



## ORIGINAL ARTICLE

# An overview of Brazilian concrete tunnel inspection practices and international procedures

*Uma visão geral das práticas brasileiras de inspeção de túneis de concreto e dos procedimentos internacionais*

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**Abstract:** The evaluation of the structural integrity of tunnels in Brazil poses significant challenges due to the absence of established guidelines, manuals, or regulatory documents regarding the inspection and maintenance protocols. This article thus endeavors to relate the best international practices with those currently employed in Brazil to contribute to possible improvements. A comprehensive comparative analysis of inspection methodologies is presented, encompassing the classification of pathologies, prescribed inspection intervals, training protocols for inspectors, and methodologies for assessing assets' criticality. The study aims to inform the development of recommendations tailored to the Brazilian context for effectively inspecting concrete tunnels. By combining global and local practices, this research seeks to enhance the efficiency and safety of tunnel infrastructure in Brazil.

**Keywords:** tunnel, inspection, maintenance, pathological manifestations, concrete, shotcrete.

**Resumo:** A avaliação de integridade estrutural de túneis em Brasil possui desafios significativos devido à ausência de diretrizes, manuais ou documentos regulamentares estabelecidos relativos aos protocolos de inspeção e manutenção. Este artigo busca relacionar as melhores práticas internacionais com aquelas atualmente empregadas no Brasil para contribuir com possíveis melhorias. Uma análise comparativa abrangente de metodologias de inspeção é apresentada, que compreende classificação de patologias, intervalos de inspeção prescritos, protocolos de treinamento para inspetores e metodologias para avaliar a criticidade dos ativos. O estudo visa informar o desenvolvimento de recomendações adaptadas ao contexto brasileiro para a inspeção eficaz de túneis de concreto. Sintetizando práticas globais e locais, esta pesquisa busca aumentar a eficiência e a segurança da infraestrutura de túneis no Brasil.

**Palavras-chave:** túnel, inspeção, manutenção, manifestação patológica, concreto, concreto projetado.

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## 1 INTRODUCTION

Tunnels are infrastructure systems that usually maintain their operating period for a long time. According to the Federal Highway Administration (FHWA), more than 40% of in-service tunnels of the United States highways are over 50 years old [1]. In Brazil, this is not different. The Brazilian Tunnels Committee [2] describes 120 tunnels built in Brazil since the 19th century. This means that many tunnels worldwide are aging and inevitably experiencing various structural defects in the tunnel linings.

Tunnel aging management is a complex process, as several degradation mechanisms act together due to underground conditions. They are greatly influenced by environmental factors, such as subsoil condition, water infiltration and temperature variation, in addition to the human factor, which, due to population growth, demands more and more from urban infrastructure systems [3]–[6].

Especially in tunnels lined with concrete or shotcrete, there are processes associated with concrete degradation, such as reinforcement corrosion, attack by ions, sulfate and chloride, and carbonation. In general, isolated damaged areas initially have little or no impact on the capacity or stability of the structure; however, over time, these damaged areas begin to exhibit more than one defect [3]. These defects can represent warnings to the tunnel's operational safety and consequently cause socioeconomic and human development losses. The main objective of tunnel inspection is to assess the existing pathological manifestations. Therefore, the inspection process throughout the life cycle of the tunnel is necessary to systematize maintenance and to prevent the emergence and worsening of pathological manifestations in the structure [4].

Hence, several competent institutions and management companies worldwide have recently created manuals and regulations to standardize tunnel inspection routines. In the last decades, the Federal Highway Administration (FHWA) [5] of the United States, developed the National Tunnel Inspection Standards (NTIS), and currently relies on detailed inspection manuals and documentation. The European Union has been creating documents on the safety of tunnels in operation since 1999, following the Mont Blanc Tunnel and Tauern Tunnel fires. These led to the creation of standards in the EU countries, with the help of the International Tunnel Association (ITA) and PIARC – World Road Association [6]. In Japan, committees on tunnel management have been held since the 1980s [7].

The standardization in tunnel evaluation allows building databases to assess a country's overall condition of infrastructures. For example, the FHWA contemplates a representative database constructed following the standardization specified by the NTIS and NBIS (National Bridge Inspection Standards) standards and manuals. This information is an important decision-making tool for infrastructure managers and serves as training data for specialized artificial intelligence algorithms [8]. In Brazil, however, there is currently no regulatory document that standardizes the inspection and evaluation of tunnels. In general, Brazilian companies have drawn up their own guidelines based on bridge inspection practices, instructions from documents such as ABNT NBR 9052 [9]; ARTESP ET-00.000.000-0-C21/002 [10]; DNIT 010:2004 [11]; and other international documents and regulations [1], [12], [13].

In view of that, this article aims to present an overview of the inspection practices adopted by several national tunnel management companies and compare them with international practices. The information presented is a result of collaboration and discussions among working group members for the Brazilian standard of tunnel inspection, composed of tunnel managers, engineers, and researchers. It serves as a starting point for creating a specific Brazilian standard for tunnel inspection and evaluation, focusing on concrete-lined tunnels.

The rest of the paper is organized as follows. Section 2 presents the methodology of the study. Section 3 details the information collected and discusses the main findings. Finally, Section 4 concludes the study.

## 2 METHODOLOGY

To identify how inspection practices have been carried out in Brazil, six Brazilian tunnel management companies are interviewed. A form containing the eight questions, shown in Table 1, is used as a script. In addition to the questionnaire, some information is acquired from public documents made available by the companies [14], [15]. For the sake of confidentiality, the companies' names are not mentioned herein. Thus, all the data presented will be linked to companies numbered from 1 to 6.

Based on the form in Table 1, information on types of inspection, personnel involved, types of structures inspected, inspection periodicity, evaluation criteria and some other relevant aspects of the inspection is collected. The information from Brazilian companies is compared with the practices described in the following international regulations and manuals:

- FHWA from EUA: Tunnel Operations, Maintenance, Inspection, and Evaluation Manual (TOMIE) from EUA [1].
- NZ Transport Agency from New Zealand: NZTA S6:2022 [16]; NZTA S7:2022 [17] and NZTA S8:2017 [18].
- Centre d'Études des Tunnels from France: Road Tunnel Civil Engineering Inspection Guide Book 1: 2015 [12] and Road Tunnel Civil Engineering Inspection Guide Book 2:2015 [13].

- ADIF from Spain: NAP 2-3-1.0 Norma ADIF plataforma – Túneles:2023 [19]; NAP 2-4-01 Norma ADIF plataforma – Inspección Básica de Túneles de Ferrocarril:2020 [20]; NAP 2-4-1.1 Norma ADIF plataforma – Inspección Principal de Túneles de Ferrocarril:2021 [21]; NAP 2-5-0.1 Norma ADIF plataforma – Inventário de Túneles ferroviários: 2020 [22];
- Highway Structures & Bridges Inspection & Assessment from England: CS 450 Inspection of highway structures: 2021 [23] and CS 452 Inspection and records for road tunnel systems: 2020 [24].

**Table 1.** Base questionnaire used to collect information on inspection practices

| Main question                                                                                      | Specific questions                                                                                                      |
|----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| 1. General characteristics of assets                                                               | a. Type of tunnels (construction methods, materials, purpose, etc.)                                                     |
|                                                                                                    | b. Numbers and statistics                                                                                               |
|                                                                                                    | c. Is there a project, as built, as is                                                                                  |
|                                                                                                    | d. Other information                                                                                                    |
| 2. Tunnel inspection methodology                                                                   | a. Type of inspection                                                                                                   |
|                                                                                                    | b. Description of inspections                                                                                           |
|                                                                                                    | c. Is there an own form? Which parameters are evaluatedd. Is there an internal manual or do they follow a specific one? |
|                                                                                                    | e. What equipment and technologies are used?                                                                            |
|                                                                                                    | f. Other data                                                                                                           |
| 3. Who conducts the inspection?                                                                    | a. Is it its own or hired team?                                                                                         |
|                                                                                                    | b. What is the education and training level of inspectors?                                                              |
|                                                                                                    | c. Other information                                                                                                    |
| 4. What are the anomalies in the tunnels?                                                          | a. What are the main manifestations of anomalies?                                                                       |
|                                                                                                    | b. How is the inspection of each anomaly carried out?                                                                   |
|                                                                                                    | c. Other information                                                                                                    |
| 5. How is the assessment carried out?                                                              | a. How is each anomaly and the condition of the tunnels classified?                                                     |
|                                                                                                    | b. Are consequences taken into account?                                                                                 |
|                                                                                                    | c. What grades or risk matrices are used?                                                                               |
|                                                                                                    | d. Other information                                                                                                    |
| 6. What is the frequency of inspections?                                                           | a. What is the frequency depending on the inspection type?                                                              |
|                                                                                                    | b. In which situations are there periodicity adjustments and why?                                                       |
|                                                                                                    | c. Other information                                                                                                    |
| 7. How is inspection included in the asset maintenance and management process?                     |                                                                                                                         |
| 8. In addition to inspection, is monitoring carried out, or is any technology used in the tunnels? |                                                                                                                         |

3 RESULTS AND DISCUSSION

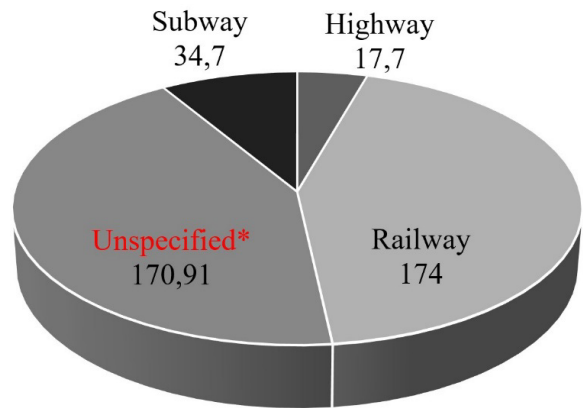
The results and discussion are presented in several topics to answer the questions raised in the questionnaire in Table 1. The topics cover statistics of tunnels, inspection types, frequency, inspection team qualification, and tunnels critical state analysis. Some information is lacking regarding the responses associated with the inquiries presented in Table 1, since these were answered based on the availability of data shared by the companies and international administrative manuals.

3.1 Tunnel statistics

This section regards the first question of the questionnaire in Table 1 with the information provided by the interviewed Brazilian companies responsible for operating and maintaining the main highways, railways, and subways in the country. A survey of Brazilian tunnels carried out with these data shows a lack of standardization in the assets register data. There is no updated database that correctly identifies all assets, making the exact number of tunnels in operation unknown.

Many tunnels are old, and the designs and specifications from the construction time have been lost. As a result, there are no exact records of the construction method employed in some tunnels, or information on structural characteristics indicating whether the tunnel was excavated in soil or rock. Nevertheless, based on the information

collected, 397 km of excavated tunnels in operation are cataloged. Figure 1 indicates the general classification of tunnels based on purpose, in relation to the kilometers excavated.



**Figure 1.** Classification of tunnels based on the purpose according to information provided by six Brazilian companies (Data collected in 2023). \* One of the companies did not specify the purpose of its tunnels.

3.2 Inspection types

National and international practices on tunnel inspection have different definitions of inspection types, i.e., despite being similar, some conceptual variations within both national and international contexts are noticed. However, to simplify the comparison, inspections are grouped into four types: registration inspection, routine inspection, detailed inspection, and special inspection.

To better understand each inspection type, the most general definition for each is presented below.

3.2.1 Registration inspection

The registration process, also called initial or acceptance in the documents, is the first inspection of the constructed tunnel. For new structures, it must be carried out immediately after construction is completed, or as soon as it is incorporated into the railway/road/metro system. It must also be carried out when there is a significant update in the project design for construction process demands, such as reinforcement and changes in the structural system.

The registration inspection is carried out at the beginning of the tunnel service life as an initial process, which is relevant for identifying construction problems that may adjust the characteristics of the inspection monitoring program. It should be extensively documented, not only by inspecting the data, but also throughout the project, data book, and all the construction reports available. In general, it should include a) identification and basic information (report numbers, reference, date, line or extension, position, section, code, name, and district), b) registration data (type, purpose, year, route, total length, tunnel reference coordinates, dimensions, initial km and final km, lining type of the structure, refuge, ballasted or non-ballasted, guardrail type, useful width, and environmental aggressiveness), c) structural scheme (longitudinal and transversal sketch), and d) photographic report (with established distance views; the numbering sequence must follow the increasing order of the route mileage).

3.2.2 Routine inspection

A routine inspection is a periodic inspection that has appropriate intervals. It is designed to collect observations and/or measurements, aiming to identify any developing anomalies, damage or any changes in relation to the previous registration inspection or routine inspection data. It is a visual inspection carried out from the road level, or from the ground or platforms, if existing. In recent years, to assist in better visualizing difficult-to-access regions, drones with on-board cameras have been used [25].

The routine inspection may be referred to by different names, such as basic and general inspection. All of these are scheduled inspections. They may have different levels of complexity according to each standard. Continuous inspections, also called superficial or surveillance inspections, are not considered as different types in this paper. The continuous inspection has the same function as the routine inspection, meant to identify any anomaly and then specify a special

inspection. The difference between them lies in the complexity of the inspection; continuous inspection is performed by all employees continuously, while routine inspection is performed by specialized workers at defined time intervals.

Routine inspections are characterized by the inspection of the main components such as: a) concrete lining or shotcrete (fissures, cracks, misalignment, reinforcement corrosion, segregated concrete; insufficient reinforcement coverage, efflorescence, infiltration, concrete spalling, spalling, deformations and displacements), b) tunnel entrance (slope stability, and containment), c) guardrails, barriers and walkways (deterioration, corrosion, general characteristics, alignment, and armor covering), and d) drainage systems (deterioration of concrete or stonework, blocked or damaged devices, corrosion or poor functioning).

3.3.3 Detailed inspection

A detailed inspection is a periodic inspection simultaneous with the routine inspection, but with a wider scope. It is also called in-depth, principal, or special inspection. It is not necessarily carried out at standardized intervals, as it can vary according to the specific needs of the inspected tunnel.

The standards and manuals describe this type of inspection differently. Depending on the country, the detailed inspection may be referred to as a more detailed structural inspection. It may include the need to check buried elements (rods, anchor bolts, crankshafts), submerged elements, or elements in difficult-to-access areas, or it may include all the components of a tunnel (structural, electrical and mechanical elements) as in CS 450 and CS 452, or even include the outside of the tunnel to evaluate the surroundings of the tunnel, as specified in the New Zealand guidelines [16]–[18].

Based on the documents evaluated, in this type of inspection, destructive and non-destructive tests must be foreseen in addition to a visual inspection, as well as periodic or constant monitoring when severe or difficult-to-interpret damage is found.

3.3.4 Special Inspection

There is a high variation within the national practices regarding the definition of special inspections, which is defined as a detailed routine inspection or as a procedure to investigate a specific event. In both national and international practices, there are special, principal, damage, extraordinary, or emergency inspections, which are performed to investigate a specific defect or after a special event. In this paper, all types of inspection performed to investigate a specific defect, or performed after the occurrence of an extraordinary event, are considered as special inspections.

The special inspections must be carried out when sudden structural damage, caused by man, equipment or the environment, occurs or there is a high risk of occurrence. When any damage with imminent risk to the structure is identified, the inspector must notify the emergency to the people in charge, so that they can apply some restrictions to the tunnel.

The inspection team must have the competence and authority to assess the damage severity, and to limit vehicle flow, loads, or traffic speed, interrupt and reestablish traffic, as well as identify the services necessary for the rehabilitation or deactivation of the tunnel, when applicable.

3.3 Comparison of inspection types from national and international practices

Table 2 shows the different types of inspections recommended by each international practice, and Table 3 summarizes the types of inspection adopted by the Brazilian companies consulted.

Table 2 shows an inconsistency in the nomenclature adopted for each kind of inspection, finding different names for the same type of inspection. The same problem is found in the Brazilian practice. Since each company creates its specific document for tunnel inspection, the definitions for the different inspection types are confused in the national practice. The major inconsistency occurs with the definition of detailed, principal, special, and extraordinary inspections. Moreover, there is a variation within the Brazilian territory regarding the type and amount of inspection performed by each company. As seen in Table 3, some companies do not have procedures for detailed and specific inspections and perform only routine and/or continuous inspections.

Table 2. Type of inspection in international practices.

| Types        | FHWA           | CETU               | NZTA                 | ADIF      | CS450/CS452         |
|--------------|----------------|--------------------|----------------------|-----------|---------------------|
| Registration | Initial        | -                  | -                    | -         | Acceptance          |
| Routine      | Routine        | Continuous Routine | Surveillance General | Basic     | Superficial General |
| Detailed     | In-depth       | Detailed           | Principal            | -         | Principal           |
| Special      | Damage Special | Special            | Special              | Principal | Special             |

**Table 3.** Types of inspection carried out by the Brazilian companies consulted.

| Types        | Company 1 | Company 2 | Company 3 | Company 4 | Company 5 | Company 6 |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Registration | x         | X         | x         | x         |           | x         |
| Routine      | x         | X         | x         | x         | x         | x         |
| Detailed     | x         | X         | x         | x         |           | x         |
| Special      | x         |           | x         | x         |           | x         |

3.4 Inspection frequencies

Table 4 shows approaches regarding inspection periodicity adopted by the international regulations analyzed, and Table 5 summarizes the periodicity adopted by each Brazilian company consulted.

**Table 4 –** Inspection periodicity adopted by international practices.

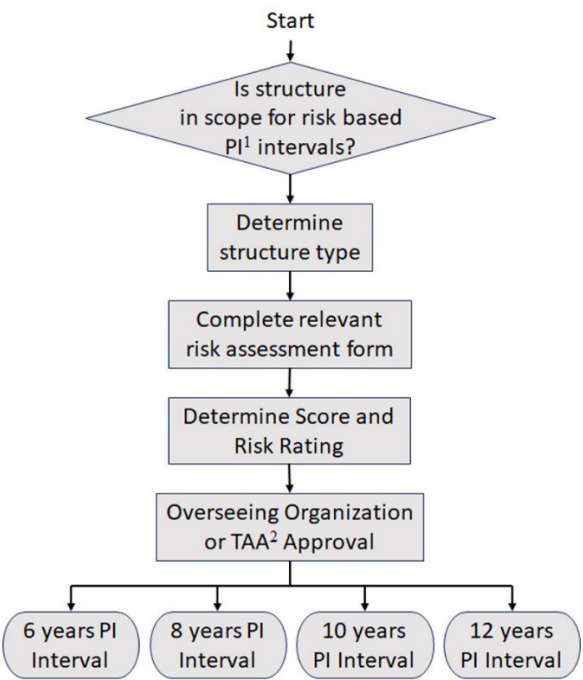
| Reference                     | Specifications                                                                                                                |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Tomic Manual (EUA) [1]        | Initial inspections of the new tunnel: Prior to opening it to traffic to the public.                                          |
|                               | For existing tunnel: within 24 months of NTIS effective date.                                                                 |
|                               | Routine inspections: every 24 months during the service life of the tunnel.<br>It possibly allows up to a 48-month extension. |
| CETU (France)<br>[12], [13]   | Continuous inspections by teams. Routine inspections on an annual basis.                                                      |
|                               | Detailed inspection every 6 years. Periodicity may vary depending on the tunnel analysis.                                     |
| NZTA (New Zealand) [16]–[18]  | Annual routine inspections for structural elements.                                                                           |
|                               | General infrastructure inspections every 2 years.                                                                             |
|                               | A major inspection every 6 years.                                                                                             |
| ADIF (Spain)<br>[20]–[22]     | Periodicity of 5 years for 500-meter tunnels.                                                                                 |
|                               | Periodicity of 4 years for tunnels of 1000 to 2000 meters.                                                                    |
|                               | Periodicity of 3 years for tunnels longer than 2000 meters                                                                    |
| CS 450/CS 452 (UK) [23], [24] | Continuous surface inspection.                                                                                                |
|                               | General inspection annual for M&E* inspection and 2 years for structural.                                                     |
|                               | Main inspection 3 years for M&E* and structural at 6 up to 12 years.                                                          |

\*M&E – Mechanical and Electrical.

The international practices (Table 4) show different approaches to the periodicity of registration, routine, and detailed inspections. Some countries adopt a fixed period with the possibility of a greater period for some specific situations, while others consider a variable period depending on the tunnel evaluation or its length; for example, in the UK [23], a detailed inspection varies depending on a risk assessment procedure (Figure 2).

The scoring system used by the UK specifications [23], [24] determines an indicator of relative risk to support decisions at appropriate intervals between routine inspections. The risk assessment scoring tables consist of five categories, each containing several criteria with several attribute options associated to a score based on the level of risk. A lower score indicates higher risk, while a higher score indicates lower risk. The sum of scores for each attribute within a category returns the actual risk score for this category. In all cases where data are unknown or unobtainable, a conservative approach should be taken by applying the lowest score available. Hence, for a structure with many unknown variables, the recommended major inspection interval may remain at six years.

A variability in the periodicity of each country is observed. However, each has a national recommendation. In the Brazilian scenario (Table 5), each company has a specific inspection periodicity rule; some have adopted fixed periods for all tunnels, and others vary their routine inspections according to each case.



**Figure 2** – Risk-based inspection period in the UK procedure [23]. <sup>1</sup>PI-Principal Inspection. <sup>2</sup>TAA – Technical Approval Authority.

**Table 5.** Inspection periodicity adopted by Brazilian companies

| Reference | Specifications                                                                               |
|-----------|----------------------------------------------------------------------------------------------|
| Company 1 | Fixed annual periodicity for routine inspections.                                            |
|           | Follow NBR 9452 [9] as standard                                                              |
| Company 2 | Fixed annual periodicity for almost all tunnels                                              |
|           | In some exceptions, a 2-year term is adopted, depending on the history of the tunnel.        |
| Company 3 | Anomalies are reported by other teams, such as the mechanical or electrical inspection team. |
|           | Every 8 years, a detailed inspection is carried out by private companies.                    |
|           | Monitoring systems are adopted for some specific pathologies.                                |
| Company 4 | Inspection is carried out continuously by the lane inspection team.                          |
|           | Inspection cycles that vary:                                                                 |
|           | 3 years for tunnels with any warning.                                                        |
| Company 5 | Up to 5 years for tunnels received or recovered.                                             |
|           | Fixed annual periodicity for routine inspections                                             |
| Company 6 | Fixed annual periodicity for routine inspections.                                            |
|           | However, periodicity may vary for each tunnel, as well as the inspection procedures.         |

3.5 Qualifications of inspectors

Five of the six Brazilian companies reported information on the technical qualifications of the inspection team. Two of them employ their own staff, while the other three employ outsourced staff. In addition, the composition of the staff and the experience required varies from company to company. Table 6 summarizes the information provided by the five companies.

As can be seen, Company 1 reported that its inspection team is composed of an Inspector, who must be a qualified engineer registered with CREA<sup>1</sup> and must have at least a five-year experience with tunnel projects, execution, and

<sup>1</sup> CREA: Regional Council of Engineering and Agronomy (entity that regulates engineering professionals in Brazil)

structural recovery. The field service must be performed by a geotechnical and a structural engineer, both having at least five-year experience with inspection. A senior civil engineer with at least 10-year professional experience in tunneling must analyze the inspection data. Finally, technical assistants must have completed high school and, preferably, have taken a technical or technologist course in the area of expertise.

**Table 6** – Summary table of Brazilian practices regarding the qualification of inspectors

| National reference | Staff/Qualifications                                                                                      | Experience                                                                 |
|--------------------|-----------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Company 1          | Inspector/Engineer registered with CREA                                                                   | 5-year experience with tunnel design, execution and recovery of structures |
|                    | Field Service/Geotechnical Engineer and Structural Engineer                                               | Minimum 5-year experience in inspections                                   |
|                    | Evaluation/Senior civil engineer                                                                          | Minimum 10-year experience in tunnels                                      |
|                    | Support team/High-school graduate and technical or technologist course preferred in the area of expertise |                                                                            |
| Company 2          | Current maintenance team                                                                                  | Instructed to carry out inspection in the tunnels                          |
| Company 3          | Coordinator/Civil engineer                                                                                | 10-year experience in inspection and/or tunnel projects                    |
|                    | Geotechnics/Civil engineer or geologist                                                                   |                                                                            |
|                    | Responsible for the field team/Civil engineer                                                             | 5-year experience in inspecting various works of art                       |
|                    | Support team/technical level professional                                                                 |                                                                            |
| Company 4          | Support team                                                                                              |                                                                            |
|                    | 2 pairs of inspectors with in-company training                                                            |                                                                            |
|                    | Official inspectors                                                                                       |                                                                            |
| Company 5          | Mechanical engineer or electrical engineer (lane inspectors)                                              | "In-field" training                                                        |

In Company 2, the current maintenance teams are instructed to carry out routine inspections in the tunnels. In case of any unusual observation, these teams must contact the Infrastructure Engineering department for an extraordinary inspection to be conducted.

Company 3 reported that the inspection team is composed of a coordinator and a geotechnical manager. The latter must have at least 10 years of experience with tunnel inspection and/or tunnel design and must be a civil engineer or a geologist. There is also a person in charge of the field team, who must be a civil engineer with at least five-year experience with inspections of artworks; finally, there is a technical support team that must comprise a building technician or technologist, and an assistant. In Company 4, the inspection is carried out by a couple of inspectors who have in-house training. Each couple is formed by an engineer and a technician.

Lastly, Company 5 reported that the inspection is carried out by official inspectors trained “in-field”. That is, the expertise is passed from inspector to inspector. These inspectors, when walking along the tunnel, visually check anomalies and, as soon as any situation that causes concern is detected, an incident report is opened and forwarded to a civil engineering team, in case of a structural problem. In the case of problems related to the permanent road, the team in charge comprises mechanical engineers and electricians.

Regarding international specifications, the information found on the technical staff, qualification requirements and experience of inspectors are summarized in Table 7.

As can be seen in Table 7, the FHWA [1] indicates that the inspection team must comprise a manager, responsible for managing the tunnel inspection plan, and a team leader. Additionally, a specialist in each specific discipline (for example, structures, geotechnics, etc.), a field inspector, and a special contractor or service provider are recommended. To qualify the team, the FHWA provides inspector certification training. However, training can also be acquired by taking alternative courses authorized by the FHWA.

In France, detailed inspections of tunnels in the national road network are carried out by the CeTU [12] itself. The CeTU specifications indicate that the entire team must receive training in tunnel inspection skills in civil engineering. It also stresses that a person with a higher technical level, with at least a three-year experience in detailed inspections, or an engineer with at least one year of experience in inspection of tunnels must manage the inspection team. It additionally states that, when the tunnel or a part of the tunnel is unlined, the inspection team must include a member competent in geology. Exceptionally, the inspection can be carried out by project consultants specialized in assessing the condition of tunnels. In this case, the organizations must be able to justify the experience and skills of their personnel.

**Table 7** – Summary of international practices regarding the qualification of inspectors

| International reference      | Staff/Qualifications                                                                                    | Experience                                     |
|------------------------------|---------------------------------------------------------------------------------------------------------|------------------------------------------------|
| Tomic Manual (EUA) [1]       | Mandatory 1 Manager (program manager): responsible for managing the tunnel inspection plan              | FHWA provides inspector certification training |
|                              | 1 Team leader required                                                                                  |                                                |
|                              | Specialist                                                                                              |                                                |
|                              | Field inspector                                                                                         |                                                |
|                              | Special contractor                                                                                      |                                                |
| CETU (France) [12], [13]     | Assistant                                                                                               | Minimum 1-year                                 |
|                              | Inspector                                                                                               | Minimum 3-year                                 |
|                              | Manager of the on-site inspection team (with a civil engineering degree)                                | Minimum 3-year                                 |
|                              | Inspection manager (with a civil engineering degree)                                                    | Minimum 3-year                                 |
| ADIF (Spain) [20]–[22]       | Team accredited by the State Secretariat for Infrastructure and Planning of the Ministry of Development |                                                |
| NZTA (New Zealand) [16]–[18] | Structure inspection engineer                                                                           | Minimum 10-year                                |
|                              | Structure inspection                                                                                    | Minimum 5-year                                 |

The ADIF documentation [20], [21] establishes that the inspection team must be accredited by the State Secretariat for Infrastructure and Planning (*Secretaría de Estado de Planificación e Infraestructuras*), which is the organization responsible for accrediting teams. The Design Manual for Roads and Bridges [23] from the United Kingdom specifies the necessary experience for highway inspectors in general, not specifically for tunnel inspectors. It indicates to include an Inspector or Senior Inspector.

Finally, the New Zealand standard [18] specifies the requirement of a structural inspection engineer, who must be trained, certified and have at least 10 years of experience. A structural inspector is also required, who must be a professional with at least five years of experience.

Summarizing the above information, it can be seen that the adopted practices on the qualification of inspectors are similar within both the national and the international contexts. Some companies and regulations are more rigorous and detailed regarding the requirements and composition of the inspection team, necessary training and level of experience, while others are more superficial. However, in general, the teams are composed of specialized technicians, civil, structural, and geotechnical engineers, as well as geologists. The level of experience required varies from five to 10 years, in general. Even so, there are no unified guidelines to be followed to composed the inspection team.

It is understood that composing the inspection team is not an easy task due to the numerous factors that can influence the required requirements. For example, demanding a high level of qualifications can lead to a shortage of human resources. In contrast, loosening the expertise level and technical requirements could result in unqualified professionals, which could compromise the quality of the inspection and, consequently, the tunnel safety and functionality.

Note that the team qualification level is directly related to the level of detail of the inspection procedures. Routine inspections may require a lower professional qualification than special inspections, for example. The level of importance of the artwork is also another key aspect that could directly impact the qualification of the inspection team, as well as the geological conditions in which the tunnel is located. A tunnel built in an aggressive geological environment is more prone to pathological manifestations than a tunnel located in favorable geological conditions, requiring a more rigorous inspection program and a more highly qualified team.

Summarizing, a tunnel inspection standard must establish unified guidelines and criteria to allow companies to set up the most efficient possible inspection team.

3.6 Analysis of the criticality of tunnels

To evaluate the criticality of tunnels, manuals and regulations classify the tunnel's performance by following some specific rules. Each specification in the national and international documents has a different procedure with different levels of detail. There are examples of evaluation systems based only on the pathological evaluation in a specific area of the tunnel, as well as procedures that take into consideration several factors, such as the potential impact of structural problems, operational failures, environmental interference, and risk-based analysis.

A scoring system is usually used to determine an indicator of the tunnel condition, which, in some cases, is just used to evaluate the tunnel condition, and also can be used to modify the inspection periodicity, as proposed by FHWA and the UK documents.

In Brazil, most of the companies interviewed reported that tunnel assessments are carried out based on specifications for bridge assessments, which are extrapolated to tunnels. Currently, the ABNT NBR 9452: 2023 [9] for Inspection of Bridges and Overpasses is widely used to evaluate the degradation of tunnel infrastructures in Brazil.

3.6.1 Pathology classification

The methodologies to classify the degradation or defect state usually have three to five levels. These levels vary from general state classifications, associated with high levels of subjectivity in the inspector's interpretation, to rigorous methodologies with classifications within pre-established levels of standardization. Table 8 shows the classifications adopted by some researchers and international regulations. There are also the classification methodologies proposed in [26]–[28] to substantiate the comparison.

Table 8 - Classification levels of pathologies and anomalies in tunnels

| Reference                                    | 3 level | 4 level | 5 level |
|----------------------------------------------|---------|---------|---------|
| ABNT NBR 9452:2023 [9]                       |         |         | x       |
| ADIF [20], [21]                              |         | x       |         |
| Highways England [23]                        | x       |         |         |
| CeTU [12], [13] for Water Rating             | x       |         |         |
| CeTU [12], [13] for Civil Engineering Rating |         |         | x       |
| FHWA [1]                                     |         | x       |         |
| Strauss et al. [26]                          | x       |         |         |
| Wang [27]                                    |         | x       |         |
| Yuan et al. [28]                             |         |         | x       |

In the classification system adopted by CeTU [12], the defects are classified according to two general categories: the presence of water (consisting of three levels and an emergency category) and civil engineering components (consisting of five levels of deterioration, including an emergency category).

The ADIF [20], [21] classification system establishes a Severity level criterion (N) detected during an inspection. The value of N is a function of the damage category (which varies depending on the type of damage and affected element) and intensity. The “damage category” is defined as the maximum level of severity a given defect could reach for a specific element of the asset in its most advanced state of evolution. In this extreme case, it receives an intensity score of 4. The intensity of the defects observed refers to the state of advancement and deterioration extent at the time of the inspection. These data are evaluated by the inspector, who classifies the extent of each damage identified on a scale ranging from 1 to 4, where 1 is the lowest level and 4 is the highest one. The ADIF classification is shown in Table 9, where the damage severity is defined qualitatively by severity level matrices. The categories presented in Table 9 are estimated according to Table 10.

**Table 9** - Severity level depending on the category of damage adopted by ADIF [20], [21].

|            | Intensity 1 | Intensity 2 | Intensity 3 | Intensity 4 |
|------------|-------------|-------------|-------------|-------------|
| Category 1 | N1          | N1          | N1          | N1          |
| Category 2 | N1          | N2          | N2          | N2          |
| Category 3 | N1          | N2          | N3          | N3          |
| Category 4 | N1          | N2          | N3          | N4          |

**Table 10** – Scale and description of damage severity levels in tunnels by ADIF [20], [21].

| Damage severity level | Description                                                                                                                 |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------|
| N1                    | Defects with no impact on structural behavior, lane operation, durability or functionality of the element                   |
| N2                    | Defects with no impact on structural behavior and lane operation, yet impair the durability or functionality of the element |
| N3                    | Defects that show the pathology evolution, and that may affect the lane structural safety, operation, or third parties.     |
| N4                    | Defects that affect the structural safety or lane operation.                                                                |

In summary, severity levels N1 and N2 occur when the damage affects only the tunnel functionality, while severity levels N3 and N4 occur when the damage affects the structural safety.

3.6.2 Tunnel condition evaluation

The infrastructure management company with the strictest critical categorization system, compared to those analyzed in Brazil, presents a criticality classification system in four levels, whereby Class A is the most critical and Class D is the least critical. The aspects considered in the evaluations cover the type of material transported within the structure (flammable, explosive, chemicals, etc.), the number of people, tunnel length, structure configuration, environment in which the structure is located, and potential for extreme events.

The assessment of the structure condition and mapping of locations with low levels of degradation occurs as a subsequent step to the inspection process (item 5.4.1), after assessing the relevance of the asset being analyzed. The inspection is conducted following guidelines stipulated by each administrator to generate effective results targeting established objectives or methodologies. With no general standardization or regulation regarding the inspection process, certain levels of subjectivity ensue.

Some countries have established national guidelines to increase the quality of inspections and to obtain more consistent results, creating rates, factors and documentation systems specific for tunnel evaluation. ADIF [20], [21], for example, shows a parameter called Potential Degradation Factor, based on specific characteristics of the structure analyzed. From this, potential levels of deterioration, ranging from mild to high, are assigned to each tunnel under its management.

In the system adopted by CeTU [12], [13], the tunnel is divided into fixed and homogeneous sections in terms of structural and geotechnical contexts. It proposes a rating method for tunnels called “*Image Qualité des Ouvrages d’Art*” (IQOA), which makes it possible to classify zones. Its purpose is to provide two indicators, one concerning the state of the civil engineering components and the other concerning the presence of water. Then, each structural region in every section is classified and given a “Civil Engineering Rating” and a “Water Rating”. The regions are then classified according to the IQOA system defined by the French State. A summary of the deterioration level for each class used in the Civil Engineering Rating is given in Table 11.

The FHWA [5] employs detailed and comprehensive specifications based on precise tables to classify each structure component. The condition of each tunnel element is quantified based on the pathology evaluation and registered into percentages of four condition states, varying from good to poor condition, and the registered information is available on public records, such as the National Tunnel Inventory (NTI).

**Table 11** - Summary of State Classes based on the IQOA system from the French guidelines: (a) Civil Engineering Rating and (b) Water rating.

| (a)   |                                                                                                                                                                                                                                                          |
|-------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Class | Description of Deterioration in Area                                                                                                                                                                                                                     |
| 1     | In good visual condition.                                                                                                                                                                                                                                |
| 2     | Minor deterioration that does not affect the stability of the structure                                                                                                                                                                                  |
| 2E    | Same as class 2, but with a higher possibility of continuous degradation and/or increase in extent                                                                                                                                                       |
| 3     | Deterioration indicates that the structure has been altered or that the stability might be affected.                                                                                                                                                     |
| 3U    | Indicates deep/severe damage that affects the overall stability                                                                                                                                                                                          |
| S     | Indicator “S” can be included in any of the classes and indicates possible danger to the user                                                                                                                                                            |
| (b)   |                                                                                                                                                                                                                                                          |
| Class | Description of Deterioration in Area                                                                                                                                                                                                                     |
| 1     | Area with no visible water flow.                                                                                                                                                                                                                         |
| 2     | <b>Area with light water flow:</b> drips (any flow rate); local puddle with a depth not exceeding five millimeters; damp stain on the tarmac; continuous flow forming a film of water, running down the lining, with a depth lesser than one millimeter. |
| 3     | <b>Area with heavy water flow:</b> continuous flow forming a film of water; water ingress under pressure; continuous flow running; puddle with a surface area of more than 10 square meters or a depth of over five millimeters.                         |
| S     | <b>Indication S is specifically used if water is:</b> in freezing conditions; due to minerals in solution; due to the absence or blockage of drainage, or could present a danger for road traffic.                                                       |

4 CONCLUSIONS

This paper presented an overview of concrete tunnel inspection practices in Brazil and international procedures. To this end, information provided by six Brazilian companies was summarized and compared with information extracted from international guidelines and regulations. This allowed observing that most of the participating Brazilian companies use inspection as a means of assessing the urgency of maintenance only. In contrast, in international standards, inspection results are also used as a means for defining inspection periodicity and composing the inspection team, for example, in CETU (France) and NZTA (New Zealand). Also verified is that, in Brazil, the inspection is conducted following guidelines stipulated by each administrator to generate results in accordance with the established objectives or methodologies. There is no general standardization or regulation on how to inspect, which results in certain levels of subjectivity. Furthermore, there is no consistency in the tunnel inspection techniques adopted by various tunnel owners. There is thus a need to create a technical standard for inspecting concrete tunnels. A national regulation can contribute to: establish written policies and procedures, maintain tunnel inventory and inspection data, maintain qualification records of personnel, including national inspector certification, and establish an effective quality control and a quality assurance program.

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REFERENCES

[1] Federal Highway Administration, *Tunnel Operations, Maintenance, Inspection, and Evaluation Manual*. Washington, D.C.: U.S. Dept. Trans., 2015, vol. FHWA-HIF-15-005.

[2] Comitê Brasileiro de Tneis, *Tunnelling in Brazil*. São Paulo, 2006.

- [3] A. Sjölander, V. Belloni, A. Ansell, and E. Nordström, "Towards automated inspections of tunnels: a review of optical inspections and autonomous assessment of concrete tunnel linings," *Sensors*, vol. 23, no. 6, pp. 1–20, 2023, <http://doi.org/10.3390/s23063189>. PMID:36991900.
- [4] N. Yasuda, "Hammering sound of concrete with defects and spalling risk," *Tunn. Undergr. Space Technol.*, vol. 131, pp. 104789, 2023.
- [5] Federal Highway Administration, *National Tunnel Inspection Standards*. Dept. Transp., 2015, vol. 80, no. 134.
- [6] Economic and Social Council, *TRANS/AC.7: Report of the Ad Hoc Multidisciplinary Group of Experts on Safety in Tunnels on its Third Session*. Vienna: Econ. Commn. Eur., 2000.
- [7] F. Ye, N. Qin, X. Liang, A. Ouyang, Z. Qin, and E. Su, "Analyses of the defects in highway tunnels in China," *Tunn. Undergr. Space Technol.*, vol. 107, pp. 103658, 2021, <http://doi.org/10.1016/j.tust.2020.103658>.
- [8] M. O. Ahmed, R. Khalef, G. G. Ali, and I. H. El-adaway, "Evaluating deterioration of tunnels using computational machine learning algorithms," *J. Constr. Eng. Manage.*, vol. 147, no. 10, pp. 04021125, 2021, [http://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002162](http://doi.org/10.1061/(ASCE)CO.1943-7862.0002162).
- [9] Associação Brasileira de Normas Técnicas, *Inspecção de Pontes Viadutos e Passarelas de Concreto – Procedimentos*, ABNT NBR 9452, 2023.
- [10] Agência de Transporte do Estado de São Paulo, *Controle das Obras de Arte Especiais da ARTESP*, ET-00.000.000-0-C21/002, 2022.
- [11] Departamento Nacional de Infraestrutura de Transportes, *Inspecções em Pontes e Viadutos de Concreto Armado e Protendido – Procedimento*, DNIT 010/2004 – PRO, 2004.
- [12] Centre d'Études des Tunnels, *Road Tunnel Civil Engineering Inspection Guide. Book 1: from Disorder to Analysis from Analysis to Rating*, 1 ed. Bron: Min. Env. Én. Mer., 2015.
- [13] Centre d'Études des Tunnels, *Road Tunnel Civil Engineering Inspection Guide. Book 2: Catalogue of deteriorations*. Bron: Min. Env. Én. Mer., 2015, vol. 1.
- [14] Engelog, *Especificação para Execução de Inspecções em Túneis. Material Didático*. São Paulo, 2023.
- [15] EcoRodovias, *Concessões e Serviços, ET-ECS.000.000-GEO/05: Procedimentos para Inspecção de Túneis do Grupo Ecorodovias. Manual Preliminar*. São Paulo, 2022.
- [16] NZ Transport Agency, *Bridges and Other Highway Structures*, NZTA S6, 2022.
- [17] NZ Transport Agency, *Geotechnical Structures Inspection Policy*, NZTA S7, 2022.
- [18] NZ Transport Agency, *Tunnels Management and Inspection Policy*, NZTA S8, 2017.
- [19] ADIF, *Norma ADIF Plataforma: Túneles*, NAP 2-3-1.0, 2023.
- [20] ADIF, *Norma ADIF Plataforma: Inspección Básica de Túneles de Ferrocarril*, NAP 2-4-0.1, 2020.
- [21] ADIF, *Norma ADIF Plataforma – Inspección Principal de Túneles de Ferrocarril*, NAP 2-4-1.1, 2021.
- [22] ADIF, *Norma ADIF Plataforma – Inventario de Túneles Ferroviarios*, NAP 2-5-0.1, 2020.
- [23] Standards for Highways, *Inspection of Highway Structures*, CS 450, 2021.
- [24] Standards for Highways, *Inspection and Records for Road Tunnel Systems*, CS 452, 2020.
- [25] F. Y. Toriumi, T. N. Bittencourt, and M. M. Futai, "UAV-based inspection of bridge and tunnel structures: an application review," *Rev. IBRACON Estrut. Mater.*, vol. 16, no. 1, pp. 1–19, 2023. <http://doi.org/10.1590/s1983-41952023000100003>.
- [26] A. Strauss et al., "Sensing and monitoring in tunnels testing and monitoring methods for the assessment of tunnels," *Struct. Concr.*, vol. 21, no. 4, pp. 1209–1702, 2020, <http://doi.org/10.1002/suco.201900444>.
- [27] J. H. Wang, "Lifecycle cost and performance analysis for repair of concrete tunnels," in *Eco-efficient Repair and Rehabilitation of Concrete Infrastructures*, F. Pacheco-Torgal, R. E. Melchers, X. Shi, N. De Belie, K. Van Tittelboom, and A. Sáez, Eds., Duxford: Woodhead Publishing, 2018, pp. 637–672, <http://doi.org/10.1016/B978-0-08-102181-1.00023-X>.
- [28] Y. Yuan, Y. Bai, and J. Liu, "Assessment service state of tunnel structure," *Tunn. Undergr. Space Technol.*, vol. 27, no. 1, pp. 72–85, 2012, <http://doi.org/10.1016/j.tust.2011.07.002>.

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