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Assessment of the conservation status of reinforced concrete viaducts: a case study of the Recife/Gravatá-PE railroad

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SUMMARY

The deterioration of engineering landmarks, such as bridges and viaducts, is a global issue. The solution lies in the maintenance and conservation of these structures, through a genuine understanding of their conditions and regular inspections. The objective of this study was to assess the overall state of conservation of viaducts, Special Art works (SAW's) located in the designated section of the railway, Central Trunk Line of Pernambuco – LTCPE. To systematically conduct the study, the survey method prescribed by NBR 9452: Inspection of Bridges, Viaducts, and Concrete Walkways - Procedure (Brazilian Association of Technical Standards – ABNT, 2023) was adopted, dividing it into cadastral (preliminary) and detailed inspections, including "graphic and quantitative mapping of anomalies of all visible and/or accessible elements of the SAW" (ABNT, 2023. p. 5). The results revealed issues such as water accumulation, sedimentation, stains, and efflorescence, along with water infiltration in the concrete, attributed to deficient or absent drainage due to incorrect system design and lack of maintenance. Concrete deterioration, and reinforcement corrosion were also, with corrosion stains, fissures, and exposure of reinforcements, caused by carbonation resulting from design errors (insufficient covering) and/or execution errors (formwork, concrete pouring, and form removal). These issues can be initially addressed through corrective maintenance, repair of affected areas, improvement of the drainage system, filling or sealing of fissures, installation of efficient drainage systems, and other repair works. A stability study of these structures is crucial to ensure lasting solutions.

KEYWORDS: Inspection. Special work of art. SWA. Viaducts.

1 INTRODUCTION

The deterioration and increased risks associated with the lack of maintenance of special structures such as bridges and viaducts are a national problem stemming from the deficiency of public strategies focused on their conservatio (SILVA; MONTEIRO; VITÓRIO, 2018).

Despite the evolution of construction methods and designs, bridge collapses still occur worldwide, some resulting in fatalities. Below is the chronology of the most serious accidents involving Special Structures (OAEs) in the last 10 years (Table 1):

Table 1 - Chronology of the most serious accidents involving Special Structures (SWAs)

Date	Event	Location	Fatalities
July 1st, 2013	Bridge collapse in the Piracicaba River.	São Paulo, Brazil	5
June 10. 2014	Collapse of a cable bridge in the Indian state of Gujarat.	Surat – Gujarat, India	10
July 3. 2014	Collapse of the BH viaduct.	Belo Horizonte - MG, Brazil	1
August 3. 2016	Bridge collapsed due to heavy rains near the Raigad district.	Maharashtra, India	28
March 9, 2017	Viaduct collapse on the highway.	Province of Ancona, Italy	2
August 14. 2018	Collapse of the Morandi Bridge.	Genoa – Liguria, Italy	43
March 14. 2019	Footbridge collapses near a station in Mumbai.	Mumbai, India	6
August 8, 2019	Part of a viaduct collapses in the North Zone of Rio.	Rio de Janeiro, Brazil	2
May 2. 2021	Collapse of the Mexico City metro viaduct.	Tláhuac - Mexico City, Mexico	24
April 28, 2022	Overloaded bridge collapses in the Loboc River.	Loay - Bohol, Philippines	4
September 28, 2022	Bridge collapse on BR-319.	Careiro, Brazil	3
October 30. 2022	Reopened after renovations, 19th-century suspension bridge collapses.	Morbi - Gujarat, Western India	More than 141
June 11. 2023	Collapse of Interstate Highway 95 after a tanker truck fire.	Route 73 in Pennsylvania - Philadelphia, United States	1

Source: Adapted from Wikipedia (2024)[1]

[1] **Wikipedia.** List of bridge failures. 2024. Available at: <https:// https://en.wikipedia.org/wiki/List_of_bridge_failures>. Accessed on: January 31, 2024.

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In general, many of these structures are implemented over urban roads or highways, often exposed to heavy traffic of vehicles perpendicular or oblique to their superstructures. This exposes the structural elements closest to the roads to the risk of receiving impacts from vehicles for which they were not designed.

All these incidents demonstrate the need to improve and expand civil engineering knowledge in pathology, inspection, diagnosis, and structural recovery, as well as control over the causes and mechanisms responsible for deterioration processes, in order to minimize the number of accidents and the serious problems in SWAs.

SWA will always be subject to the effects of natural aging, and identifying the true state of conservation of reinforced concrete structures is the initial step to maintaining the desired service life. This enables the promotion of appropriate maintenance practices for their preservation and prevents accidents with fatal damages.

The present study aims to analyze the structural, functional, and durability conditions of railway viaducts located in the municipality of Gravatá-PE, which are part of the Central Railway of Pernambuco (Central Trunk Line), and determine their state of conservation.

2 REINFORCED CONCRETE AND SPECIAL WORKS OF ART

There is a significant need for monitoring and maintaining the integrity of reinforced concrete SWAs which is essential to ensure the safety provided daily by these structures that are part of the daily lives of many users. Nevertheless, there is noticeable neglect from responsible entities, such as the government, in maintaining the operation and maintenance of these structures, which become more complex and costly as they age (CHANG; FLATAU; LIU, 2003; REHMAN *et al.,* 2016; GIBB *et al.,* 2018).

According to the Federal Highway Administration – FHWA (2017), approximately 25% of bridges in Canada and about 7.7% in the United States are in poor condition. It is estimated that in Canada, $50 billion is needed to replace all these assets, and by 2025, the rehabilitation of Special Structures (OAEs) will cost the United States $3.9 trillion. (*American Society of Civil Engineers* – ASCE, 2016).

There is no in-depth knowledge of the overall condition of all Brazilian Special Structures (OAEs). It is estimated that there are about 120.000 bridges in the national inventory. However, Brazilian highways are divided among three governmental levels (federal, state, and municipal), with the private sector also involved (Mendes, 2009). At the federal level, the National Department of Transportation Infrastructure (DNIT) currently has jurisdiction over 6,151 structures (DNIT, 2020).

Through the analysis of the last five years of the DNIT Management Report, it was found that until December 2020, approximately 4.646 inspections of SWAs had been conducted. However, as of May 2021. it is projected that the total number of OAEs under the agency's jurisdiction inspected will reach 6,151 structures, all of which are recorded in the Special Structures Management System database (DNIT, 2020). This number represents an improvement compared to previous years. Nevertheless, out of the total of approximately 4.646

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inspections conducted, only 19.43% (903 structures) were estimated to be in critical condition. This indicates that none of the cited regulations had been followed in the past five years, but the situation has shown some improvement in the last year.

Even with efforts at the federal level in Brazil, the culture of inspecting and repairing SWAs is not yet common, often being carried out only as a last resort when structures are in a critical state. Developed countries are already effectively using management and conservation systems for SWAs, such as the Nevada Department of Transportation (Nevada DOT or NDOT). In North America, inspections typically occur at 24-month intervals, as required by national standards. In the United States, nearly 600.000 bridges are inspected every two years, and depending on their condition, repairs are conducted to maintain their service life. In other parts of the world, different inspection intervals are adopted, such as 48, 72 months, or even longer (NASROLLAHI; WASHER, 2014; PINES; AKTAN, 2002).

3 INSPECTION OF SPECIAL WORKS OF ART

Although various methods and equipment for inspection are available in the market, as demonstrated by authors such as Stochino, Fadda, and Mistretta (2018), Rashidi, Samali, and Sharafi (2016), Rehman et al. (2016), Stanislav et al. (2016), and Hesse, Atadero, and Ozbek (2015), visual inspection remains the most commonly used technique in this type of assessment. This is because it has a simple methodology that not only involves identifying pathological manifestations but also considers the structural characteristics and details of the environmental conditions in which the structure is located. Visual inspection often involves surveys conducted with the naked eye or with the assistance of filming or photographic equipment, which are similarly simple, thus favoring their widespread adoption (SALES *et al.*, 2018; XIE, 2018; PUSHPAKUMARA; SILVA, S.; SILVA, G., 2017).

For this purpose, regulations have been created worldwide, gathering guidelines to ensure the effectiveness of inspection practices and establishing standardized methodologies, providing guidance so that procedures result in uniform and reliable data. According to Sales et al. (2018, p. 292), "in countries such as the United States, Canada, and the United Kingdom, visual inspection guides are used, such as the Strategic Highway Research Program (SHRP) or The Concrete Bridge Development Group Technical Guide 2 [...]". In Brazil, the two main regulations for the inspection of Special Structures (OAEs) are NBR 9452 (ABNT, 2023): Inspection of concrete bridges, viaducts, and footbridges - Procedure and DNIT 010/2004-PRO (DNIT, 2004): Inspections on reinforced and prestressed concrete bridges and viaducts.

4 INSPECTION METHOD

The study segment concerns a designated section of the LTCPE, located in the municipality of Gravatá, where the conservation status of the six reinforced concrete viaducts that make up the section will be assessed. Inspections were conducted between April 2021 and July 2021.

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With the aim of systematically conducting the study in question, the survey method prescribed by NBR 9452 (ABNT, 2023) will be adopted. This standard outlines procedures for inspecting concrete bridges, viaducts, and footbridges.

The procedures outlined in this standard are commonly adopted in Brazil to identify and diagnose the main anomalies present in the structures in question. The routine of this method will begin with a cadastral (preliminary) inspection, followed by a detailed inspection, as described in NBR 9452 (ABNT, 2023. p. 5), presenting the "graphic and quantitative mapping of anomalies of all visible and/or accessible elements of the SWA."

The study area for the development of this work is located in the LTCPE, more precisely in the section of the Serra das Russas crossing in Gravatá. Its strong historical connection to the population of the state of Pernambuco led to its designation as a landmark of the engineering feat that this 19th-century railway represents, due to the construction of its various tunnels and viaducts, SWAs ensuring that the segment of the Recife/Gravatá Railway was designated a historical site through State Decree No. 11.238 of 1986, by the state government, an initiative of the Foundation for Historical and Artistic Heritage of Pernambuco (FUNDARPE) (Pernambuco, 1986). The section in question, located between kilometers 51.54 (Pombos) and 76.04 (Gravatá) of the railway, has a total length of about 25 km.

Regarding the Special Structures (viaducts), the focus of this study, the railway section designated in the Serra das Russas, with approximately 17 kilometers in length, was built at the end of the 19th century between 1886 and 1894. During this eight-year period, 21 tunnels and nine viaducts were constructed, which later reduced to 14 tunnels and six viaducts, as seven tunnels were converted to open sky and three viaducts were filled (Figure 1).

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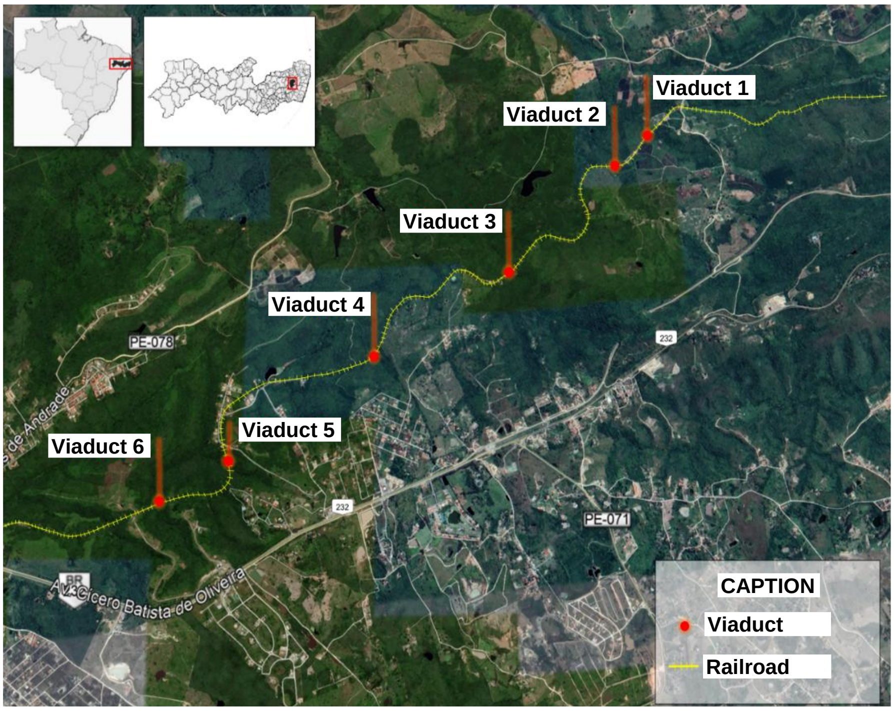
Figure 1 – Viaducts of the Pombos/Gravatá section of the Central Trunk Line.



Source: Adapted from Google Maps (2020)[2].

The viaducts in this section had their original metal structures, made of puddled iron prefabricated pieces, replaced by concrete between 1945 and 1947 by the Great Western Railway. In 1986, the railway section between Recife and Gravatá was designated a historical site through State Decree No. 11.238, as it constitutes a landmark of engineering in the state of Pernambuco (PERNAMBUCO, 1986).

5 ANALYSIS AND DISCUSSION OF RESULTS

The information in this section was gathered through field visual inspection. The data comply with the recommendations of NBR 9452 (ABNT, 2023) for an initial cadastral survey. The original project and previous inspection records were not located. Only the sketch of the structure and its written dimensions were found in IPHAN (2009).

*5.1.1 **Construction Characteristics***

The viaducts presented the following construction characteristics:

Alignment

- Horizontal alignment: straight axis structure;
- Longitudinal slope: 0%;

[2] Google Maps. **-8.193904237245006, -35.517487193131245**. Available at: https://www.google.com.br /maps/@-8.1824213,-35.5073169,4420m/data=!3m1!1e3. Accessed on: January 25, 2020.

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- Transverse superelevation: 0%, and
- Angle of obstacle crossing: crossing perpendicular to the valley axis, no skewness.

Material and Execution

- Structures of abutments, superstructure, midstructure, and substructure of reinforced concrete cast in place with rough wood formwork, except for the masonry substructure.

Superestructure

- Longitudinal structural system: continuous beam;
- Transverse structural system: slab supported by two beams;
- Slab: monolithic;
- Longitudinal beams: constant cross-section in spans, with increased height at intermediate supports;
- Supporting transverse beams: integral with the slab, with height equal to that of the longitudinal beams, and
- Span transverse beams: not integral with the slab, with height lower than that of the longitudinal beams and thickness lower than that of the supporting transverse beams.

Midstructure

- Columns: support at the abutments and two intermediate supports. Columns with support line under the axis of the longitudinal beams;
- Bearings on the abutments (ends): fixed joint type Freyssinet, and
- Bearings on the columns (intermediates): fixed joint type Freyssinet.

Substructure

- Blocks: one masonry block per support line (one under each portal). Two blocks at each end (one for the extreme supports of the superstructure and one for supporting the retaining walls and wing walls of the abutments).

Ends

- Abutment structures: retaining wall, wing walls, and support for the superstructure, and
- Side slopes: variable slope from 1:3 to 1:5, with natural vegetation, without surface protection.

Deck and abutment drainage

- Deck: short PVC scuppers at the bottom of the slab, and
- Abutments: there are no devices for guiding rainwater or surface protection of slopes against erosion.

Expansion joints of the deck

- Joints between the deck and the abutment structures without sealing.

Table 2 presents the main differences in the structures.

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Table 2 - List of Special Work of Art and Construction Characteristics. (continued)

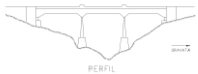
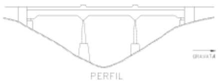
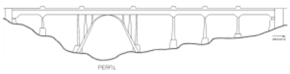
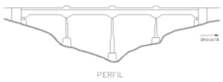
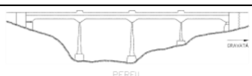
	Sketch	View	Number and length of spans	Maximum height	Pillars	Accessories
Viaduct 1			3 (20.25/ 20.25/ 22.00 m)	22.00 m	Reticulated structure pillars consisting of a two-column portal	There are four refuges (two on each side).
Viaduct 2			3 (20.25/ 20.25/ 22.00 m)	21.50 m	Stiffened wall-pillar	There are four refuges (two on each side).
Viaduct 3			7 (20.25/ 23.00/ 40.00/ 23.00/ 20.25/ 22.00/ 23.00 m)	40.00 m	Pillars of a reticulated structure consisting of a two-column portal	There are 12 refuges (six on each side).).
Viaduct 4			4 (22.00/ 22.00 / 20.25/ 20.25 m)	23.00 m	Pillars of a reticulated structure consisting of a two-column portal	There are six refuges (three on each side).

Table 2 - List of Special Work of Art and Construction Characteristics. (conclusion)

Viaduct 5			4 (22.10/ 22.10/ 20.25/ 20.25 m)	31.00 m	Pillars of a reticulated structure consisting of a two-column portal	There are six refuges (three on each side).
Viaduct 6			4 (22.00/ 20.70/ 20.25/ 20.25 m)	24.00 m	Pilares de estrutura reticulada constituído por um pórtico de duas colunas	There are six refuges (three on each side).

5.1.2 Pathological Framework

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During the inspection, existing problems and possible mechanisms of deterioration, their causes, and extent were identified. Next, the mapping of the pathological manifestations detected in the Viaduct will be shown, based on visual inspection. However, before that, Figure 2 presents the legend used to represent such manifestations.

Figure 2 - Legend of detected pathological manifestations.

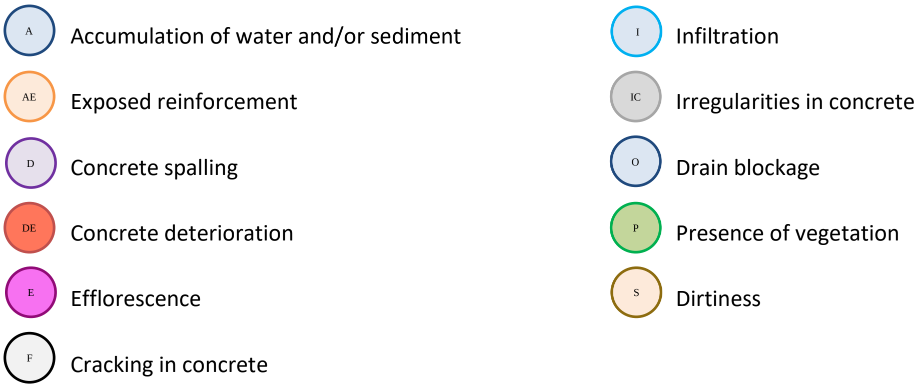
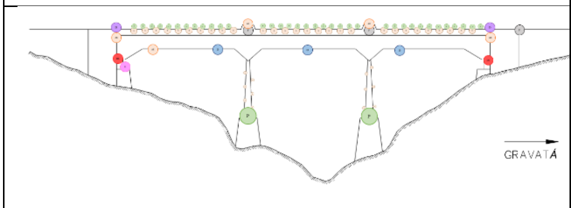
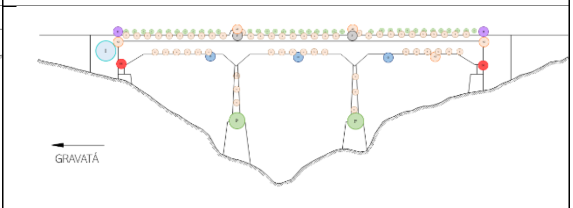
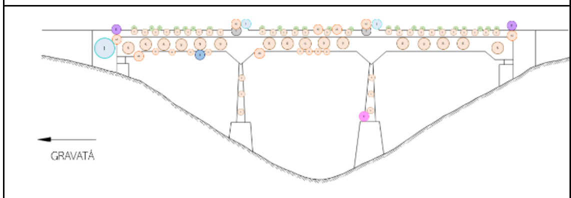
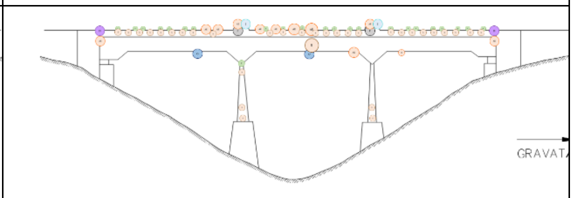
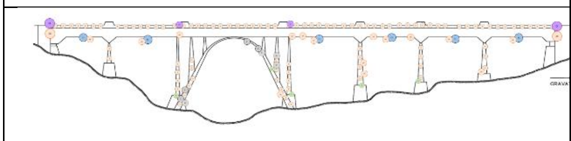
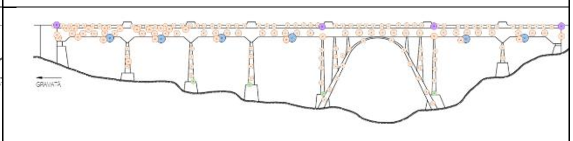


Table 3 presents the right lateral view and left lateral view of the Viaducts, respectively.

Table 3 - Mapping of pathological manifestations.

Viaduct 1	
Rigt/north sideV1	Left/South sideV1
	
Viaduct 2	
Left/South sideV2	Left/South sideV2
	
Viaduct 3	
Left/South sideV3	Left/South sideV3
	
Viaduct 4	
Left/South sideV4	Left/South sideV4

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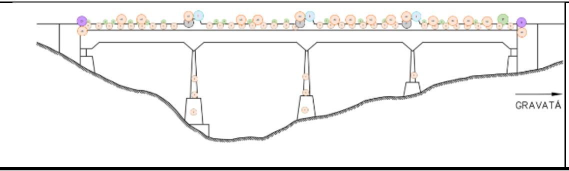
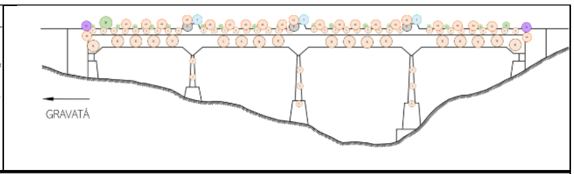
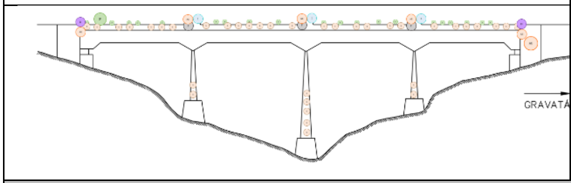
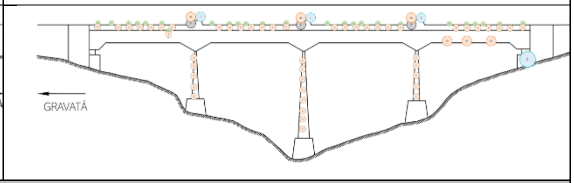
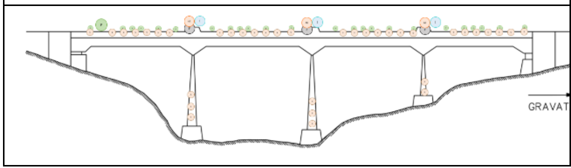
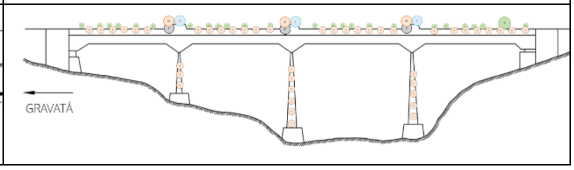
	
Viaduct 5	
Left/South sideV5	Left/South sideV5
	
Viaduct 6	
Left/South sideV6	Left/South sideV6
	

The overall conservation conditions of the structure observed in the preliminary inspection are (Table 4):

Table 4 - Identified pathological manifestations. (continued)

Location	Pathological manifestation	Figure
Expansion joints:	They are not sealed. There was no access for the examination of the concrete elements under the joints.	
Superstructure	Advanced stage corrosion of reinforcements in the spans (I) and in the region of the intermediate supports of the longitudinal beams (II). Cracks and detachment of concrete. Deteriorated concrete and exposed reinforcements at the bottom of the longitudinal beams in all viaducts.	I - Advanced stage corrosion of reinforcements in the spans of V1.  II - Advanced stage corrosion of reinforcements in the central spans of V3.

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Midstructure	Deteriorated concrete and presence of vegetation, mold, and mildew. Reticulated structure pillars with exposed reinforcement due to lack of cover (III).	III - Exposed reinforcement due to concreting error, insufficient cover for steel in V3. 

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Table 4 - Identified pathological manifestations. (continued)

Loc.	Pathological manifestation	Figure
Substructure	Presence of vegetation and white stains indicative of leaching (IV). Advanced stage corrosion of reinforcements in the blocks. Cracks and detachment of concrete. Deteriorated concrete and exposed reinforcements.	IV - Presence of vegetation and white stains indicative of leaching in V2. 
Support devices	The movable support devices are completely crushed (V), in some cases making it impossible to visualize and identify them. Deteriorated concrete and presence of vegetation, mold, and mildew	V – Crushed support devices in V2. 
Accessories	The refuge structures show cracks and fissures on the sides, with concrete detachment, deteriorated concrete, and exposed reinforcements (VI). Crack at the connection between the refuges and the longitudinal beam	VI - Refuges showing cracks and exposed reinforcements in V4. 

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Table 4 - Identified pathological manifestations. (conclusion)

Loc.	Pathological manifestation	Figure
Abutments	The retaining structures of the embankments at the abutments show cracks and fissures in the upper part of the side walls, with moisture presence (VII and VIII), and the abutment slopes are in good condition.	VII - Abutments with cracking, detachment, and exposed reinforcement in V5.  VIII - Cracking in the structures of the abutments of V2. 
Drainage	The tubes installed at the bottom of the slab do not appear to be obstructed, but there are moisture stains and fungi around the drainage holes and in nearby areas, revealing the inefficiency of the system (IX and X).	IX - Bottom of the slab with cracking, detachment, and exposed reinforcement in V5, caused by infiltration.  X - Moisture stains and fungi in the drainage holes of V3. 

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Although many pathological manifestations can be identified, the manifestation that appears to be in the most advanced state regarding severity, urgency, and trend of evolution is corrosion, as there is noticeable loss of section in structural elements in this case.

5.1.3 Diagnosis

In the assessment of the inspections of the works carried out for this study, the grading parameters of NBR 9452 (ABNT, 2023) were used, and for comparison purposes, the grading parameters of DNIT 001/2004 - PRO (DNIT, 2004) were also employed. The grades in these standards range from 01 to 05. However, in NBR, a single value is not assigned to the work; rather, three different parameters are evaluated: structural, functional, and durability. Meanwhile, the DNIT methodology assigns an evaluation grade to each component element according to the severity of the pathological manifestations.

The rating was assigned for the studied works in case the typology of the survey performed was routine, considering the execution of the tests. In Table 1, the structural rating considers the presence of cracks in secondary reinforced concrete elements and exposed and corroded main reinforcements in main elements with section loss. Although it is a deactivated section, no evidence was found to penalize the functional rating for the concrete structure, therefore, the value given was 05, but this rating does not consider the railway or its operational capacity. Regarding the durability parameter, the rating assigned was given due to the presence of exposed reinforcements in main elements in an evolving corrosion process.

Table 1 - Evaluation of the structures

Grades according to the NBR 9452 method (2023)						
PARAMETER	**V1**	**V2**	**V3**	**V4**	**V5**	V6
Structural	3	3	2	3	3	2
Functional	5	5	4	5	5	4
Durability	3	3	2	3	3	2

Grades according to the DNIT method (2004)							
PARAMETER	**DAMAGE**	**V1**	**V2**	**V3**	**V4**	**V5**	V6
Slab	Moisture stain	4	3	2	3	2	2
Longitudinal girders	Concrete spalling and corrosion	3	3	2	3	2	2
Abutment	Cracks	3	3	2	3	2	2
DRAINAGE	Moisture stain around the holes	3	3	3	3	3	3
Pillars	Presence of vegetation, mold, and mildew	4	3	3	3	3	3
Transverse beam	Mold and mildew.	3	3	3	3	3	3
Support device	Crushed	3	3	3	3	3	3
Blocks	Vegetation	3	3	3	3	2	2
Final grade		3	3	2	3	2	2

Some elements could be classified with different grades depending on the column considered in the DNIT parameters. For example, in V1, regarding the longitudinal girders, the column 'damage in the element/structural insufficiency' would be classified as having some damage but no signs of generating structural insufficiency, thus receiving a grade of 4. Meanwhile, the 'corrective action' column would be classified as grade 3. In these cases, we opted for the lower grade to ensure greater safety. Therefore, the Brazilian method shows

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sensitivity and the interference of just one defect, as the most damaged element governs the final grade, which is 3. Thus, the bridge was classified as apparently in good condition.

6 FINAL CONSIDERATIONS

The case study presented in this work is a small demonstration of how the lack of maintenance results in the deterioration of concrete structures. The pathological manifestations presented were largely due to the absence of maintenance over time, mainly because of the condition of abandonment in which the structures are found.

It was found, through inspections and damage maps, that Viaduct 3 is the most damaged. Due to its complex design and its susceptibility to human action, being a spot for adventure sports such as rappelling, as well as Viaducts 5 and 6, located in a less protected area compared to the others, making them more susceptible to the actions of aggressive agents.

The final rating assigned to the structures, according to the parameters established by NBR 9452 (ABNT, 2023), was structural rating 3, functional rating 5, and durability rating 3 for Viaducts 1, 2, and 4, and structural rating 2, functional rating 4, and durability rating 2 for Viaducts 3, 5, and 6. Regarding the DNIT Instruction 001/2002 - PRO (BRASIL, 2004), opting for the lower rating that ensured greater safety, it was a rating of 3 (apparently good) for Viaducts 1, 2, and 4, and a rating of 2 (poor) for Viaducts 3, 5, and 6.

It was found that the main anomalies include water and/or sediment accumulation, stains, and efflorescence, water infiltration into the concrete interior, either congenital or construction-related in origin, caused by poor drainage or absence of drainage organs due to incorrect drainage system design and lack of maintenance. Concrete deterioration and steel reinforcement corrosion were also identified, with the appearance of corrosion stains, cracks, and exposure of reinforcements, caused by carbonation related to design errors (insufficient cover) and/or execution errors (formwork, pouring, and demolding), insufficient drainage, and lack of maintenance.

It is of utmost importance to determine whether, in their current condition, the structures pose any risk to the population, as well as to provide a prognosis to ensure the integrity of the SWAs, in order to enable the reactivation of the section, further fostering tourism in the region.

The problems found, in most cases, can be corrected initially through corrective maintenance by repairing the affected areas and improving the drainage system, filling or sealing cracks, installing efficient drainage systems, and other repair work. It is also important to conduct a structural stability study.

As a conclusion, it can be stated that the use of NBR 9452 (ABNT, 2023) as a guideline for conducting visual inspections is a tool that meets the proposed objectives and ensures a systematic approach to carrying out the activity, thus promoting good results.

In conclusion, it is understood that although the deterioration of large engineering monuments, such as bridges and viaducts, is a global problem, the solution lies in the maintenance and conservation of these structures through a real understanding of their conditions through periodic inspections.

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