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Tunnel assessment: The Italian case

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ABSTRACT: The age of the infrastructures and the ever-increasing levels of traffic make it necessary to deal with the problem of safety of the structures with the greatest rigor, by fully reviewing the methods of inspection, investigation and intervention adopted up to that moment. This article illustrates the experience gained by Rocksoil company on the tunnels of the Italian motorway network by proposing a new methodological approach that starts from an in-depth knowledge of the tunnel and its history and evaluates its state of consistency through a detailed inspection and a series of supportive diagnostic investigations. After complete defect identification and cataloging, the interventions aimed at re-establishing the safety conditions are planned and subsequent checks and monitoring are defined in order to verify their duration over time.

1 INTRODUCTION

Given the geomorphological conformation of the Italian peninsula, the national motorway network has more than 350 km of tunnels, built from the 1930s to the present day. In particular, from the post-war period up to the 1980s, over 400 tunnels were built for almost 200 km, which, according to the construction techniques of that time, did not provide for the adoption of waterproofing systems. Starting from January 2020, a half of this important component of the heritage of Italian tunnels has been under a systematic assessment process aimed at verifying and guaranteeing the safety conditions of these dated works. In about 18 months, concrete lining tunnels, measuring almost 100 km in total, were inspected. The inspections were then followed by a phase of analysis of the encountered problems, deepened thanks to a series of diagnostic and instrumental investigations. Thanks to an accurate cataloging of defects and their subdivision into categories, it was therefore possible to plan typological safety measures, which were promptly applied.

This article aims to illustrate the new methodological approach proposed for the assessment of tunnels, which consists of 4 sequential phases: investigative, diagnostic, therapy and monitoring phases.

The development of this methodology, perfected by Rocksoil company together with two other Italian design companies, Lombardi Ingegneria and SWS Engineering, was coordinated by Rocksoil and validated by the "Politecnico di Torino" University (Barla M. et al. 2021). This new approach finally merged into two official documents issued by Italian Infrastructure Ministry addressed to road infrastructure managing institutions, becoming the reference guideline at the national level (Italian Infrastructure Ministry 2020, 2021).

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2 THE NEW METHODOLOGICAL APPROACH

The new approach adopted for the assessment of Italian tunnels is organized into the 4 sequential phases described in the following: investigative, diagnostic, therapy and monitoring phases.

2.1 *Investigation phase*

The proposed methodology starts from the investigative phase, which involves the examination of the available historical documentation, the execution of a set of basic investigations, the in-depth inspection of the tunnel with the identification of all defects and their severity, and finally further in-depth investigations chosen on the basis of the type of defects found during the inspection.

2.1.1 *Historical documentation and basic investigations*

Even before entering the tunnel to conduct an in-depth inspection, it was necessary to collect as much information as possible by examining all the available historical documentation to reconstruct age, general geometry, thickness of the structural components and used materials, as well as methods and construction phases dating back to the era of construction. Any previous investigations and documents attesting past modification or restoration interventions also played an important role in dating the onset of defects and in understanding their evolution. In fact, good knowledge of the long term behavior will make it possible to direct the choice of repairs more effectively.

Once the past information had been reconstructed where possible, it was important to consolidate the current state of tunnel through a set of basic investigations. First, a laser scanner was performed on the entire archway aimed at reconstructing the intrados shape and detecting surface defects. A series of georadar scans was then carried out along the entire length of the tunnel to verify the thickness of the lining and investigate deep anomalies. Finally, three concrete samples were taken every 50 m from tunnel lining for its mechanical characterization.

2.1.2 *In-depth tunnel inspection and further testing*

The key element of the investigation phase is represented by the in-depth inspection of the entire surface of the tunnel with identification of individual defects and attribution of their severity. This detailed inspection defined the reference state against which the other monitoring actions can be used to assess how it changes.

The in-depth inspection has been conducted by adequately qualified technicians who had relevant civil engineering experience. In addition, those persons had received specific training on tunnel inspection.

In general, the detailed inspection of the tunnel has taken place during night shifts completely closed to traffic and has always required the use of mobile elevating work platforms. In addition, since the areas of the vault affected by the presence of water were often covered with corrugated sheets, an "inspection train" has been organized to allow inspectors to examine the entire surface of the archway without exclusion, consisting of:

- Site team dedicated to the disassembly of corrugated sheets.
- Team of 4 inspectors on 2 elevating work platforms, each dedicated to a section of the tunnel, and foreman on the ground.
- Technical assistance for in-depth investigations contextual to the inspection.
- Site team ready to intervene for the resolution (if possible) of the problems that otherwise would not allow the reopening to traffic at the end of the inspection and for the reassembly of the previously disassembled corrugated sheets.

The procedures for observing, analyzing and classifying deteriorations that appear on the various parts of a tunnel have been established in accordance with the provisions of the "Road tunnel civil engineering inspection guide" issued by the Center d'Études des Tunnels (CETU Book 1-2, 2015). This manual has been selected as the best international reference currently available for people in charge of conducting detailed civil engineering inspections of bored road tunnels.

According to the manual, the inspection method is visual and by hammer testing, as shown in Figure 1. This non-destructive method allows for a good evaluation of the condition of structures but does not prevent the inspector from asking for the implementation of other analysis methods to help him assess the “state of health” of all or a portion of the structure. In general, it is necessary to go further with the inspection by using non-destructive testing (sonic or ultrasonic measurements, infrared thermography, radar measurements…) or destructive testing (core drilling, window sampling…) depending on the nature and the extent of the defect and the state of the structure.

All anomalies detected during the inspection were transcribed on special inspection sheets referring to 20 m long portions of tunnel, as shown in Figure 2.

For defect identification it was decided to adopt the detailed catalog defined by CETU, shown in Figure 3, which grouped together the deteriorations or faults of concrete lining that are most often observed during tunnel inspection and classified by theme.

The manual even proposes the rating method “Image Qualité des Ouvrages d’Art” (IQOA), shown in Figure 4, which is based on two indicators, one concerning the state of the civil engineering and the other concerning the presence of water, which makes it possible to classify zones.

It is worth noting that defects or deficiencies which can endanger users’ safety require urgent remedial actions (S-class). In case it is not possible to promptly intervene, the tunnel must be close to traffic until the problem is solved.

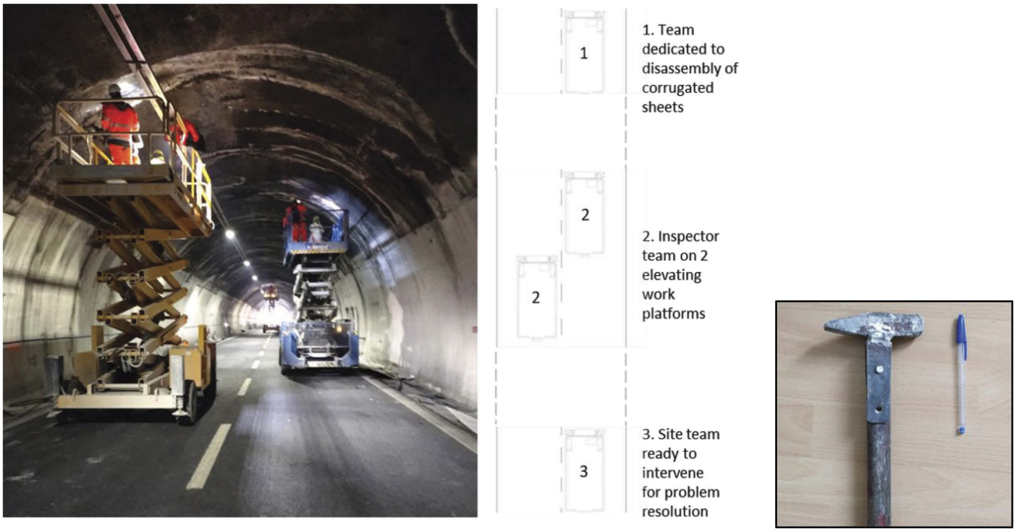

Figure 1. Inspection team organization and hammer for testing used during tunnel in-depth inspection.

2.2 *Diagnostic phase*

The investigative phase is followed by an accurate analysis of all the data collected and their correlation in order to complete the overall picture of the encountered problems, defining in detail their nature, extent, triggering causes and potential repercussions on tunnel and user safety.

Once all the defects have been catalogued, it is essential to study their interactions and evaluate the establishment of potential combined effects that are far worse than the single defect considered isolated.

In general, any noted defects are the consequences of a deterioration mechanism that may have various root causes:

- the geological, geotechnical and hydrogeological conditions of the rock mass surrounding the tunnel section may affect the extrados of lining or the tunnel walls;
- the construction of the tunnel may cause negative consequences when defects in the design, use or even nature of the materials constituting the tunnel are proven;

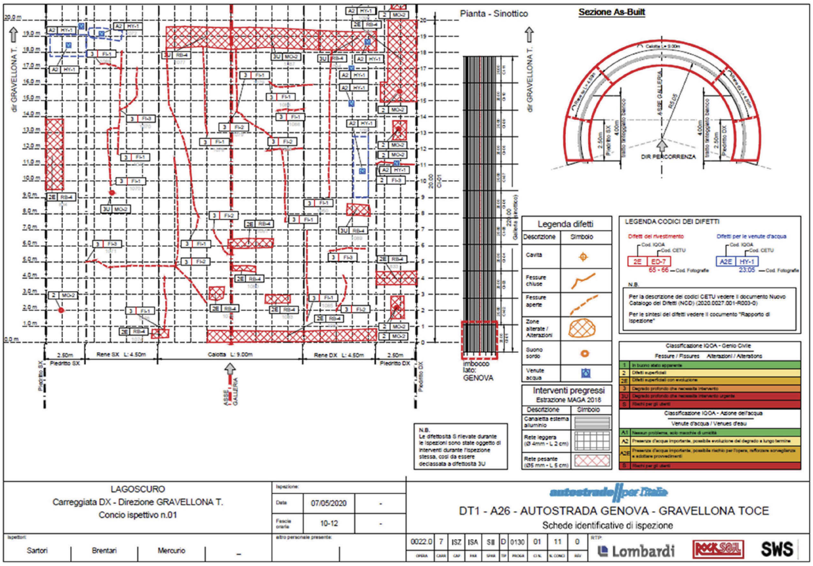

Figure 2. Tunnel inspection sheet to record and catalogue all defects referring to 20 m long portion.

Deteriorations due to water	
Water ingress	HY-1
Concretions	HY-2
Effects of freezing	HY-3
Efflorescence on mortar and concrete	HY-4
Deteriorations due to the surrounding ground	
Karsts and cavities	ZI-1
Deteriorations at the portals	ZI-2
Slope instability	ZI-3
Deteriorations of lining materials	
Stone or brick masonry linings	
Honeycombing	RM-1
Flaking	RM-2
Exfoliation	RM-3
Spalling due to compressive load	RM-4
Deterioration of mortar – Voids in joints	RM-5
Deteriorations of Concrete lining (cast in situ or precast)	
Chipping	RB-1
Concrete deterioration – Swelling	RB-2
Spalling due to compressive load	RB-3
Spalling due to corrosion of reinforcement	RB-4
Sprayed concrete deteriorations	RB-5
Deteriorations in waterproofing, drainage and surface water collection systems	
Deteriorations in intrados drainage	ED-1
Deteriorations in extrados drains and culverts	ED-2
Deteriorations in roadway drains	ED-3
Deteriorations in extrados waterproof membranes	ED-4
Deteriorations in sheeting	ED-5
Deteriorations in waterproof tanking	ED-6

Deteriorations in thin mortar coatings	ED-7
Deteriorations in waterproof insulating panels	ED-8
Deteriorations in swellable waterstops	ED-9
Deteriorations affecting the structural elements and geometry of the tunnel	
Cracks	
Horizontal structural cracks	FI-1
Diagonal structural cracks	FI-2
Verticale structural cracks	FI-3
Shrinkage cracks	FI-4
Crescent-shaped cracks	FI-5
Deformations	
Flattened crown – Symmetrical squeezing – Asymmetrical	DF-1
Bulging	DF-2
Offset stone or brick courses	DF-3
Invert deterioration	DF-4
Arch rupture	DF-5
Defects linked to workmanship	
Unstable blast hole bottoms	MO-1
Voids in the lining near the intrados	MO-2
Honeycombing	MO-3
Deteriorations in concrete construction joints	MO-4
Cosmetic defects with cast concrete	MO-5
Deteriorations in civil engineering elements	
Deteriorations in carriageways	EQ-1
Deteriorations in slabs and partitions	EQ-2
Deteriorations associated with fire	
Deteriorations due to fire	IN-1
Deteriorations associated with poor maintenance	
Poor maintenance	EN-1

Figure 3. CETU catalog of deterioration.

Civil engineering IQOA classes	
1	Good visual condition
2	Minor deteriorations which do not endanger the stability of the structure
2E	Deteriorations which could degrade and increase in extend, endangering the stability of the structure
3	Deteriorations which indicate structural alterations or local instability problems
3U	Deteriorations which indicate deep damage or global instability problems
S	Defects or deficiencies which can endanger users' safety and hence require urgent remedial action

Water IQOA classes	
1	No visible water flow
2	Area with light water flow
3	Area with heavy water flow
S	Defects or deficiencies which can endanger users' safety and hence require urgent remedial action

Figure 4. Rating method “Image Qualité des Ouvrages d’Art” (IQOA) for civil engineering and water.

- the ageing of materials may caused or accelerated by the various chemical attacks to which the structure is subjected.

The purpose of the diagnostic phase is therefore to identify the relative contribution of each of these factors.

Based on what was observed in the inspected tunnels, mainly built between the 60s and 80s, the most common defects can be traced back to the following categories:

- Surface faults in the concrete (up to 5 cm);
- Impairment/deep disintegration of concrete due to the action of water which can lead to detachment of portions of concrete;
- Construction defects such as sub-thicknesses induced by the non-completion of the concrete castings in the excavation phase;
- Presence of widespread cracking states to be attributed mainly to the half-section construction methods that can isolate unstable portions of concrete;
- Corrosion of steel reinforcement and spalling of concrete cover;
- Cavity on the back of the lining due to the effect of extra-excavations or releases during construction.

2.3 *Therapy phase*

On the basis of the diagnosis formulated in the previous phase, the interventions necessary to restore the safety of the tunnel are planned in the therapy phase. Thanks to the extensive experience gained in the field, a catalog of possible interventions has been developed according to the nature of the defects, their extent and location, as well as the surrounding conditions. This has made it possible to considerably reduce the designing time and therefore to be able to promptly carry out the restoration works, limiting the closing periods of the tunnel.

2.3.1 *Development of Standard Interventions*

For each defect category, also depending on the type of coating and the nature of the mass, typological intervention solutions were perfected aimed at temporarily securing the tunnels in such a way as to ensure their practicability during the necessary period of time to develop the lining reconstruction project and carry out the works. For this purpose, the useful life assigned to the interventions in the project has been set at 3 years, possibly extendable after the results of specific surveillance controls and monitoring activities.

From a regulatory point of view, the provisional safety measures are classified as local interventions according to Italian Standard 2018, as they concern individual parts of the structure and do not alter the overall behavior of the tunnel. They are aimed at restoring or possibly improving the initial resistance characteristics of the damaged parts and preventing the formation of local collapse mechanisms.

In total, 48 standard interventions were developed, validated by the Politecnico di Torino and approved by Italian Infrastructure Ministry as a national reference standard for the safety of tunnels (Italian Infrastructure Ministry 2021).

Based on the experience gained so far, it can be said that, on all the tunnels examined starting from January 2020, provisional interventions to protect superficial and deep deteriorations have been installed on about 16% and 19% of total concrete lining surface, respectively.

In a nutshell, the types of intervention can be traced back to the 5 cases illustrated below. In the rare cases where standard interventions were not suitable, tailor-made interventions were designed.

2.3.2 *Stainless steel nets anchored by means of dowels*

For the safety of the surface deterioration of the concrete (thickness ≤ 5 cm), stainless steel nets arranged on two layers are used (Figure 5a): the first layer, 1.6 mm thick, has fine mesh (12x12 mm) and is designed to retain small fragments, while the second layer, coupled to the first, has a structural function and wider mesh (50x50 mm). Both nets are anchored to the lining by means of dowels (Figure 5b).

2.3.3 *Reinforcement with bolts and nets*
For the safety of deep deterioration or detachment with thickness up to 40 cm, radial bolts with continuous adherence are used together with a double layer of protective stainless nets. Bolts are usually 3 m long and their spacing is 1x1 m (Figure 6). In case of detachment of concrete, this is previously reconstituted by means of a layer of high resistance concrete. The bolting system is also used to support cracked concrete blocks in case of potential fall from above.

2.3.4 *Support interventions with metal ribs*
A system of metal ribs is used to retain possible detachment of concrete blocks with important and deep cracks spread over the entire vault as well as in case of reduced thickness of the concrete lining caused by an incomplete casting during the construction phase. In order to speed up the installation of the protective system, coupled rectangular hollow sections 80x40mm, 5 mm thick and 0.40 m spaced, are adopted, as shown in Figure 7.

If there is also a cavity beyond the excavation perimeter, this is filled by using lightened material, while the entire structural thickness is restored by pumping high-strength concrete.

Figure 5. a) Double coupling layer nets; b) Anchoring net system by dowels.

Figure 6. a) Reinforcement with bolts and nets; b) Detail of bolt anchoring.

2.3.5 *Intervention for reinforcement corrosion protection and concrete cover reconstruction*
In case of concrete cover and reinforcement deterioration, first of all it is important to strip the reinforcement by removing all the concrete cover by means of hydro-milling.

In the areas where the reinforcement is intact and superficially rusted only, the rust layer is eliminated by sandblasting and subsequent laying of a protective coating. On the contrary, in the areas where the reinforcement is damaged or corroded, it must be replaced with new bars of the same diameter suitably anchored.

Figure 7. a) Reinforcement with steel ribs; b) Detail of coupled rectangular hollow steel profiles.

Upon completion of the intervention, the concrete cover is rebuilt with high-strength concrete and electro-welded steel net (Figure 8).

2.3.6 *Drainage and laying of corrugated sheets*

In tunnels without waterproofing, where the action of water has over time established a significant deterioration of the concrete, especially in the areas of the joints, a radial drainage system is performed by means of 60 mm diameter tubes. These drainages have the primary function of conveying groundwater from the boundary directly inside the tunnel, avoiding the contact with the concrete. To this aim, particular attention must be paid to use a fenestrated section, 1.5 m long, in contact with the boundary mass and a blind section, 1.5 m long, passing into the lining thickness (Figure 9), ensuring the ceiling by means of chemical resins. At the completion, corrugated sheets are positioned to avoid waterfalling on the carriageway.

Figure 8. Intervention for reinforcement corrosion protection and concrete cover reconstruction.

2.4 *Monitoring phase*

The new methodological approach does not end with the completion of the restoration work but requires that the monitoring and control activities of the possible occurrence of new problems continue throughout the entire operating life of the work, also including the parts already treated. For this purpose, specific visual and instrumental checks and monitoring have been defined to be performed periodically to maintain the effectiveness of the interventions performed during their useful life.

To maintain the effectiveness of the interventions and their components during the entire useful life of the project (3 years), visual and instrumental checks have been defined to be carried out according to specific frequencies, which, according to the new regulatory framework, can alleviate the frequency of inspections according to Circ. Min. N. 6736/61A1 of 1967.

Figure 9. a) Drainage intervention for joint area; b) Detail of fenestrated and blind section of drainage tube.

Depending on the outcome of the periodic checks, the interventions can be integrated or replaced, if necessary.

At the end of the 3 years, a detailed re-verification of the intervention is required, also based on the analysis of the monitoring data, to evaluate the possible possibility of extending its useful life.

Before the end of the useful life, the definitive intervention of complete reconstruction of the coating must be provided. Given the impact of these works on road traffic, their planning will necessarily have to pass through a risk analysis aimed at defining the priorities ("Classes of Attention") between the various tunnels at national level. This activity has been outlined in the guidelines of the recently issued Superior Council of Public Works.

3 CONCLUSIONS

The age of most of the tunnels of the Italian motorway network, which are often built without waterproofing to protect the coatings from the erosive action of the circulation water, has led to a progressive deterioration of the concrete and the onset of defects of varying severity.

It was therefore necessary to implement an articulated methodological approach for the assessment of the tunnels that would allow, through specific systematic inspections of the vault, to recognize and catalog all the punctual defects present, to diagnose a macro-category of defect at the scale of the segment, associating them a severity, and to define and apply different types of provisional safety measures according to the severity itself. It was thus possible to restore about 100 km of motorway tunnels, putting them in safety for the time necessary for the planning of subsequent definitive reconstruction interventions.

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