maintenance works

Maintenance work is intended as minor repairs aimed at guaranteeing standard safety levels during service, referred to as minor maintenance, or slightly extending the structure's lifetime, referred to as major maintenance, awaiting longer-term interventions to be designed and realized. Therefore, maintenance does not only imply repair works dealing with tunnel structural components but also not structural ones, such as sidewalks and manholes, fire extinguishing systems, mechanical, electrical, and hydraulic equipment, safety systems, and much more. In the following, attention is focused solely on tunnel lining maintenance.

Maintenance works are, by definition, quick-to-apply, low-durability, and nearly noninvasive interventions that allow controlling or slowing down the evolution of defects in the short term. However, these generally do not provide reliable, long-lasting solutions but rather options to delay more laborious and onerous works depending on the current necessities.

Securing the intrados

When inspections reveal superficial deteriorations related to the materials and/or affecting the structural elements and the tunnel geometry (in particular, cracks and workmanship defects) with tolerable thicknesses, nets are arranged onto the tunnel intrados to prevent the detachment of thin concrete slabs. These coarse nets, made up of electro-welded steel wire or monolithic fiber-reinforced polymer meshes, are commonly coupled with a finer one, thus making small concrete fragments remain in place and fixed through mechanical or chemical wall plugs. Such maintenance work is versatile and prone to being coupled with most of the others discussed below.

Agresti et al.[37] documented electro-welded steel wire meshes used to temporarily cope with superficial, i.e., up to 5 cm deep, defects (mostly cracks, shallow voids of the lining and shotcrete deteriorations) in the innermost portion of the Scampitella tunnel (Avellino, Italy). Fig. 5a illustrates an analogous installation in the Citerna tunnel (Florence, Italy). In the U.K., instead, an innovative and novel variant was developed: the *Ram-Arch*® system. This consists of modular V-shaped corrugated elements that enhance self-support

against local detachments. Among others, as depicted in Fig. 5b, *Ram-Arch*® was utilized to maintain the Whiteball tunnel in Somerset.[11]

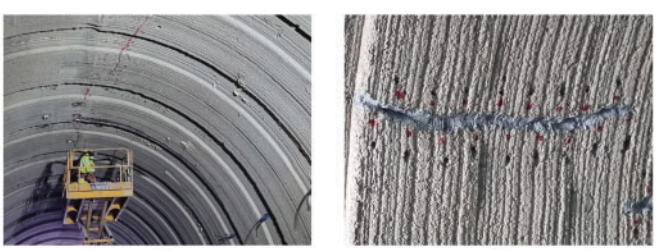
(a) (b)

Figure 5. Installation of (a) protective steel nets in the Citerna tunnel and (b) *Ram-Arch*® system in the Whiteball tunnel[38]

Crack stitching

Despite being affected by cracks, countless tunnels are fundamentally unloaded, thus supporting only their weight. Such cracks are not a consequence of the stress–strain state in the structure but rather shrinkage, which occurs due to aging and depends on manufacturing, casting, and curing parameters. For instance, this is a recurrent situation with shallow motorway tunnels in Italy,[37] unless very specific issues arise.[39] In such a condition, crack stitching is a valid option to stop cracks from enlarging and seal such a preferential water path. This involves drilling micro-holes across cracks, which should be reinforced with steel rebars and sealed with resins. Preliminarily, the crack trace should be sealed to avoid pressurized resins pouring out.

Fig. 6a shows crack stitching works in the Croci di Calenzano tunnel (Florence, Italy). Specifically, Fig. 6b illustrates a close view of a stitched crack where its sealed trace (in grey) and stitching points (micro-holes nearby red dots) are visible.



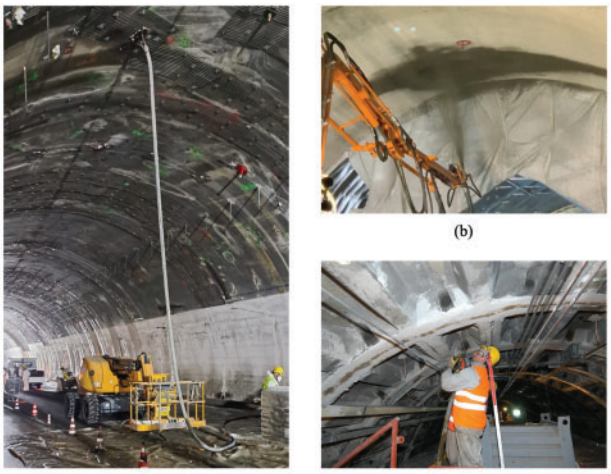
(a) (b)

Figure 6. (a) Crack stitching operations in Croci di Calenzano tunnel and (b) close view of a stitched crack (courtesy of Lapo Baccolini)

Cavity filling

It is not uncommon that tunnel inspection outcomes reveal anomalies in the lining thickness[40,41] or even voids[42,43] and karsts[44] affecting the surrounding ground. To address this issue, the cavities are typically filled with high-performance concrete in the first case and with lightweight mortar or foam in the second. Whether high-performance concrete ensures structural continuity within the tunnel lining, lightweight fillers achieve the double aim of avoiding excessive additional loads to the existing structure (due to the material weight and ground fragments falling from above) and allowing stress redistribution along the structure. Cavity filling may be coupled to structural reinforcements, which act as additional support to sustain the overload in the case of highly deteriorated concrete.

In Fig. 7, different applications in terms of material and technique, but with even planned durability, are shown. Fig. 7a is an image taken from ground void filling operations behind the Poggio tunnel (Genoa, Italy) through lightweight mortar. Fig. 7b, instead, depicts a lining anomaly being filled with sprayed concrete in the Olimpia tunnel (Alessandria, Italy). Indeed, despite the rehabilitation intervention planned in this tunnel,[15] spot interventions were necessary to ensure worker safety.



(a) (b) (c)

Figure 7. Filling operations of (a) voids behind the Poggio tunnel lining (courtesy of Alessandro Tonghini), (b) an anomaly within the lining of Olimpia tunnel, and (c) the gap between the Rome tunnel Metro Line A and the ground[45]

Depending on the application and the design, cavity-filling interventions may also be longer-lasting. For instance, expanding foam was pumped in the gap between the tunnel lining of the Metro Line A in Rome and the surrounding ground, as visible in Fig. 6c.[45] The aim was to avoid water infiltrations, which induced several disruptions. Such maintenance work, realized in 2005, results still effective nowadays.

Corrosion protection or substitution of steel reinforcements

Steel rebars allow reinforced concrete tunnel linings to absorb tensile stresses. Therefore, their corrosion due to concrete cover deterioration may result in abrupt strength losses. Depending on the corrosion level, steel reinforcements can be either coated with an anti-corrosive agent or even replaced. In both instances, in the area to be treated, steel has to be entirely exposed through hydro-demolition of the concrete cover. Finally, this is commonly rebuilt through shotcrete.

Fig. 8 illustrates the rebar corrosion protection in the Monte Baldo tunnel (Treviso, Italy).

Figure 8. Rebar corrosion protection intervention in the Monte Baldo tunnel: (a) exposed rebars treated with protective coating and (b) concrete cover reconstruction

Groundwater drainage

In the absence of waterproofing systems, coping with groundwater infiltration is paramount. Indeed, water induces significant deterioration over time of concrete, especially in correspondence with the construction joints that act as preferential seepage pathways. Hence, when water incomes, but even concretions, freezing traces, and efflorescence are encountered during tunnel inspections, a drainage system is usually realized. To this end, polyvinyl chloride (PVC) drainage tubes are usually installed along the tunnel vault to convey groundwater inside the tunnel. Interaction with the concrete lining is avoided by employing half-fenestrated tubes able to collect groundwater only from behind it. Water is then funnelled into collectors through corrugated metal sheets that prevent water from falling onto the carriageway or tracks. As for nets, such maintenance work is also prone to being coupled with others.

Fig. 9a shows the drainage solutions with PVC drains and corrugated metal sheet collectors implemented in the San Fermo tunnel (Como, Italy).

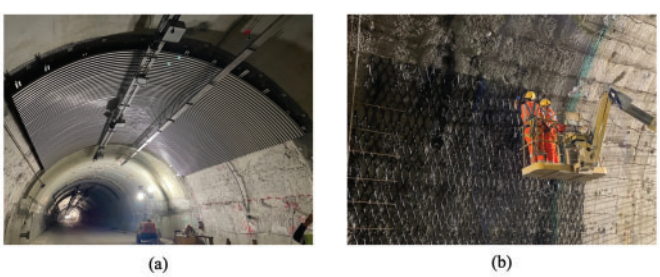


Figure 9. Installation of drainage systems with (a) fenestrated tubes and metal collectors in the San Fermo tunnel and (b) *Dolenco Drains*® in the Olimpia tunnel

Alternatively, plastic modular drainage meshes could be arranged on the intrados by simply nailing them onto the tunnel wall, thus ensuring high installation rates. To protect them from fire and physical damage, these are commonly encapsulated into shotcrete layers. Hence, this kind of drainage solution could be combined with thin surface scarification of the existing lining for clearance reasons. However, in contrast with the previous drainage methodology, this would allow groundwater to seep through the existing lining, thus not slowing down its aging process. Such meshes may also fit as drainage systems to be installed along with rehabilitation interventions.

Fig. 9b depicts the installation of the *Dolenco Drains*® in the Olimpia tunnel. Such a drainage mesh was chosen to handle water infiltrations and relieve the related overpressures from behind the newly built lining.

Waterproofing the intrados

The philosophy is twofold for managing groundwater infiltrations: handling them with drainage or waterproofing systems. The latter option is usually preferred in cold climates where icing risk in tunnels is real. To this end, the *Norwegian Public Roads Administration* (NPRA) developed different water and frost protection interventions depending on the annual average daily traffic of tunnels.[46] While structural rehabilitation solutions concern only high-traffic tunnels, for low-traffic ones, shorter-term solutions are used, such as the Miljøhvelv inner lining. This consists of an aluminum cassette, mineral wool mats, and an overlay of high-quality PVC foil.

Conversely, considering the proper tunnel clearance, waterproofing envelopes made of polyethylene (PE) or foam layers encapsulated within shotcrete or even waterproof sprayed concrete[47] can be employed. In case of isolated water dripping at construction joints, these may be sealed with resins.[48]

Maintenance works for masonry tunnels

The techniques used for maintaining masonry tunnels are borrowed from the masonry buildings field.[49] Hence, analogously to above-ground structures, the bed joint remake with either high-performance mortar (Fig. 10a) or steel or composite tendons (Fig. 10b) represents a viable solution for enhancing the bearing capacity of the structure. To manage groundwater infiltrations, instead, hydrophobic resins may be sprayed on the intrados or injected behind the extrados.

Figure 10. Bed joint remake of a motorway masonry tunnel in Italy through (a) high-performance mortar and (b) steel tendons (courtesy of Lapo Baccolini)

Structural reinforcements

Structural reinforcement refers to major repairs aimed at improving bearing capacity, stiffness, ductility, or a combination of all the preceding, fairly extending the structure's lifetime. This approach is usually opted for if rehabilitation is technically and/or economically unfeasible, but high safety levels and/or new standards are to be met as soon as possible. Hence, structural reinforcement shapes up to be a bargain between maintenance and structural rehabilitation, thus providing reliable but not definitive solutions to secure existing tunnels.

Lining bolting

Tunnel lining bolting, through steel self-drilling or *Swellex*® anchors or fibreglass dowels, is usually adopted when tunnel lining is affected by deep deteriorations such as triggering potential block detachments. These can happen due to the aging of the lining materials, honeycombing, flaking, and exfoliation, as well as interconnected crack patterns shaping unstable wedges. The same technique may also be used to underpin tunnel abutments to control time-delayed convergence.

Fig. 11 illustrates two installations in Italian motorway tunnels. If Fig. 11a shows drilling operations in the Della Maddalena tunnel (Genoa, Italy), Fig. 11b presents a picture of a completed intervention in the Monte Baldo tunnel. In the latter case, this consists of the anchorage of the lining through *Swellex*® anchors and electro-welded steel wire meshes for finer concrete fragments.

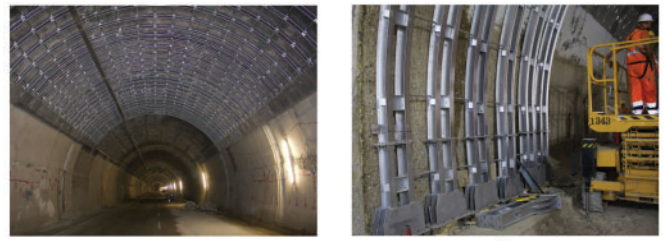
(a) (b)

Figure 11. (a) Drilling operations in the Della Maddalena tunnel and (b) a completed lining bolting intervention in the Monte Baldo tunnel

Steel rib reinforcement

As an alternative to bolting, steel ribs are also capable of providing additional reinforcement to tunnel structures to cope with local detachments or even significant strength losses. Based on the aging conditions of the lining, these may be either fixed on the tunnel wall through high-performance plugs or anchored to the surrounding ground through bolts. However, in critical situations, ground-footed solutions may be required. The latter should be preferred in the case of shallow tunnels where local lining detachments in soil masses may also induce sinkholes. Moreover, based on the relative stiffness with respect to the existing tunnel structure, size of the intervention along the tunnel development and interposition of waterproofing sheeting, ground-footed steel arching may also be intended and designed as a structural rehabilitation work.

Fig. 12 illustrates two examples from the Monte Baldo tunnel and the Pozzolatico tunnel (Florence, Italy), where dowelled (Fig. 12a) and ground-footed (Fig. 12b) steel ribs were respectively installed to address different degrees of deterioration of the tunnel lining.



(a) (b)

Figure 12. Installation of (a) dowelled steel ribs in the Monte Baldo tunnel and (b) ground-footed steel ribs in the Pozzolatico tunnel

Invert arch construction or reinforcement

Not infrequently, it may happen to chance upon tunnels with unlined inverts. Invert arches and base slabs react to lateral thrusts, which, otherwise, would provoke the lining to accommodate horizontal convergence and coherently develop intrados and extrados cracks at the springlines and the crown, respectively. The same, depending on the deterioration level and with different orders of magnitude, may happen when the invert is lined but the structural element is highly damaged. In such circumstances, a horizontal slab may be built and, eventually, underpinned[4] to strengthen the bearing system. In the presence of a structural element at the invert, the intervention is usually built above it and connected through metal pins.

Fig. 13 illustrates the works for the reinforcement of the invert arch carried out in the Bellosguardo tunnel (Florence, Italy).

Figure 13. Invert arch reinforcement works for the Bellosguardo tunnel (courtesy of Lapo Baccolini)

Fiber-reinforced material strengthening

Structural reinforcement is also achievable with Fiber-Reinforced Cementitious Matrices (FRCMs) or Ultra-High Tensile Strength Steel Fabrics (UHTSSFs). These represent compelling but flexible solutions able to increase the bearing

capacity of the tunnel lining (specifically tensile strength capacity) while preserving the clearance. To this end, however, the tunnel intrados should be roughened to guarantee the proper adhesion. Such high-strength materials may also be employed for systematic reinforcement of plain concrete linings against unexpected loads or seismic conditions. To this end, these would be arranged along the entire tunnel profile with regular strip distances and not only nearby defects.[50]

Fig. 14 shows the application of UHTSSFs in tunnels belonging to the Bologna-Florence stretch of the A1 motorway for corrective (Fig. 14a) and preventive (Fig. 14b) structural reinforcement of the lining.

(a) (b)

Figure 14. Installation of UHTSSFs in Bologna-Florence motorway tunnels for (a) corrective and (b) preventive structural reinforcement[50]

Rehabilitation interventions

Rehabilitation means major repairs planned to largely extend the designed tunnel service life with long-term interventions whose goal is the integral or partial replacement of single structural components or even the entire bearing system. Moreover, these may also be aimed at fulfilling new requirements due to recent in-force legislation and standards, for instance, about electrification lines, fire protection, safety equipment, etc.

When facing severe aging conditions spread along entire tunnel structures, cost-benefit analyses, as well as technical considerations, often prove that rehabilitation interventions represent the best alternative compared to numerous local repair works of a limited lifespan. As a function of the deterioration level, existing tunnel linings can be replaced to various extents, thus involving them whole or only partially. Partial replacement is preferred from the economic and safety points of view. Indeed, apart from the obvious economic benefits, limiting demolition thickness to the needed extent would allow the residual lining portion to join fibreglass dowels, usually employed as pre-consolidation, in acting as temporary support during demolition.[5] However, less invasive solutions affecting only the lining cortex, depending on the regular implementation along the tunnel development and the presence/absence of waterproofing sheeting, may also be utilized for structural reinforcement. The following briefly presents case histories from around the world.

Utilizing precast concrete elements for tunnel lining rehabilitation saves time, offers high-quality, durable components, and requires less maintenance compared to cast-in-place concrete.[51] Grossauer et al.[2] and Modetta et al.[52] reported on the development, testing, and implementation of the *Standard Tunnel Construction* method. This approach was developed in response to the urgent need to renovate centenarian Rhaetian Railway tunnels with longer-lasting and more reliable interventions than the *Gentle Repair* approach. The *Standard Tunnel Construction* method envisages the rehabilitation of existing tunnels with precast elements under continued operation through a mobile protective shield. Supporting the lining with hydraulic cylinders, this protects workers and passing trains from falling masonry. After being tested with positive results, the *Standard Tunnel Construction* method was implemented in the Glatscheras tunnel, as shown in Fig. 15a, and the Sasslatsch tunnel I (Grisons, Switzerland). Fortunato and Barbieri[3] reported that this approach was also used for enlarging the Mistail tunnel (Grisons, Switzerland). For all three, waterproofing was entrusted only to segment gaskets.

(a) (b)

Figure 15. (a) Precast segment installation in the Glatscheras tunnel[53] and (b) precast predalle positioning in the Colle Marino tunnel[6]

The thicker the lining depth to rehabilitate, the heavier the precast segments to handle through the tunnel safely. Contingent upon the machinery and the available underground space, this might represent a limit. For instance, Grossauer et al.[2] identified a limit of 5.2 t per segment during testing. To cope with this issue, precast arched predalles can be employed as disposable shuttering. Such structural elements have experienced widespread use in recent years in Italy. For instance, Agresti et al.[37] and Mazzola et al.[5] reported on the structural rehabilitation of, respectively, the Scampitella tunnel and the Colle Marino tunnel (Pescara, Italy) through arched predalles. In the former tunnel, three types of interventions, differing in terms of lining thickness and portions to rehabilitate, were designed based on the deterioration level. In the latter, instead, the complete replacement of the lining was planned for the entire tunnel length. Both tunnels were provided with waterproofing sheeting, as shown in Fig. 15b.

Alternatively, the rehabilitated tunnel lining can be cast in place. That is the case of the T3 tunnel (Bern, Switzerland), where partial structural rehabilitation took place.[54] The project envisaged equipping the structure with a groundwater collection system and replacing a 20 cm thick layer of the existing lining with an inner shell, as depicted in Fig. 16a. Furthermore, during the works, sprayed liquid and conventional synthetic waterproofing were tested. Despite the

former being initially preferred, the latter guaranteed better results and faster installation. A similar rehabilitation work, but using sprayed concrete, was experienced by the Manfreida tunnel (Genoa, Italy), as reported by Panebianco[6] and illustrated in Fig. 16b. The same concept was also revealed effective for masonry tunnels, such as the Brunel's Thames tunnel (London, U.K.), which was waterproofed and relined to accomplish new clearance requirements.[55]

(a) (b)

Figure 16. (a) Modified shuttering used for T3 tunnel rehabilitation[54] and (b) shotcreting of the Manfreida tunnel[6]

Special mention, in terms of material choice, technique adopted, and/or underlying motivations, goes to Broch et al.,[46] Burgess et al.,[10] Warren and Tromans,[43] and Bowers and Moss.[56] As stated above, Broch et al.[46] illustrated the NPRA solutions to cope with the icing risk in existing tunnels. For high-traffic tunnels, options envisaging the interposition of an insulation membrane behind a cast-in-place or precast concrete inner lining were implemented, as shown in Fig. 17a. Thereafter, the *Ekeberg* solution came. Combining precast elements at the springlines and sprayed concrete along the crown allows for cutting the construction time, thus costs, and withstanding high vehicle loads due to impacts at the bottom of the vault. At the time of the reference, 9 Norwegian tunnels with an overall length of about 13 km underwent the same structural rehabilitation work just outlined.

(a) (b)

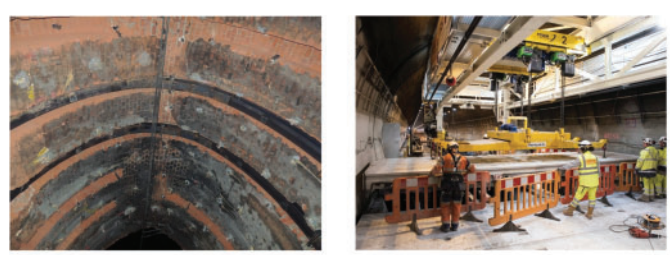
Figure 17. (a) Insulation of the Porsgrunn tunnel[57] and (b) train-mounted segment erector used in the Jubilee line[56]

Burgess et al.[10] and Bowers and Moss[56] discussed two similar applications to the London Underground, Northern and Jubilee lines, respectively. Both rehabilitation plans envisaged the existing lining replacement through metal segments. However, whether in the former, duplex stainless steel was selected to cope with corrosion from acids; in the latter, bolted spheroidal graphite iron segments were used to deal with difficult geological conditions posed by shrinkable clays. Heating and ventilation due to train service accelerated clay desiccation, thus provoking a reduction of ground support to the original concrete ring over time. For both, most of the work was performed during night shifts, but for the Jubilee line, the original plan was sped up thanks to the use of two train-mounted segment erectors, one of which is shown in Fig. 17b.

Also, Warren and Tromans[43] chronicled the rehabilitation of two British tunnels. Higham and Strood (Rochester, U.K.) are centenarian Victorian tunnels built among 1819 and 1824 and rehabilitated in 2004 after several flooding events following sustained periods of heavy rainfall and chalk falls. The rehabilitation projects envisaged, among other things, lining the unlined sections (62% and 25% of Higham and Strood tunnels, respectively), brickwork repairs where required, and the installation of a drainage system. These were carried out through protective canopies, marking the operation time. Indeed, the new bearing system foundations were cast ahead of the canopy, the tunnel wall secured from beneath it and the concrete lining built behind it.

As for the Higham and Strood tunnels, the Bricchetto tunnel (Asti, Italy) is a centenarian railway tunnel that only underwent structural rehabilitation in 2014.[4] This was a masonry tunnel with an unlined invert whose rehabilitation plan envisaged the construction of an underpinned "U"-shaped invert arch acting as a strut against horizontal convergence. For this purpose, a precise staggered pattern of masonry demolition and concrete casting was followed to ensure safety and avoid local instabilities. Then, as depicted in Fig. 18a, the existing vault was partially hydro-demolished, shaping accommodations for steel ribs made monolithic with the masonry lining through shotcrete.

Despite being less common, rehabilitation interventions may only affect invert arches or base slabs. This is the case of the Mont-Blanc tunnel, where the base slab was renewed over a 555 m section in the center of the tunnel.[58] Structural rehabilitation works were only handled during night shifts using custom-designed ready-for-use lifting gantries able to deal rapidly with slab loading, transportation, and unloading (Fig. 18b). To expedite the process, precast concrete male/female shear key slabs were used, thus ensuring easy-to-make and safe connections between adjacent ones. Such rehabilitation may also be carried out when only roadbed or track lowering is pursued.



(a) (b)

Figure 18. (a) Steel ribs accommodation in the Bricchetto tunnel[59] and (b) slab installation in the Mont-Blanc tunnel[58]

Upgrading interventions

Upgrading involves major repairs intended for either structural rehabilitation or in-force legislation meeting or the fulfilment of new requirements due to upgrades in the intended use of tunnels. This proves necessary whenever a network capacity improvement is needed (e.g., the ever-growing demand for transportation leads to the quick obsolescence of tunnels) and new bore excavation is unfeasible for a list of reasons (economic, technical, increasing environmental sensitivity, etc.).

Upgrading interventions always involve enlarging the original size of underground structures. To this end, different techniques can be adopted depending on the ground typology, the need to keep service, and the standardization of the machinery to employ.[11,59] From the perspective of closing the traffic lines, tunnels may be conventionally or mechanically re-bored. However, this rarely fits with the will of owners and/or concessionaires. Indeed, stopping major traffic lines affects the economy and society of the served area. Hence, several approaches to allow tunnel enlargement during continuous traffic have been developed. With this aim, traffic is always protected by purpose-built movable steel shields or the existing linings. In the following, case histories from all over the world will be briefly illustrated.

Being the eldest ones, thereby designed for traffic levels of yesteryear, masonry tunnels usually undergo upgrading. Among others, Gall et al.[55] and Zeidler et al.[8] made some pioneering work in this sense regarding the Berry Street tunnel (Pittsburgh, Pennsylvania) and the Bergen tunnels (Jersey City, New Jersey). After almost 40 years of closure, the former was reopened to host a new busway connection. After rock bolting and shotcreting where needed, the existing horse-shoe brick-lined tunnel was enlarged into a circular concrete-lined one, passing from around 8 m width to 12 m diameter (see Fig. 19a). Compliant with the technology of the time, the Berry Street tunnel was provided with waterproofing and ventilation systems. The latter, analogously, were upgraded to improve the clearance gauge and safety, threatened by water leakages and ice accumulation during winter.

(a) (b)

Figure 19. (a) Berry Street tunnel enlargement[55] and (b) concrete-filled section of the Grazia Bassa tunnel[61]

Years later, the same fate met the Grazia Bassa tunnel (Genoa, Italy), which, as for the two case histories above, was enlarged for transportation purposes through conventional excavation technique.[61] In this case, pre-consolidation works were performed along the entire tunnel development since the tunnel intercepted a weak rock formation. For safety reasons, at the most critical points, the Grazia Bassa tunnel was even filled with lightweight concrete and then dug from scratch (see Fig. 19b). This approach, but with a different technique, was adopted for the narrower Farnworth tunnel (Manchester, U.K.) tube.[62] Indeed, after filling the bore with 7500 m of foamed concrete, this was re-bored with a Tunnel Boring Machine (TBM).

Tunnel closure was allowed in Berry Street, Bergen, and Grazia Bassa tunnels. As previously remarked, this is rarely possible except for critical cases (e.g., the Grazia Bassa and Farnworth tunnels extended close to other railway and motorway facilities) and already disused tunnels (e.g., the Berry Street tunnel remained unused for several years). Most often, during enlargement works, full, at most reduced, traffic capacity must be ensured and, consequently, the necessary safety level for customers. To overcome this specific challenge, a mechanized approach is usually preferred, thus employing Tunnel Enlargement Machines (TEMs). Despite technology differing based on the specific applications, these generally consist of a front shield preventing the existing lining from breaking, one or more central units containing the equipment for demolition, pre-consolidation and relining and a rear unit transporting supply devices, such as hydraulic, power, and ventilation units.

For instance, TEMs were successfully used to upgrade, thus meeting modern requirements for rail traffic, the Gaintxurizqueta, Loyola and Capuchinos tunnels in San Sebastian, Spain[63] and the Kuckuckslay tunnel in Cologne, Germany.[12] Whether, in the former cases, demolition and excavation were carried out through hydraulic breakers, in the latter, explosives were used according to the *Tunnel-in-Tunnel* method. The TEMs employed are shown in Fig. 20.

(a) (b)

Figure 20. TEMs used for the (a) Gaintxurizqueta, Loyola, and Capuchinos tunnels[63] and (b) Kuckuckslay tunnel[12]

In the field of concrete-lined tunnels, the examples are fewer but equally virtuous and, probably, more peculiar. The Shikishima tunnel (Hokkaido, Japan) underwent enlargement operations to double the cross-sectional area, thus accommodating a larger volume of vehicles.[64] The upgrading plan envisaged the portals to be rebuilt through the cut-and-cover technique and the central portion to be repoured on site with a longitudinally movable and transversally expandable shield. Such features allowed traffic regulation so that this would have been folded while working and unfolded during work shifts, thereby permitting halved and full traffic capacity, respectively. During competent rock excavation

through explosives, traffic was temporarily prohibited. The works lasted 5 months, reaching an average advancement rate of 1 m per day.

To deal with softer grounds, Maeda and Takatsuji[65] and Honda et al.[66]) patented the so-called *Enlargement Shield Tunnelling* method. This envisages enlarging tunnel cross-sections by means of two main machines: the circumferential shield machine and the enlargement shield machine (see Fig. 21a). After stabilizing the surrounding ground through chemical grouting, the starting base for the circumferential shield machine is excavated. To this end, a square dugout is realized directly beneath the tunnel. Starting from here, the machine is driven through guiding rods carved in the existing lining to widen the excavation behind it and install concave segments. Starting from there, the first existing ring is demolished, and, in the gained over space, the enlargement shield machine is assembled. This has an annular structure, which allows over-excavating behind the existing tunnel structure and installing a new lining. Water inflows, if any, are handled by pneumatically applying pressure on the excavation boundary. Such upgrading work was applied in the Minamisenju utility tunnel (Tokyo, Japan) and other tunnels around Japan.[66]

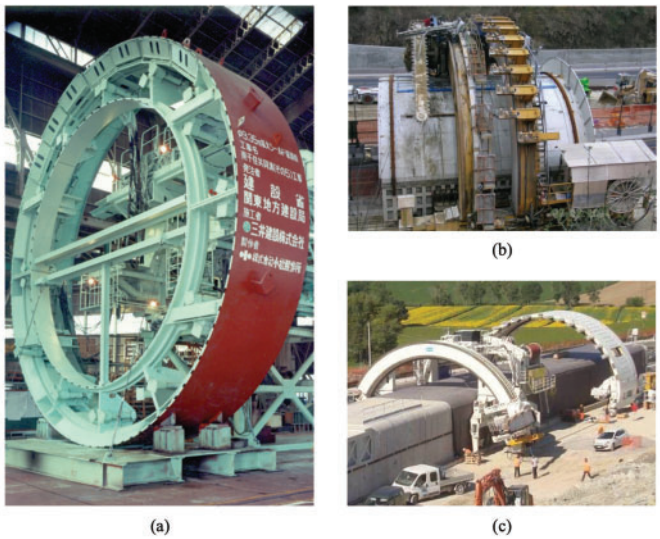


Figure 21. (a) Enlargement shield machine used for the Minamisenju tunnel,[66] (b) multipurpose excavation machine used for the Nazzano tunnel,[67] and (c) mechanical pre-cutting and segment erection machines used for the Montedonimi tunnel[68]

The main drawback of the above technology is the impossibility of traffic transit during enlargements. In this sense, the Italian experience led by Lunardi et al.[67,67]) has been pioneering worldwide with the enlargement of the Nazzano (Rome, Italy) and the Montedomini (Ancona, Italy) tunnels. Based on the application (the first numbers refer to Nazzano and the second ones to Montedomini), after surrounding ground improvement through precut technology and, where needed, jet-grouting for a length of 4.5–6 m, a cyclic alternation of excavation rounds of 1–2 m and precast segmental arch erections was carried out until an advancement of 3–4 m was reached. The experience gained during the Nazzano tunnel enlargement was key to improving the machinery. Indeed, while, in the former case, a multipurpose machine (see Fig. 21b) able to either precut or erect segments was used, in the latter, two different machines (see Fig. 21c) were built. This aspect was revealed to be paramount in terms of downtime alternation for maintenance purposes.

Comparative Technical Assessment and Selection Criteria for Refurbishment Interventions

Whereas, in most maintenance works, a direct correspondence can be established between an identified defect and the corresponding repair works, the same relationship does usually not apply to structural reinforcement or rehabilitation and upgrading interventions. In such cases, the most appropriate intervention results from the combination of multiple technical, operational, and contextual factors, none of which is individually decisive.

Tunnel dimension and geometry influence the feasibility of certain types of interventions, as restricted cross-sections limit the size and weight of elements that can be handled and installed. Clearance gauge requirements may further impose stricter limits on the inward encroachment of additional lining thickness, in some cases ruling out otherwise structurally advantageous solutions. Lining typologies also directly affect the material compatibility, demolition techniques, and structural interaction between existing and new bearing systems.

The current stress state of the existing lining becomes critical whenever demolition induces stress redistribution across the structural elements, as inadequate phasing may trigger local instabilities. This aspect may be less demanding in case of integral demolition, provided that surrounding ground stability is appropriately ensured through pre-consolidation. Consequently, the hydrogeological context also plays a fundamental role: ground characteristics influence the stress regime of the lining, while water inflows or persistent infiltrations highlight the need for a waterproofing system setup.

Finally, traffic disruption constraints are often the most binding operational parameters. The requirement to maintain traffic, even at reduced capacity, or to complete refurbishment within limited time windows tends to favor faster and ease-to-deploy solutions, whereas full tunnel closure can allow a broader range of options to be considered. The spatial extent of interventions may further condition the overall technical and economic viability.

Table 2 provides a comparative overview of the principal refurbishment interventions discussed in the previous sections, outlining their typical fields of applicability based on specific technical and operational criteria.

Table 2 condenses the information and analysis developed throughout Subsections 3.1 to 3.4 into a comparative decision framework. Rather than ranking interventions hierarchically, the table highlights their compatibility with

Table 2. Field of applicability for refurbishment interventions (modified and implemented from Panebianco[6])

Refurbishment intervention	Tunnel geometry and dimension		Clearance gauge requirements		Lining typology and materials			Stress regime of the lining		Geological context		Hydrological context		Traffic disruption		Frequency or extent	
	Na	Wi	Y	N	C	M	RC	H	L	R	S	D	W	T	P	Di	Lo
Maintenance works																	
Securing the intrados	+	+	+	+	+	○	+	+	+	+	+	+	+	+	+	+	+
Crack stitching	+	+	+	+	+		–	+	+	+	+	+	–	+	+	○	+
Cavity filling	+	+	+	+	+	–	+	○	+	+	○	+	○	+	○	○	+
Corrosion protection or substitution of steel rebars	+	+	+	+	–	–	+	–	+	+	+	+	○	○	+	–	+
Groundwater drainage	+	+	○	+	+	+	+	+	+	+	+		+	+	+	+	+
Waterproofing the intrados	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+	+
Masonry interventions	+	+	+	+		+		○	+	+	+	+	–	+	+	○	+
Structural reinforcement																	
Lining bolting	○	+	+	+	+		○	○	+	+	+	+	○	+	○	○	+
Steel rib reinforcement	○	+	–	+	+	+	+	+	+	+	+	+	○	+	–	+	○
Invert arch construction or reinforcement	+	+	○	+	+	+	+	○	+	+	+	+	+	+	○	+	○
Fibre-reinforced material strengthening	+	+	+	+	+	○	+	+	+	+	+	+	○	+	+	+	+
Rehabilitation interventions																	
Integral replacement with cast-in-situ concrete	+	+	+	+	+	+	+	○	+	+	○	+	+	+	–	+	–
Partial replacement with precast concrete elements	○	+	+	+	+	○	+	+	+	+	+	+	+	+	–	+	○
Partial replacement with cast-in-situ/sprayed concrete	+	+	+	+	+	○	+	+	+	+	+	+	+	+	–	+	○
Partial replacement with metal segments/plates	+	+	○	+	+	○	+	+	+	+	+	+	○	+	–	+	○
Upgrading interventions																	
Tunnel enlargement via conventional re-boring	+	+	+	+	+	+	○	○	+	+	○	+	+	+	–	+	○
Tunnel enlargement through TEMs	+	○	+	+	+	+	○	+	+	○	+	+	○	+	○	+	–

Note: + = Applicable; ○ = Applicable with limitations; – = Not applicable; Na = Narrow; Wi = Wide; Y = Yes; N = No; C = Concrete; M = Masonry; RC = Reinforced Concrete; H = High; L = Low; R = Rock; S = Soil; D = Dry; W = Wet; T = Total; P = Partial; Di = Distributed; Lo = Localised.

a set of governing technical and operational parameters, including structural requirements, environmental conditions, geometric constraints, and service continuity demands.

Maintenance works generally prove suitable for localized defects regardless of tunnel dimension and geometry, yet their applicability diminishes when deterioration becomes widespread, as maintenance interventions are inherently limited in scope, structural impact, and frequency of application. Conversely, rehabilitation and upgrading interventions become more and more technically and economically justified when deterioration is widespread, extends over notable tunnel length, and performance deficiencies affect the structure globally. This confirms the progressive logic introduced at the beginning of Section 3: as the performance level declines and deterioration becomes systemic, increasingly invasive and structurally transformative measures are required.

The hydrogeological context also exerts a decisive influence. In wet conditions, drainage and waterproofing systems gain particular relevance, while certain structural reinforcement techniques may prove challenging to execute or require further preventive measures to ensure long-term durability. For instance, reinforcing tunnel lining through bolting involves drilling operations that can prove challenging under significant groundwater pressure, while even the mere presence of water inflows or surface humidity may compromise the adhesion of composite materials to the tunnel intrados. In competent rock masses, where lining deterioration is typically non-evolutive or advances slowly and remains largely independent of the stress state, a broader range of strategies remains technically viable. In soils associated with a wider range of stress regime of the linings based on the overburden, greater caution is required during both design and execution: steel ribs in shallow tunnels, for instance, must be designed not only to reinforce the existing structure but also to sustain potential sinkhole formation, while full lining replacement should generally be preceded by extensive pre-consolidation.

Stress regimes of tunnels may be critical if partial demolition of the lining triggers stress redistribution phenomena potentially leading to local collapses, unless adequate preconsolidation is ensured and a proper staged demolition sequence is designed. With regard to lining material, plain concrete linings are compatible with the broadest range of refurbishment options. Reinforced concrete linings introduce constraints during demolition, where hydro-demolition is mandatory in place of milling. Masonry linings, on the other hand, demand careful preliminary assessment of their overall condition, as, for instance, drilling operations or any intervention that perturbs the static equilibrium of the structure may pose significant risks.

The need to maintain traffic, even at reduced capacity (with partial closures or night shifts), strongly favors precast, sprayed, or mechanized solutions over conventional approaches. On the contrary, where full closure is permissible, a broader range of technically optimal but operationally disruptive interventions becomes feasible. Tunnel geometry and available clearance also directly affect feasibility, limiting the use of thick inner linings in narrow bores.

While the selection of a refurbishment strategy is ruled by the contextual and operational parameters discussed above, its effectiveness ultimately depends on the type and severity of the defect being addressed, as the same technique may prove decisive in one scenario and entirely inadequate in another. Table 3 provides a defect-oriented complement to the applicability-based framework of Table 2, mapping the principal refurbishment interventions against the most typical deterioration typologies encountered in existing tunnel linings.

Maintenance is inherently suited to structurally shallow and localized defects, with each technique targeting a specific and well-defined deterioration mechanism. Securing the intrados provides immediate containment against light detachments and shallow lining deterioration, without any structural ambition. Crack stitching effectively arrests sporadic cracking (e.g., shrinkage-induced) and seals preferential water paths, though its effectiveness diminishes when cracking is persistent, as the underlying structural cause remains unaddressed. Cavity filling targets lining anomalies and ground voids, with effectiveness in the latter case depending on cavity geometry and extent. Drainage systems prove notably effective against active dripping, where pressure relief is paramount, whereas intrados waterproofing better suits damp conditions with diffuse infiltrations, avoiding the development of ice in cold climates. Corrosion protection or substitution of steel rebars applies exclusively to reinforced concrete linings (being irrelevant for both masonry and plain concrete tunnels, as shown in Table 2). Masonry interventions (confined to their respective lining typology as shown in Table 2) are principally effective against localized deterioration of and/or cracking along mortar beds, exfoliation, and chemical degradation in masonry tunnels.

Structural reinforcement interventions address defects of greater severity and structural implication. Lining bolting is effective against detachment-driven instabilities to provide active or passive restraint. Additionally, steel rib reinforcement also addresses deterioration-induced defects across a range of severities and, when ground-footed, provides an effective response to significant local strength losses in the lining. Notably, both lining bolting and steel rib reinforcement are frequently implemented in combination with maintenance works (e.g., intrados wire meshes, drainage systems, or ground cavity filler) to enhance the overall effectiveness of the repair and to address multiple concurrent defects that commonly coexist in deteriorated tunnel linings. Invert arch construction or reinforcement is specifically suited to structural deficiencies at the base of the structure, while fiber-reinforced material strengthening proves effective for cracking and shallow deterioration requiring tensile capacity enhancement but may become ineffective as the severity of defects increases.

Rehabilitation and upgrading prove consistently effective across a wide range of defect categories, including also shallow and localized ones, yet the associated technical and economic effort renders them disproportionate and unjustifiable outside the most severe deterioration scenarios. The same applies to enlargement techniques through both conventional reboring and TEMs, even if their implementation is almost exclusively driven by capacity or clearance requirements, being unrelated to deterioration-driven defects.

Overall, Tables 2 and 3 together offer a tool for the preliminary comparative assessment of refurbishment interventions, the former from an applicability-based standpoint, the latter from a defect-oriented perspective, to be complemented by detailed structural, cost-benefit, and risk assessments in the subsequent design stages.

Innovative Techniques for Tunnel Refurbishment

In recent years, Building Information Modelling (BIM) and Artificial Intelligence (AI) have gained huge momentum in the field of tunnel refurbishment. On the one hand, BIM represents an innovative process for managing and storing different kinds of data on physical assets throughout their life cycle. On the other hand, AI is a powerful and versatile tool that takes advantage of the brute computational power of modern computers to carry out detection, classification, or even decision-making activities.

BIM technology solves problems related to fragmentation and decentralization of data, thus allowing for a collaborative and efficient workflow that addresses not only design and construction stages but also operation, maintenance, and possibly demolition.[69] Zhou et al.,[70] for instance, considered the Shigu tunnel case history (Baoji, China) whose design envisaged the generation of a 3D BIM model including geometrical, design, operational data, and other information. This was particularly beneficial during the operational stage to simulate emergency-saving cases and organize ventilation and personnel evacuation. Yin et al.[71] developed a BIM-based framework for the operation and maintenance of utility tunnels. Data stored in a BIM

Table 3. Refurbishment interventions for most of the typical defects in existing tunnels

Refurbishment intervention	Deterioration of the lining		Water-related deteriorations		Voids or anomalies		Local detachments		Intense cracking		Steel rebar corrosion
	D	S	Dr	Da	Gr	Li	H	L	Pe	Sp	
Maintenance works											
Securing the intrados	–	+	–	–	–	–	–	+	–	–	–
Crack stitching	–	–	–	–	–	–	–	–	○	+	–
Cavity filling	–	–	–	○	+	+	–	–	–	–	–
Corrosion protection or substitution of steel rebars	–	–	–	–	–	–	–	–	–	–	+
Groundwater drainage	○	–	+	+	–	–	–	–	–	–	–
Waterproofing the intrados	–	–	○	+	–	–	–	–	–	–	–
Masonry interventions	○	+	–	–	–	–	–	+	○	+	–
Structural reinforcement											
Lining bolting	○	–	+*	+*	+*	+	+	–	–	–	–
Steel rib reinforcement	+	+	+*	+*	+*	+	+	+	○	–	–
Invert arch construction or reinforcement	+	+	–	–	–	–	–	–	–	–	–
Fiber-reinforced material strengthening	–	+	–	–	–	–	–	+	○	+	–
Rehabilitation interventions											
Integral replacement with cast-in-situ concrete	+	+	+	+	+	+	+	+	+	+	+
Partial replacement with precast concrete elements	○	+	+	+	○	+	+	+	+	+	+
Partial replacement with cast-in-situ/sprayed concrete	○	+	+	+	○	+	+	+	+	+	+
Partial replacement with metal segments/plates	–	+	+	+	○	+	+	+	+	+	+
Upgrading interventions											
Tunnel enlargement via conventional reboring	+	+	+	+	○	○	+	+	+	+	+
Tunnel enlargement through TEMs	+	+	+	+	○	○	+	+	+	+	+

Note: + = Effective; +* = Effective in combination with proper maintenance works; ○ = Conditionally effective; – = Ineffective D = Deep; S = Shallow; Dr = Dripping; Da = Damp; Gr = Ground; Li = Lining; H = Heavy; L = Light; Pe = Persistent; Sp = Sporadic.

model was shared in real-time with maintenance and management personnel, thus allowing for more cost-effective management decisions. In Italy, Ciccone et al.[72] dealt with the digitalization of the existing Cancello-Benevento railway line, including the informatization of six different tunnels. This was paramount for supporting the decision-making process and assisting management, operation, and maintenance of the assets. However, the BIM potential does not stop here: Alsahly et al.,[73] indeed, developed a BIM-to-FEM approach that allows producing a Finite Element Method (FEM) model starting from a cross-sectional view of the BIM leading to the development of a tunnel digital twin. Despite being applied for predicting the surface subsidence during mechanized tunnelling at the design stage, this may also be revealed as an interesting and effective feature to examine the evolution of the behaviour of tunnels in time to schedule refurbishment activities.

Conversely to BIM, AI addresses a larger variety of issues depending on the versatility and complexity of the algorithm implemented. For instance, Ahmed et al.[74] tested diverse models to forecast the deterioration of existing tunnels starting from geometrical, construction, and operational information, reaching accuracies of 80%. Schneider et al.[75] and Panella et al.,[76] instead, tested two BIM-compatible systems for automatic defect detection. In both cases, an overall time saving of around 30–60% was experienced, with a noteworthy time and personnel reduction during surveys of 90% and 50%, respectively. Focusing only on cracks, Protopapadakis et al.[77] and O'Brien et al.[78] used Deep Learning (DL) and Convolutional Neural Networks (CNNs) to automatically spot their presence on the tunnel lining. Furthermore, in the latter case, the detected cracks were also classified among four categories (vertical, horizontal, diagonal, and complex), achieving accuracies of 98.4% and 92.3% for the detection and classification tasks, respectively.

The growing trend towards BIM and AI usage in tunnel refurbishment is a symptom that the current modus operandi, made up of human-based visual inspections and manual defect detection, will soon be replaced by automated systems. Besides being a time- and resources-consuming operation, the current process is also prone to inherent limitations such as human subjectivity or lack of repeatability. To achieve an objective and consistent outcome, Protopapadakis et al.[77] and Foria et al.[79] developed and tested the ROBO-SPECT (Fig. 22a) and ARCHITA (Fig. 22b) robotic platforms for automatic inspection of existing tunnels. Whereas the former appears as an intelligent device able to detect and localize cracks in real-time through AI, the latter is a multi-dimensional mobile mapping system consisting of linked and integrated equipment (linear and thermal cameras, laser scanner sensors, georadar, etc.) aimed at retrieving as much data as possible to post-process at a later time. This approach proved considerable advantages in terms of time and cost reduction and improved resource management. More recently, Chen et al.[80] proposed an autonomous mobile robotic system for in-process tunnel lining deformation detection during construction, integrating high-precision laser and compensation algorithms to achieve high accuracy even under complex site conditions.

(a) (b)

Figure 22. (a) ROBO-SPECT[77] and (b) ARCHITA[81] robotic platforms for tunnel inspection

In parallel, drone-based inspection strategies are gaining relevance. Among others, Bendris and Cayero Becerra[82] highlighted the potential of aerial platforms equipped with vision- and thermal-based sensors for rapid, noncontact tunnel assessments, particularly in hard-to-access areas, thus expanding the operational flexibility of automated inspection technologies.

Analogous to inspection methodologies, BIM and AI are also influencing the way of conceiving refurbishment, which is currently intended as either corrective or preventive. Whether the corrective approach consists of restoring the operability of a system once a defect or failure has occurred, the preventive one aims at preserving its service life by anticipating any impending problems. However, the current race for informatization and automation is paving the way to predictive refurbishment. In line with recent advancements in AI- and BIM-based real-time monitoring frameworks (Afrazi et al.[83] among others), this approach relies on continuous data acquisition, sensor integration, and data-driven analytics to support proactive decision-making. It enables a wiser management of material and personnel resources, as refurbishment activities are deferred in time until they are actually required, thereby optimizing intervention procedures. To this end, incipient faults should be detected, identified and tracked until an acceptable and a priori established level of degradation and then the refurbishment strategy activated.

Yuan et al.[84] differ between two types of predictive refurbishment, namely, condition-based maintenance (CBM) and prognostics and health management (PHM). CBM utilizes data-driven or physics-based reliability models to predict the residual service life and the extent of refurbishment to perform. PHM, instead, uses high-frequency monitoring systems for real-time performance diagnostics. Regardless of the type, the predictive approach aims at evaluating the residual useful life of a system or a part of it. For instance, Han et al.,[85] considering a physics-based CBM approach based on tunnel lining aging due to carbonation penetration and chloride erosion, evaluated a probabilistic-based maintenance strategy that accounted for different failure modes. Farahani et al.,[86] instead, proved through small-scale laboratory testing how existing tunnels may extremely benefit from the PHM approach.

Recent and more operation-oriented applications have been proposed by Bellini Machado and Massao Futai,[87] Vollmann et al.[88] and Khan.[89] From a degradation modelling perspective, Bellini Machado and Massao Futai[87] developed an inspection digital twin for a railway tunnel in Northern Brazil, coupled with serviceability indices to quantify structural deterioration and support predictive refurbishment planning. These indices are derived from visual inspection data transformed into service-level indicators, which are subsequently used to calibrate stochastic degradation models aimed at estimating target refurbishment times and optimizing management during service. Vollman et al.[88] developed a BIM-based methodology supporting predictive operation and refurbishment for German road tunnels. This approach couples static inspection logs and dynamic real-time monitoring data, pays particular attention to data interoperability, and applies AI-based defect recognition to support lifecycle-oriented decision-making. Khan,[89] instead, advanced a data-driven digital-twin framework integrating BIM, monitoring systems, and facility management

databases, using AI algorithms to predict component-level asset states and generate refurbishment actions.

Alongside digitalization and automation, an emerging research frontier in the sustainable refurbishment of existing tunnels is energy retrofitting,[26,89] a concept that broadens the traditional role of underground transport infrastructure by enabling tunnels to function not only as mobility assets but also as systems capable of generating, storing and, where feasible, efficiently utilizing renewable geothermal energy. Within this perspective, tunnels are reconceptualized as thermo-active infrastructures, i.e., energy geostructures,[91,92] able to harness ground-trapped thermal energy that would otherwise remain unexploited and, potentially, interacting with surface thermal energy grids.[93,94]

Energy retrofitting entails instrumenting existing tunnels for heat exchange, either for direct exploitation or for cyclic storage. Energy retrofitting is conceived to be implemented along with scheduled rehabilitation and upgrading interventions or functional repurposing activities, thereby minimizing additional construction impacts and costs. In this context, De Feudis[90] introduced a comprehensive and systematic framework for transforming existing tunnels into energy geostructures through the installation of geothermal piping. The framework encompasses 6 different energy retrofitting solutions, specifically conceived to fit several decay contexts and diverse levels of refurbishment necessity, spanning from minimally invasive options for tunnels requiring limited intervention to highly invasive configurations fully integrated within major structural repair works. In addition, De Feudis[90] assessed the economic attractiveness of such an approach through an LCOE analysis, demonstrating high profitability with representative LCOE values of around 100 €/MWh$_t$. In this regard, the Olimpia tunnel in Italy,[15] illustrated in Fig. 23, represents the first documented worldwide example of an existing tunnel instrumented for geothermal heat exploitation while simultaneously undergoing structural rehabilitation, marking a significant milestone in the advancement of sustainable underground infrastructure refurbishment.

Figure 23. Energy retrofitting of the Olimpia tunnel

Conclusions

This paper has offered a state-of-the-art review of current practices, regulatory frameworks, and technological developments in the refurbishment of existing tunnels, with particular focus on established maintenance, structural reinforcement, rehabilitation and upgrading techniques, as well as emerging digital tools supporting lifecycle management of the assets.

Such a review is based on the authors' experience in the field, published literature, technical guidelines, and documented case studies, which, while offering a broad international perspective, may not fully capture unpublished operational data and performance records or region-specific practices. Owing to the authors' background, a non-negligible proportion of the detailed case studies refers to Italian applications. This may introduce a degree of geographical imbalance; however, it also represents a strength, as several of these examples derive from direct technical involvement and first-hand knowledge rather than exclusively from secondary sources. In addition, emerging technologies such as BIM-integrated asset management, AI-supported inspection, and energy retrofitting are, in several cases, at varying stages of implementation, with long-term validation data still limited. Within these boundaries, and based on the synthesis of international experiences and methodological advancements, the main conclusions can be drawn as follows.

- Tunnel refurbishment worldwide is converging toward structured, risk-based methodologies, where inspection frequency, defect classification, and refurbishment prioritization follow codified practices aimed at ensuring consistent performance, safety, and regulatory compliance over service lives.
- Maintenance works, although essential for stabilizing degradation and preserving short-term safety, generally constitute temporary measures that require long-term planning of structural reinforcement or rehabilitation to achieve sustainable performance recovery.
- Structural reinforcement offers substantial improvements in load-bearing capacity while maintaining service continuation, thus serving as an effective intermediate strategy between local maintenance actions and full-scale rehabilitation.
- Rehabilitation interventions enable comprehensive and durable renewal of aging tunnel structures and their adoption is increasingly guided by cost–benefit analyses, operational constraints, and the opportunity to integrate modern waterproofing, safety, and functional upgrades.
- Upgrading interventions reflect noteworthy technological progress, especially through mechanized enlargement and shield-based methods that permit complex works under traffic, thereby limiting disruptions in increasingly capacity-constrained transport networks.

- BIM and AI are increasingly becoming key for integrating asset information, improving inspection objectivity, and supporting decision-making; when combined with robotic inspection platforms, they offer large gains in survey efficiency, defect detection accuracy, and worker safety. Future research on BIM should concentrate on the development of integrated, all-in-one BIM infrastructures capable of managing tunnel assets throughout the entire lifecycle, from design and construction to management, including the implementation of BIM-to-FEM interoperability to design refurbishment interventions. This BIM-to-FEM integration represents a promising research direction that could be extended beyond tunnels to bridges, viaducts, and other infrastructures, linking digital asset information with structural analysis, condition assessment, and refurbishment decision-making. With regard to AI, the next logical step would be the development and validation of fully autonomous robotic inspection systems capable of navigating tunnel environments, performing real-time defect detection, and directly updating BIM models with minimal human intervention.
- The transition toward predictive refurbishment, empowered by monitoring systems, data analytics, and model-based performance forecasting, provides a promising opportunity for optimizing resource allocation and extending tunnel service life. Further investigations should aim at integrating long-term monitoring data with probabilistic deterioration models, defining threshold-based intervention criteria linked to measurable performance indicators, and validating them in diverse geological and structural contexts.
- Energy retrofitting is emerging as a viable complement to conventional refurbishment interventions, enabling existing tunnels to be converted into energy geostructures while undergoing rehabilitation, upgrading, or repurposing, thereby enhancing the sustainability and life-cycle performance of tunnel assets. As the Olimpia tunnel currently represents the only documented worldwide application, future research should prioritize replicating and adapting this framework across diverse geographical, geological, climatic, and regulatory contexts, alongside developing novel solutions to support a range of refurbishment scenarios, as well as on the integration of such multi-purpose tunnel assets within dense urban environments, where it can function as both thermal energy exploitation and storage facilities. Particular attention shall be devoted to their effective connection with district heating and cooling networks in order to quantify and maximize their potential contribution to reducing urban carbon emissions.

Acknowledgements

The authors gratefully acknowledge the support of the *Autostrade per l'Italia* Group for co-funding the PhD scholarship of Simone De Feudis, which led to this work, and Lapo Baccolini (*Tecne S.p.A.*) and Alessandro Tonghini (*Autostrade per l'Italia S.p.A.*) for kindly providing some of the images used in the article.

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