Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 06, June - 2025

Hintze Ribeiro Bridge Collapse: Mistakes & Lessons Learned

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Individual article for obtaining credit in the discipline of Structural Analysis
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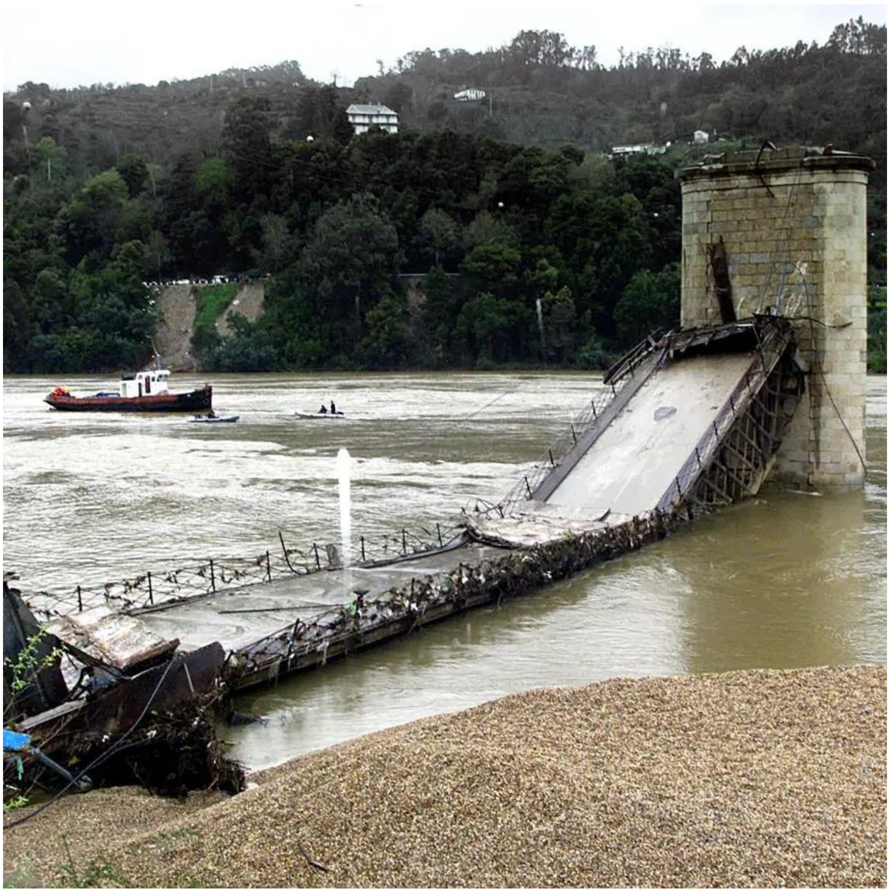

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INTRODUCTION:

During the development of a bridge project, one of the main concerns of the engineer in charge is to ensure that the actions to which the structure will be subjected throughout its useful life, both during construction and in the operational phase, do not exceed its resistance capacity.

However, despite all the technical rigor, it is impossible to guarantee with complete certainty that a structure will always be immune to collapse. This is due to the randomness of external actions (such as natural phenomena) and, above all, to the possibility of serious human errors occurring, whether in design, construction, inspection or maintenance. The history of civil engineering contains several examples of structural collapses that highlight these vulnerabilities.

To achieve this goal, one of the most effective ways is to study and analyze accidents that have occurred in the past, understanding their causes and learning from their mistakes. In this way, we can apply this knowledge to the continuous improvement of future projects, defining safer standards and training more aware professionals.

In this work, the collapse of the Hintze Ribeiro Bridge (Entre-os-Rios, 2001) will be analyzed, seeking to identify the factors that led to the accident, and above all, reflect on how engineering can learn from such events to avoid their repetition.

BRIEF HISTORY:

The Hintze Ribeiro Bridge, located in Entre-os-Rios, began construction in February 1884 and was opened to the public in September 1888. The project and execution of the work were under the direction of Engineer Luciano de Carvalho, who later, in 1895, published a detailed technical report on the construction of the bridge, contributing significantly to the technical record of engineering at the time.

It was built on a bend in the Douro River, near the mouth of the Tâmega River. In the 1980s, the Crestuma–Lever dam was built downstream, and its reservoir reached the bridge, affecting its pillars. Above the bridge are the Carrapatelo dam on the Douro River and the Torrão dam on the Tâmega River, both of which influence the flow of water that passes through there.

Figure 1.
Hintze Ribeiro Bridge in 1908 - Phot.ª Guedes.

International Journal of Engineering Research & Technology (IJERT)
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Figure 2.
Hintze Ribeiro Bridge and the Douro Valley

From the photographs of the Hintze Ribeiro Bridge taken before the construction of the Crestuma-Lever dam, we can see a very small river flow and a huge sandbank. Furthermore, the structure was not immune to the country's historical events. During the Northern Monarchist Revolt in 1919, the bridge was partially destroyed by explosives, which caused significant damage to one of the pillars and the extreme section of the deck, close to the left bank of the Douro River, on the Castelo de Paiva side.

Repairs to the damage began after the preparation of specifications in March 1926, with the rehabilitation work completed in March 1928.

Later, in 1959, the bridge underwent further work, with the widening of the carriageway to adapt to the increase in road traffic and the functional requirements that arose throughout the 20th century. This work did not prevent, however, a few years later, the population and local authorities from calling for an inspection and work on the bridge, which was beginning to show signs of deterioration.

THE COLLAPSE:

On the night of 4 March 2001, at around 9:10 pm, the Hintze Ribeiro Bridge in Entre-os-Rios, an infrastructure that provided a connection between the municipalities of Penafiel and Castelo de Paiva, partially collapsed. The tragedy occurred following the fifth significant flood of the Douro River since December 2000, all with flows exceeding 8,000 m^3/s.

The collapse involved one of the bridge's piers, the two deck spans resting on it, as well as a third adjacent span. At the time of the accident, a passenger bus and, presumably, three light vehicles were crossing the bridge, which fell into the river.

The tragedy occurred after several days of heavy rain, which caused a significant increase in the flow and strength of the current of the Douro River, contributing to the instability of the infrastructure. However, this disaster had a strong national impact, raising crucial questions about the maintenance of the infrastructure and risk management.

BRIDGE DESCRIPTION:

The Hintze Ribeiro Bridge had a total length of 336 meters, distributed over five intermediate sections with 50-meter spans in continuous beam, two extreme sections with 25-meter spans simply supported and two abutments: one of 12.5 meters on the right bank and another of 23.5 meters on the left bank.

The upper platform, intended for road traffic, had a total width of approximately 5.9 metres, including the sidewalks. The main structure consisted of a metal deck in pudellated iron, on which rested a concrete slab and two main beams with a split web, braced between them. Each web was made up of a multiple truss with diagonals and counter-diagonals arranged at 45º.

The intermediate sections of the deck were supported by six granite masonry pillars, with heights varying between 15 and 30 meters, all covered in masonry of the same rock. The extreme sections were supported by stone abutments (granite) and the adjacent pillars.

SUMMARY OF EXISTING REPORT:

Following the collapse of the old Hintze Ribeiro Bridge over the Douro River, which occurred in Entre-os-Rios on 4 March 2001, several technical and expert investigations were carried out with the aim of determining the causes of the incident. These investigations resulted in legal proceedings to determine who was responsible for the incident.

This report presents a summary of the conclusions contained in the Experts' Report on the Collapse of the Hintze Ribeiro Bridge, prepared within the scope of the technical investigation coordinated by VELOSO GOMES et al. (2001).

Firstly, it is essential to carry out a detailed characterisation of the structure of the old Hintze Ribeiro Bridge, in order to allow a more rigorous understanding of the mechanisms that led to its structural collapse. The structure “had a total length of 300 metres, with two 25-metre end spans, simply supported, and five continuous inner spans, with a span of 50 metres. The continuous area of the deck consists of two beams, 4.7 metres high, made up of an upper and a lower flange connected by a multiple truss with bars inclined at 45º. The deck consists of a concrete slab supported by the side beams. The metal beams are supported by pillars, using support devices”.

The damaged pillar, pillar P4, was founded in the riverbed using a method“which was beginning to be used at the time, which consisted of using a metal coffin progressively buried in the alluvium of the riverbed, into which compressed air was injected to allow work to be carried out inside, and from which the alluvial material was removed and replaced with a resistant material”. Based on the inspections carried out and referred to in the report, it is estimated that the plates had“a thickness of 3 millimeters, to which more rigid rings were associated”. The P4 pillar“had a total height of 40.9 meters”. From the inspection report, carried out in 1986“it can be inferred that the height of the pillar itself was around 25 metres and that of the caisson was around 16 metres. The part made with the metal caisson has a cross-section with a length of 9.7 metres, with semicircular ends with a radius of 2.0 metres and a width of 4.0 metres. The partially visible section has a cross-section slightly smaller than the part enclosed by the metal caisson, and is made up of an outer covering in dressed masonry – granite ashlar –, filled on the inside with mortared masonry. The filling of the metal caisson was similar to that of the pillar”.

Despite the differences in the length of the pillars, their cross-sections have identical geometry and similar construction characteristics. All the pillars installed in the bed of the Douro River were built using the same construction technique previously described.

Figure 3 shows a longitudinal diagram of the old Hintze Ribeiro Bridge, which illustrates the evolution of the riverbed level in the bridge section between 1913 and 2001. The morphological changes that occurred in the area will be discussed in greater detail in the following sections.

In terms of any protection measures existing on bridge pillars, it is possible to mention pillar P4 that“at the time of the accident there was no work to protect the foundation, namely rockfill, and everything leads us to believe that it never existed, unlike pillars P2 and P3 which had rockfill protection”.

One of the issues raised in court was related to the state of conservation of the structure, given that the bridge was built at the end of the 19th century. Although the deck had adequate dimensions for the demands of the current road traffic, in particular the impossibility of two heavy vehicles crossing simultaneously, it was stated regarding the structure of the bridge that “the conservation conditions can be considered good overall” and that “in relation to the state of conservation of the pillars, no anomalies were detected in the emerged parts”. Regarding the conservation of the foundation elements, with particular interest to the metal caissons, it is indicated based on an underwater inspection carried out by divers in 1986 that “the iron is in good condition, with only small nodules of rust in several places and is not disintegrated by the knife, while for pillars P2 and P3 it is reported that the iron plate is very corroded, with extensive areas where it no longer exists... (pillar P2) and that the iron or metal alloy that served as formwork... has almost completely disappeared (pillar P3)”. It is also said that “the deck had sufficient resistance capacity for the road traffic that circulated there”.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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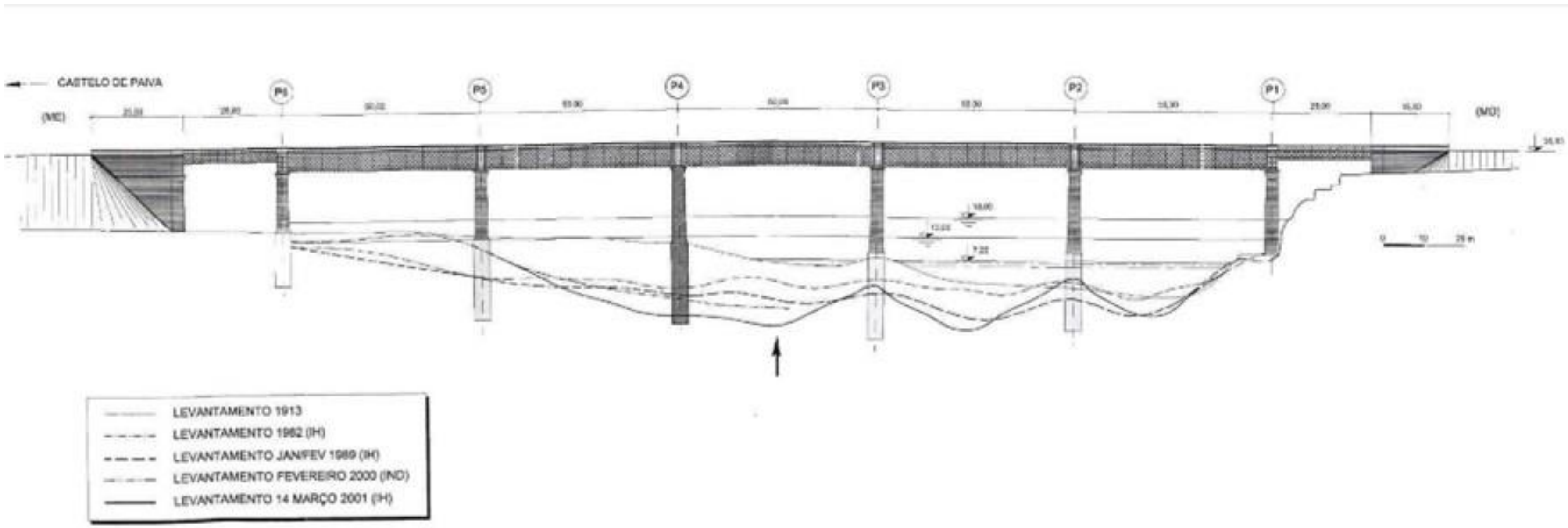

Figure 3.
Longitudinal diagram of the old Hintze Ribeiro Bridge over the Douro River, in Entre-os-Rios, and evolution of the riverbed level in this section between 1913 and 2001.

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International Journal of Engineering Research & Technology (IJERT)
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Throughout this individual presentation work, the importance of the characteristics of the material at the bottom surrounding the foundation elements in the development of erosion cavities was discussed. Specifically, for pillars P2, P3, P4 and P5, which were located in the lower riverbed or in its vicinity, it was identified that they were resting on sandy alluvium by the inspection carried out in August 2001. Therefore, after the collapse of the bridge, it is indicated that the thickness of the sandy material between the base of the foundation box and the granite massif "was of the order of 13 meters in pillar P2, 6 meters in pillar P3, 5 meters in pillar P4, and 4 meters in pillar P5". Table 1 shows the elevations of the alluvium after the surveys carried out in the bridge section by Tecnasol FGE, commissioned by Somague Engenharia, in August 2001.

Table 1 – Alluvial elevations, in metres, after surveys carried out in August 2001, in the section of the Old Hintze Ribeiro Bridge (VELOSO GOMES ET AL. 2001).

Polls	S102	-	S103	-	S104	-	S105	-	S106
Top of the surveys quota	0.97	-	- 7.33	-	- 10.50	-	1.17	-	13.71
Pillars	-	P2	-	P3	-	P4	-	P5	-
Coffin base dimension	-	-8.12	-	-13.97	-	-10.37	-	-6.39	-
Base elevation of alluvium	-1.4	-21.0 (*)	- 24.8	-20.0 (*)	-16.5	-15.3 (*)	- 12.8	-10.5 (*)	-1.3
Thickness of alluvium under the base of the caissons	-	12.9 m	-	6.0 m	-	4.9 m	-	4.1 m	-

(*) Inferred based on survey results

Characterizing the foundation base in geotechnical terms, it can be noted that the "alluvium was compact sandy and gravelly with SPT test values increasing in depth, between 30 strokes, at the top of the formation, and 50 strokes, at the base" and that, below this layer there was "granite with varying degrees of alteration (essentially, W4-5, very altered to decomposed, and W2, little altered) and alternating, which always correspond to high SPT test values".

From an engineering perspective, it is important to understand the structure's failure mechanism in order to analyze the event. "The failure of the deck occurred in the sections close to pillars P3 and P5, as there were forces incompatible with its resistance capacity resulting from the yielding of pillar P4, since the deck was now supported by these two pillars and, therefore, with a span twice as large as the initial one (approximately quadrupling the values of the forces developed), in addition to the dynamic effect developed by the sudden disappearance of pillar P4."

The rupture mechanism presented in the report as being the most likely, despite all the difficulty in characterizing it, is the following:"The base of pillar P4 must have rotated around an axis that is roughly perpendicular to the direction that the pillar is now facing after the collapse (approximately 30º upstream in relation to the axis of the bridge, towards pillar P3). This rotation must have been caused by the fact that the rounded edge furthest north (upstream area) settled, which caused the pillar to lose its balance. After the aforementioned rotation began during the collapse process, the pillar rotated on its own axis, with its right-hand side (north) coming to rest on the riverbed".It is also mentioned that"in the initial stages of the collapse of the pillar, it fractured into two large portions, which may have been caused by some opposition to the collapse that developed at the connection to the deck. The remaining fractures that the pillar presents must have occurred when it settled on the presumably undulating riverbed".

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Figure 4 – Hintze Ribeiro Bridge with high flow after the pillar fell

According to the experts' analysis, the main cause associated with the structural collapse was the occurrence of erosion processes in the alluvial material that made up the foundation, induced by the intense hydrodynamics observed in the vicinity of the event. This condition was aggravated by the extraction of sand in the region, causing the progressive instability of the foundation soil. The report states that "given the speed with which pillar P4 fell, the position it occupied (lying to the side of pillar P3 and making an angle of approximately 30º, upstream, with the direction of the bridge axis) and the bathymetric data that point in this direction, the signatories consider the most likely mechanisms to be those whose main cause is erosion of the ground under the base of the caisson".

From the analysis of the results obtained by various surveys and geotechnical soundings carried out, it is possible to conclude that “in the area where pillar P4 was installed, the lowering of the riverbed was greater than that observed near the other pillars of the bridge, to such an extent that it reached the level of the base of the foundation box”.

Comparing the results of the surveys carried out in 1986 and 2001, it is possible to prove the existence of this process. However,, “it is noted that, in the case of pillar P2, the evolution between the situations detected at the two inspection times is not very relevant. The same is true on the right side of pillar P3, that is, on the side facing pillar P2. On the other hand, on the face of pillar P3 belonging to the gap between pillars P3 and P4, between those two dates, there was a very significant localized erosion of the rockfill, with its elevation next to the face of the pillar having dropped between 7 and 9 meters”.

The fact that no protective measures were placed on pillar P4 when the bridge was built is justified because“when the bridge was built, pillar P4 was located outside the lower bed of the Douro River, except during periods of flooding; a 1913 survey shows that the elevation of the land around the pillar was 11-12 meters”, with the free surface elevation being 7 meters.

The analysis of Figure 1 allows us to observe the evolution of the riverbed level in the bridge section between 1913 and 2000. It is possible to verify the sharp decrease in the height of alluvial material above the base of the pillars' caissons, especially in pillar P4. Between the years of 1913 and 1982, no bathymetric surveys of the riverbed were carried out, which presents a significant time lapse in data collection. Although the behavior over this period is not known, it is plausible to consider that the lowering of the riverbed“it worsened sometime between 1913 and 1982, a time that probably coincided with the construction of the Douro River dams and the increase in the amount of sand extracted, and therefore this worsening was a consequence of these factors”.

Figure 5 shows the presence of deep waters both upstream and downstream of the bridge, using a plan of the area, presented with distorted scales. The depth values indicated correspond to the variations observed between the survey carried out in 1982 and the subsequent survey carried out in 2001, after the accident, by the Hydrographic Institute.

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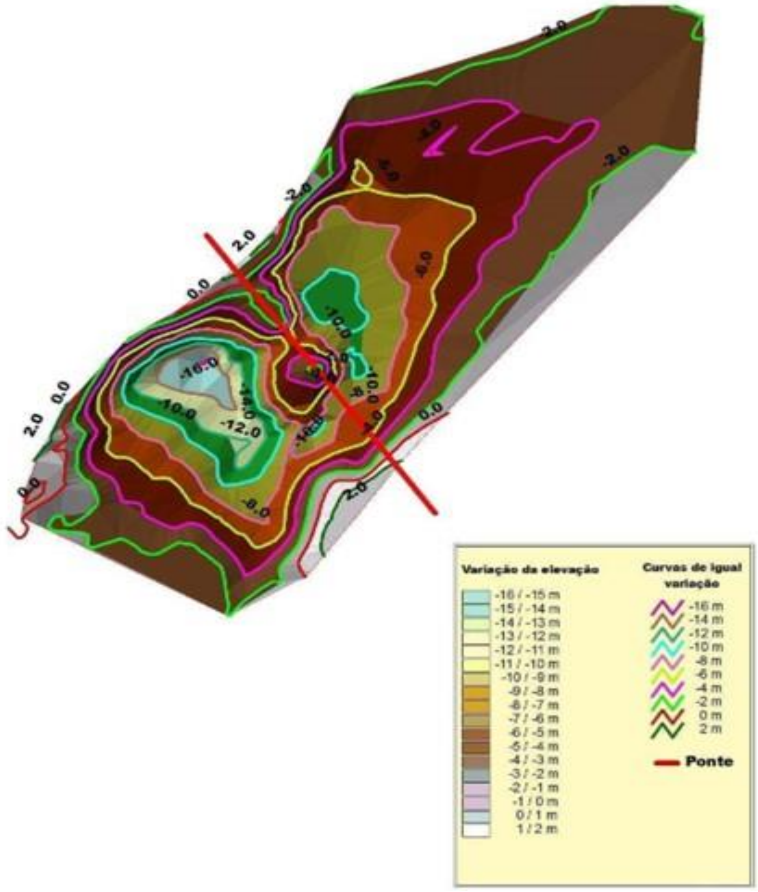

Figure 5 – Change in depths in the area of the Entre-os-Rios Bridge comparing the surveys of the Hydrographic Institute between April 2001 and 1982. Plan with distorted scale (VELOSO GOMES ET AL. 2001).

The development of erosion processes and their ability to remove sediment from the riverbed are directly related to the flow rates that cross the bridge section. As already discussed during the analysis, the 2000/2001 hydrological year presented severe flood conditions on the Douro River. Based on the flow rates recorded by the Carrapatelo Dam, located upstream of the bridge, from 1982 onwards, the following hydrological years stand out:

- “84/85 with average, maximum and minimum values of the average daily flow, respectively, equal to 1026, 4267 and 0 m3/s;
- 89/90 with average, maximum and minimum values of the average daily flow, respectively, equal to 1382, 9547 and 392 m3/s;
- 95/96 with average, maximum and minimum values of the average daily flow, respectively, equal to 1858, 8084 and 96 m3/s;
- 97/98 with average, maximum and minimum values of the average daily flow, respectively, equal to 1224, 3589 and 365 m3/s;
- 95/96 with average, maximum and minimum values of the average daily flow, respectively, equal to 2815, 7737 and 999 m3/s”.

It is stated, based on the flow rates presented above, that “it is in fact the persistence of the flow rate that occurred in the hydrological year of 00/01, reflected in the average value of the average daily flow rate – 104% and 52% higher than those of 89/90 and 95/96, respectively – that explains the radical lowering of the riverbed near pillar P4. In the same sense, it is also worth noting the greatness of the minimum value of the average daily flow rate, much higher than that of any other hydrological year analysed, which means that there were no calm periods that would allow the replacement of some of the solid material eroded on the days with the highest flow rates”. However, it is important to note that up until the date of the bridge collapse, there had already been five floods that year, which had never been seen since the hydrological year of 1727/1728.

Figure 6 shows the flood hydrograph corresponding to the average hourly flows between midnight on 4 March and 12 noon on 5 March 2001.

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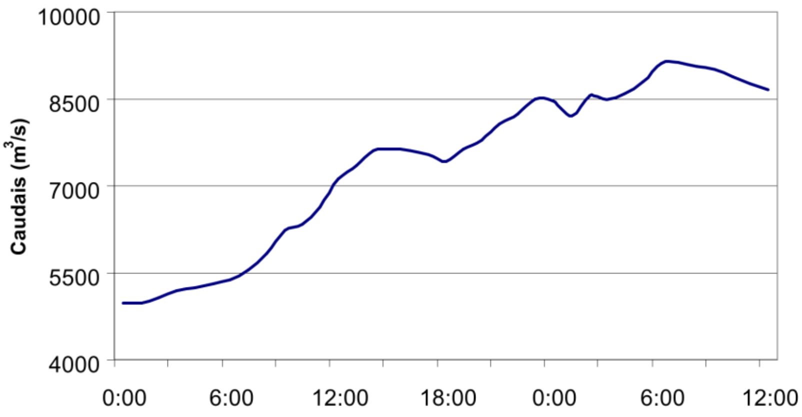

Figure 6 – Flood hydrograph corresponding to the collapse of the bridge.
The flow rates indicated refer to 4 and 5 March 2001.

Another cause identified for the processes that culminated in the collapse of the bridge is the extraction of sand, both upstream and downstream of the bridge section, an activity that is regularly practiced in the region. Years before the accident, the occurrence of clandestine extractions was reported in the press. However, “these hypothetical sediment extractions would be highly detrimental to the safety of the bridge foundations”.

Monitoring of sand extraction in the Crestuma reservoir was inadequate or even non-existent. The same report mentions the “Final Report on the Causes of the Accident at the Entre-os-Rios Bridge” in which it is stated that “the extraction of inert materials in the Douro River, and in particular in the Crestuma dam, continued to be carried out without the support of specific plans and technical studies that demonstrate that, among other environmental values, the integrity of the bed and banks is not affected” and that “there does not appear to be adequate supervision of the extraction of inert materials in the Douro River”.

LESSONS LEARNED:

During an underwater inspection carried out in December 1986 by Underwater Investigation and Technique, ITS, it was found that “the elevation of the ground around pillar P4 was approximately 6 metres below that of pillars P2 and P3”. Unlike the other two, pillar P4 did not have any natural rockfill protection, so it was suggested that it be installed. Warnings were also given about the need for repairs to the footings of pillars P2 and P3. Installing rockfill around pillar P4 was not justified, so the suggestion was rejected. However, in 1989 it was decided to only carry out repair work, “without interventions on the pillars, as there was no capacity to understand that the issue raised by the ITS recommendation regarding rockfill protection of pillar P4 had not been resolved”.

In short, “more than a lack of supervision and maintenance, what appears to have occurred was a lack of clear perception of the possibility of progression of erosion of the bedrock that could endanger the stability of the bridge foundations”. However, the Experts’ Report states that “in 1986, a more in-depth analysis of the situation of the bedrock in the vicinity of the pillar and the foundation conditions would have required corrective or mitigating intervention”.

As previously mentioned, these types of bridges in particular, due to the nature of their foundations, require more detailed visual inspections. However, “as far as we know, there are no regulations or standards in Portugal that stipulate mandatory procedures for the inspection of bridges”.

In Portugal, the inspection and maintenance activity of bridges remains devoid of a legal framework of a binding, systematic and standardized nature at national level, which establishes, in a rigorous and mandatory manner, the technical criteria, methodologies, frequency and types of inspection to be applied, including specialized inspections, such as underwater inspections, which, in the case in question, are fundamental for the preventive detection of structural pathologies, safety assessment and guarantee of the durability of submerged foundation elements.

Although there are scattered regulatory instruments, such as sectoral technical regulations and internal guidelines of concessionaires or infrastructure managers, these do not have the force of universal law.

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Thus, the responsibility for inspection falls essentially on the managers of road or rail infrastructures, such as:

- Infrastructures of Portugal (IP): for bridges on publically managed roads and railways
- Municipal Councils: for bridges on municipal roads
- Private concessionaires: in the case of motorways and other delegated infrastructures

IP, for example, follows procedures based on internal asset management systems, such as SGIPP (Bridge and Pontoon Inspection Management System), which includes routine visual inspections, main inspections and, in specific or high-risk situations, specialized inspections (including underwater inspections) such as this case. However, these practices, although technical, do not derive from standardized legal obligations, and may vary according to internal criteria, budget or operational priorities.

Comparison with International Standards

Unlike the Portuguese reality, several countries have mandatory technical standards, generally integrated into national legislation or directives from federal bodies, which guarantees uniformity, rigor and accountability in bridge inspection and maintenance processes.

United States – FHWA / NBIS

In the United States, the bridge inspection system is governed by the National Bridge Inspection Standards (NBIS), issued by the Federal Highway Administration (FHWA). The NBIS are legally binding and are mandatory for any federally funded bridge on a public highway.

Key requirements include:

- Regular inspections (Routine inspections) every 24 months (maximum)
- Mandatory underwater inspections every 60 months (5 years) for critical submerged components
- Special inspections in case of exceptional events (earthquakes, collisions, floods)
- Certification of inspectors according to federal criteria
- Standardized structural rating system (condition rating).

This robust system emerged after iconic structural disasters, such as the collapse of the Silver Bridge in 1967, and aims to ensure public safety, infrastructure longevity and administrative transparency.

Germany – DIN 1076

In Germany, DIN 1076 clearly and mandatorily regulates the inspection, monitoring and maintenance of engineering works, including road and railway bridges.

- Main inspection (Hauptprüfung) every 6 years, with detailed assessment of all components, including submerged foundations
- Routine inspection (Einfache Prüfung) every 3 years
- Regular (usually annual) visual inspections (Besichtigungen)
- The standard specifies intervention levels, methodologies, and reporting formats
- Strong integration with databases and asset management systems.

France – Instruction Technique pour la Surveillance et l'Entretien des Ouvrages d'Art (ITSEOA)

ITSEOA, in France, is a mandatory technical instruction for public entities that manage bridge inspections and maintenance:

- General inspection (inspection détaillée) every 3 to 6 years
- Simplified inspections with annual or biannual frequency
- It involves visual, tactile and instrumental evaluation, with strict criteria for classifying the state of the structure
- It also covers submerged structures, using certified divers.

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Technical and Safety Implications

The absence of mandatory national regulations in Portugal for bridge inspections, including underwater inspections, raises technical and ethical concerns:

- Accumulated structural and functional risk without timely diagnosis
- Discontinuity in maintenance practices between public and private entities
- Lack of legal liability in case of structural failure
- Uncertainty about the real structural condition of many old and fundamental bridges.

With the advancement of the average age of Portuguese infrastructures and the increase in traffic loads, it is becoming increasingly critical to adopt mandatory standards based on life cycle management and risk assessment.

PREVENTIVE AND CURATIVE MEASURES

IMPORTANCE OF PROTECTION AND PREVENTION MEASURES.

Erosion protection measures are defined as measures introduced into the system consisting of the bridge and the river, with the aim of monitoring, inhibiting, altering, delaying or minimizing river instability or erosion processes on the bridge. These measures can be used to control the slope of the riverbed, protect and stabilize banks and slopes, change flow conditions and provide local protection for bridge pillars and abutments. Monitoring and carrying out periodic inspections of the foundations and the area surrounding the bridge are considered by several researchers to be two types of protection and prevention measures (LAGASSE ET AL. 2001).

PREVENTIVE MEASURES TO BE CONSIDERED IN THE DESIGN PHASE OF A NEW BRIDGE.

Additional protective measures, such as natural or artificial rockfill, gabion systems, etc., should be provided to increase the safety of the bridge. However, they should be a second line of defence to support the structural measures adopted. The designer should take advantage of the fact that he has more options when constructing a new bridge to ensure its stability throughout its service life. In general terms, these options can be described as follows (AGRAWAL ET AL. 2007):

- selection of an appropriate location for the bridge, away from confluences, bends or dams
- construction of a structure with larger spans, reducing flow contraction
- laying of deeper and more stable foundations
- planning and construction of runoff control measures during bridge construction, in order to take advantage of cost savings, since the necessary equipment and labor are already on site.

Choosing the location of the bridge is one of the most important factors in preventing erosion on bridges. Given that the geological and hydraulic characteristics of a river change over time, it is advisable to carry out studies that move the bridge away, if possible, from unstable locations.

Table 2 - Recommendations for the design of new river crossing bridges (adapted from AGRAWAL ET AL. 2007)

Component of the bridge structure	Recommended action	Advantages	Disadvantages
Bridge location	Straight stretches of the river.	More uniform speed profile.	Increase in the size of the bridge with increased costs.
	Avoid curved sections or downstream of curves, confluences and dams.	Reduction of total erosion depth and flow turbulence.	Difficulties in the layout of the plan to ensure that the bridge is located on a straight segment.
Flow direction	Align the abutments and pillars with the flow.	Reduction of local erosion depth due to reduction of flow obliquity	Difficulties in the layout of the plan to ensure that the bridge is aligned with the flow.
Meeting Locations	Placement of the abutments so as not to contract the main bed and, if possible, the flood bed of the river too much.	Desilting is less due to the larger flow section.	Increased bridge costs.
Form of meetings	Adoption of abutments that end on a slope and not on a vertical wall.	Reduction of local erosion at abutments.	Greater work to regularize the walls.
Foundations of the meetings	Placement of piles at greater depths.	The greater length of the foundation piles allows them to withstand greater erosion depths.	Increased costs in carrying out the piles.
Flow guidance structures	Placement of guides upstream of the bridge abutments in order to align the flow with the bridge structure.	Reduction of local erosion along the bridge foundations.	They do not exist.
Location of pillars	Installation of pillars away from the river thalweg.	Reduced erosion due to lateral contraction and lower pillar height.	It is necessary to carry out bathymetric surveys.
Type of pillars	Use of slender pillars.	Decreased tendency for debris to accumulate.	They do not exist.
Shape of the pillars	Adoption of slender shapes, preferably with wedge or circular ends.	Reduction of local erosion due to less interference in runoff.	Increased formwork and labor costs.
	Circular shape.	Good behavior, even in oblique flows.	Increased interference in the flow.
Pillar foundations	Increased depth of piles.	Lower risk to bridge stability due to erosion.	Increased costs in carrying out the piles.
Foundations based on the ground	Placement of foundations below the estimated level for total erosion.	The need to increase the strength of the foundation layers is avoided.	They do not exist.
Foundations based on weathered rock	Determination of rock resistance to erosion.	Erosion risk assessment.	They do not exist.
Rock-based foundations	Installation of rock foundations.	Stability virtually assured even in the presence of erosion.	They do not exist if the rock is not at great depths.
Position of supports	Position of the connecting supports to the deck above the design flood level.	Reduction of damage to supports.	Increase in bridge height.
Bridge slopes	Protection of the banks upstream and downstream of the bridge with erosion-resistant material.	Controlling riverbed width and reducing erosion on the banks.	Additional costs for carrying out protection.
Bridge length	Development of the bridge through multiple spans along the entire flood bed.	Less obstruction to flood flow, reducing erosion by contraction.	Increased costs and expropriations of existing buildings.
Number of spans	From single span to multiple spans.	Redundancy in the number of supports increases the safety of the bridge.	Increased costs in constructing foundations when there are multiple spans.
Length of isolated spans	Increase in its length.	Less obstruction to flood flow, reducing erosion by contraction.	Increased bridge costs.
Bridge bulwark	Preference for walls with openings over solid walls, if the bridge can be crossed during flood conditions.	Increases flow capacity in flood situations and reduces flow contraction.	They do not exist.
Board profile	A curved profile must be adopted in the vertical plane.	Potential increase in the river's flow area.	Increased costs of holding meetings.

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EXAMPLE OF SOME PROTECTIVE MEASURES FOR BRIDGE PILLARS

NATURAL ROCKFILLING

Figure 7 – Bridge pillars protected by natural rockfill. Pinhão Bridge (Portugal)

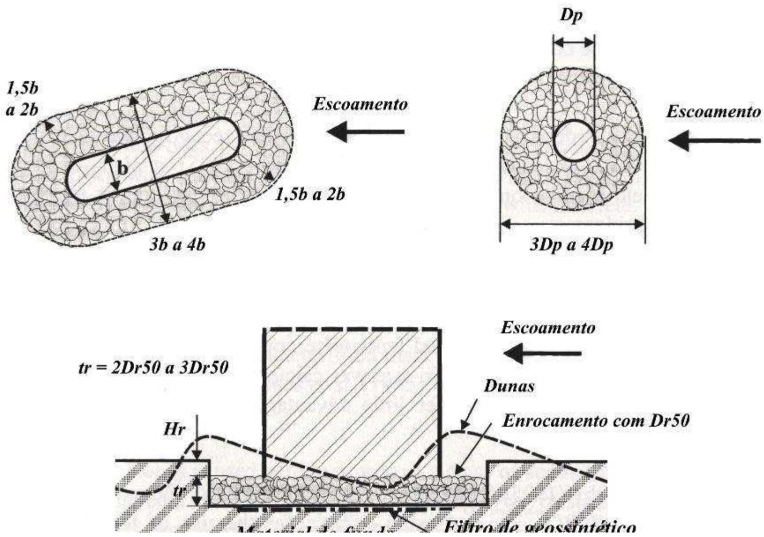

Figure 8 - Recommendations for placing natural riprap on a pillar
(adapted from MELVILLE AND COLEMAN 2000).

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RENO GABIONS AND MATTRESSES.

Figure 9– Example of application of gabion systems in the protection of bridge pillars (https://www.mdpi.com/2673-4117/1/2/13)

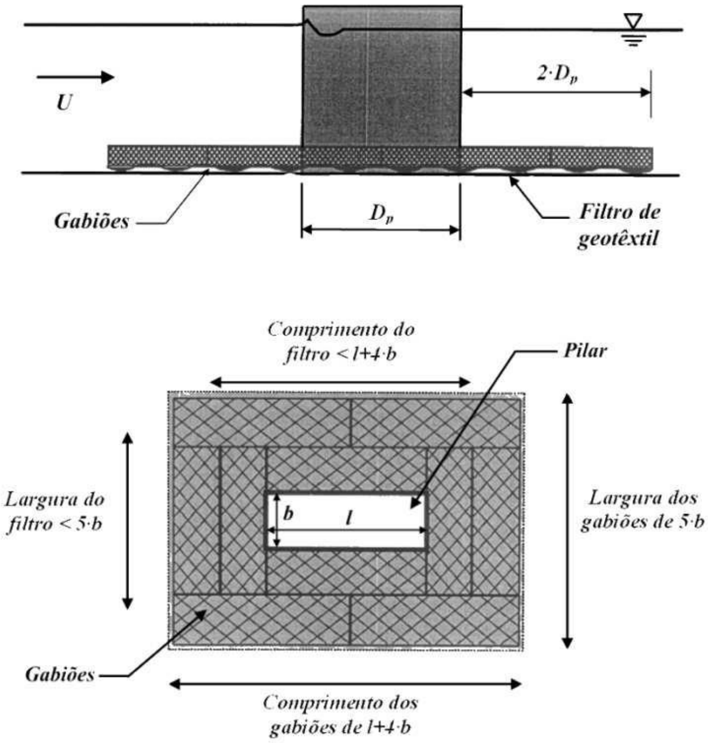

Figure 10 – Construction arrangements for gabion systems on bridge pillars (AGRAWAL ET AL. 2007).

GEO-BAGS FILLED WITH SAND OR GRAVEL.

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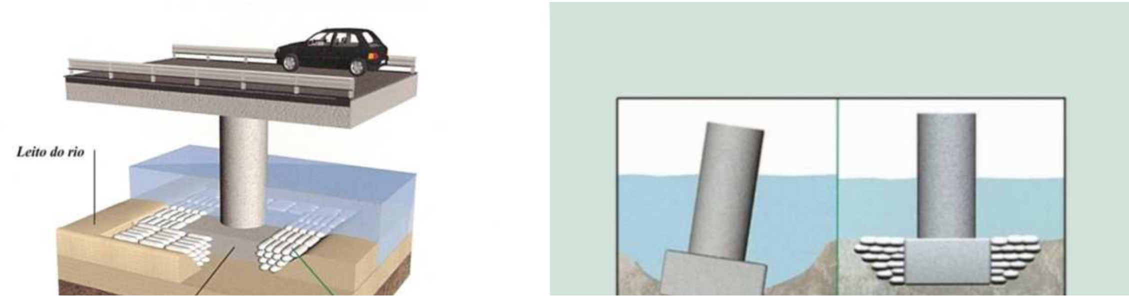

Figure 11 – Application of geo-bags filled with sand to protect bridge pillars (NAUE 2005).

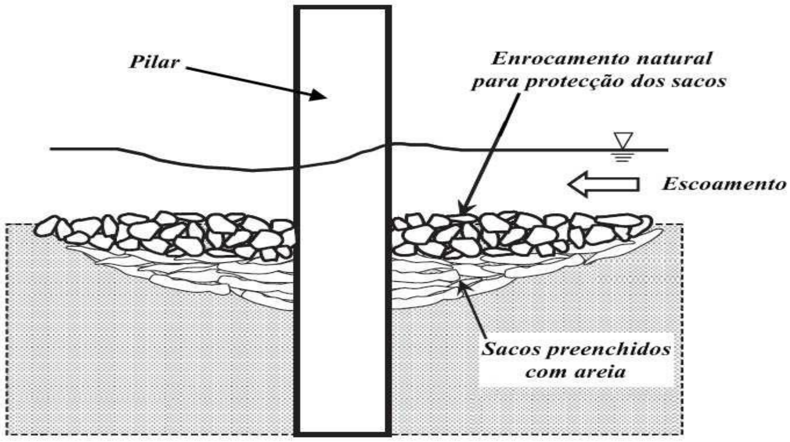

Figure 12- Geo-bags filled with sand placed in an existing erosion cavity and protected with natural riprap (LAGASSE ET AL. 2007).

BRIDGE MONITORING.

Figure 13 – Sonar placement on the upstream face of a bridge pier over the Salinas River in California, USA, to measure local erosion depths

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Figure 14 – Wireless sensors with strain gauge monitoring, accelerometers, and IoT devices that telemetrically communicate data.

CONCLUSION OF THE REPORT:

The study developed allowed an in-depth understanding of the various physical mechanisms associated with the phenomenon of erosion in bridge piers. The main forms of river erosion were analyzed, highlighting the complexity of these processes and the high number of intervening variables, which makes their precise quantification difficult.

The need to predict these phenomena and quantify erosion depths is very important for the engineer because it allows the adoption of measures that can protect the bridge structure.

One of the main conclusions of this study is that the occurrence of erosion phenomena in pillars founded on alluvial beds cannot be completely eliminated, given the natural and dynamic characteristics of these river environments. However, it is possible to significantly mitigate their effects through the adoption of effective protection and prevention measures.

Among the most common solutions, natural rockfill placed around the foundation elements stands out, whose function is to protect the finer soils against the erosive action induced by the turbulence of the flow. In addition to this approach, there are other complementary techniques, such as the use of gabions, Reno mattresses, geo-bags filled with sand or concrete, and even articulated concrete blocks, each with different applications depending on the hydraulic and geotechnical context. Additionally, anti-erosion collars can be used on the pillars and sacrificial piles, with a view to mitigating the localized effects of the excavation.

It was also clear that the most effective solutions are those that are integrated into the infrastructure design phase, particularly in the careful selection of the location, the geometry and orientation of the pillars and the appropriate definition of the depth of the foundations. These preventive measures, when complemented with regular monitoring and inspection programs, especially after extreme events such as floods, constitute the most robust way of minimizing the risk of collapse due to under excavation.

The systematic implementation of underwater inspection plans and continuous monitoring of foundations plays a strategic role in the management of structural safety. These programs not only provide in-depth and timely knowledge of morphological changes in the riverbed, but also enable the rapid implementation of corrective measures, significantly mitigating the risk of instability or collapse associated with erosion processes.

In Portugal, this field still has great potential for development, and it is imperative to promote the standardization and institutionalization of these practices, in order to reinforce the resilience and safety of transport infrastructures.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 06, June - 2025

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