Reinforcement and replacement interventions in some bridges located on Aguieira dam road network

Intervenções de reforço e substituição das pontes inseridas na rede rodoviária da barragem da Aguieira

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Abstract

After an underwater inspections campaign, carried out by IP, S.A. on Aguieira dam road network, it was detected the existence of generalized deteriorations related with the effects of swelling reactions in the concrete, mainly on the submerged elements of 7 bridges.

These bridges, designed by Prof. Edgar Cardoso and built on the 70´s, have prestressed concrete girder decks, with total length between 180 m and 340 m, with longitudinal and transverse prestress beams. All bridges have piers founded on the rock mass foundations under the dam reservoir.

In order to define the reinforcement solution to be performed in each of the bridges, IP, S.A. promoted their structural assessment and monitoring, culminating in the replacement of one bridge and the structural reinforcement of the others.

This paper intends to describe the interventions carried out in these structures, considering the challenge of intervening in deep infrastructures in a dam reservoir, with no traffic restrictions.

Resumo

Na sequência de uma campanha de inspeções subaquáticas promovida pela IP, S.A nas obras de arte inseridas na albufeira da barragem da Aguieira, constatou-se a existência de anomalias generalizadas, principalmente nos elementos submersos de 7 pontes, associadas a reações expansivas no betão.

As pontes, projetadas pelo Prof. Edgar Cardoso e construídas nos anos 70, são em betão armado, com comprimentos totais entre 180 e 340m, com pré-esforço longitudinal e transversal nos tabuleiros. Todas as pontes são fundadas na albufeira da barragem.

No sentido de definir as soluções de reforço em cada uma das pontes, a IP, S.A promoveu a realização dos projetos de intervenção e a monitorização estrutural das obras, culminando no reforço de 6 pontes e na substituição da Ponte Foz Dão.

Este artigo pretende descrever as várias intervenções realizadas nas estruturas, considerando o desafio de intervir em elementos localizados dentro da albufeira, sem restrições de tráfego.

Keywords: Aguieira bridges / Swelling reactions of concrete / Rehabilitation / / Reinforcement

Palavras-chave: Pontes da Aguieira / Reações expansivas / Reabilitação / Reforço

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1 Introduction

The Aguieira dam road network, located in the center of Portugal, was built in the late 1970s, and includes several bridges located in its reservoir.

Within the preparation of a project for the rehabilitation of those bridges, an inspection and testing campaign was carried out, where a set of serious deteriorations were identified in the bridge piers, caused by swelling reactions in the concrete.

According to this situation, Infraestruturas de Portugal, S.A. (National Authority for Road and Rail Infrastructure) decided to define a phased interventions plan, as follows:

- 1st phase – Deck and abutments rehabilitation and structural reinforcement, in order to repair existing anomalies and the structural deteriorations;
- 2nd phase – Piers and foundations rehabilitation and structural reinforcement, since the deteriorations detected, caused by the concrete swelling reactions, required a convenient evaluation of residual expansion, in order to correctly define the scope of the intervention.

Therefore, with the collaboration of the LNEC (National Laboratory for Civil Engineering), it was decided to implement monitoring systems on the bridge piers and to perform a set of complementary tests, in order to evaluate the concrete residual expansion and to evaluate the structural safety conditions.

This paper intends to summarise the various stages of a complex process that culminated with the replacement of Foz do Dão Bridge, and with the rehabilitation works of the remaining bridges.

Thus, it will be described the deterioration found on the bridge piers during the several inspections that were carried out and from the concrete laboratory tests results. It will also be briefly described the structural monitoring system and the dynamic tests performed, in order to guarantee the structural and the users safety, while the bridges were not intervened.

The assumptions and conditionings considered in the rehabilitation, structural reinforcement and replacement projects will also be addressed, as well as described the implemented solutions.

2 Bridges general description

The bridges are located in the reservoirs of Aguieira and Raiva dam, in the following roads:

- IP3, between Cunhedo and Santa Comba Dão, in Viseu district:
  - Cunhedo Bridge over Mondego River
  - Mortágua Bridge over Mortágua River
  - Foz do Dão Bridge over Dão River
  - Santa Comba Dão Bridge over Dão River
- EN234, between Mortágua and Santa Comba Dão, in Viseu district:
  - Criz I Bridge over Breda River;
  - Criz II Bridge over Criz River
- EN234-6, between Vimieiro and Tábua, in Coimbra district:
  - São João de Areias Bridge over Mondego River

Figure 1 Lower view of Cunhedo Bridge [1]

Figure 2 General view of Mortágua Bridge [1]

Figure 3 General view of Foz do Dão Bridge [2]

Figure 4 General view of Santa Comba Dão Bridge [3]

Figure 5 General view of Criz I Bridge [4]

Figure 6 General view of Criz II Bridge [4]

Figure 7 Lower view of São João de Areias Bridge [5]

These girder bridges, made of reinforced concrete, with longitudinal and transverse prestressing, were designed in 1975 by Prof. Edgar Cardoso, and were built between 1976 and 1979.

The bridges have multiple spans, with 30 m length end spans and 40 m length middle spans. The decks are 15,20 m wide, with 4 longitudinal girders with variable height, from 2,00 m up to 2,50 m, and cross girders on the first 2/3 of the span, and above the piers and abutments.

The piers have solid cylindrical shape or hollow diamond shape cross-section, with hammer head in the top, which support the deck through structural bearings.

The abutments are U-abutments type, composed by front walls and wing walls, of the harmonium type, provided by counterforts and supported on footings.

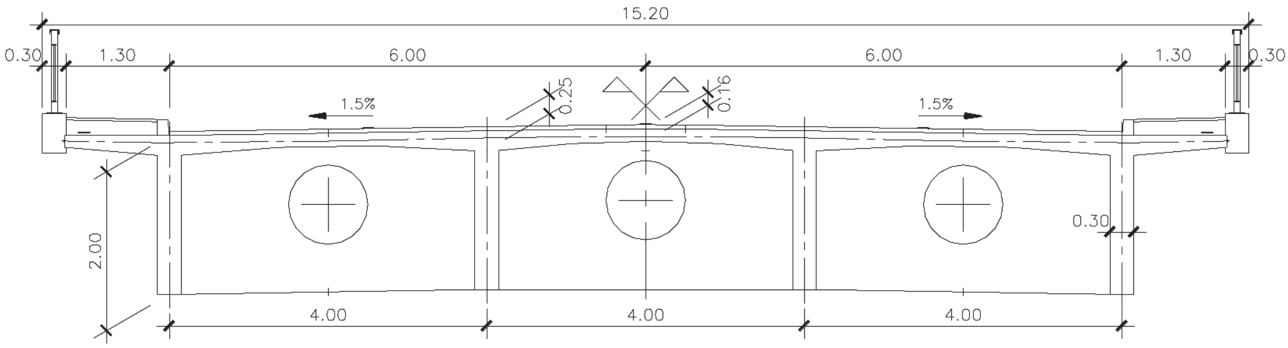


Figure 8 Deck cross section [1]

Table 1 Number of spans, total length and highest pier of each bridge

Bridge	Cunhedo	Mortágua	Foz do Dão	Santa Comba Dão	Criz I	Criz II	São João de Areias
Number of spans	9	5	9	5	5	8	7
Total length [m]	340	180	340	180	180	300	260
Highest pier [m]	25	29	85	31	39	69	51

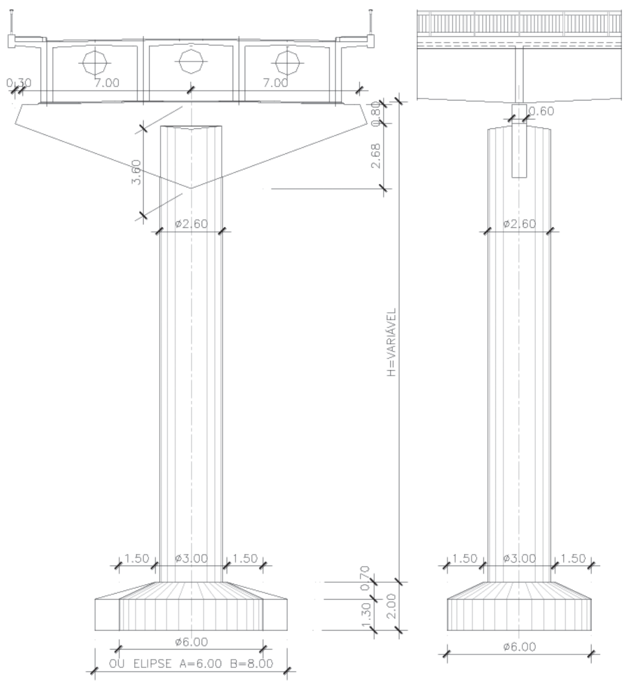


Figure 9 Cunhedo, Mortágua and Santa Comba Dão Bridge piers [1]

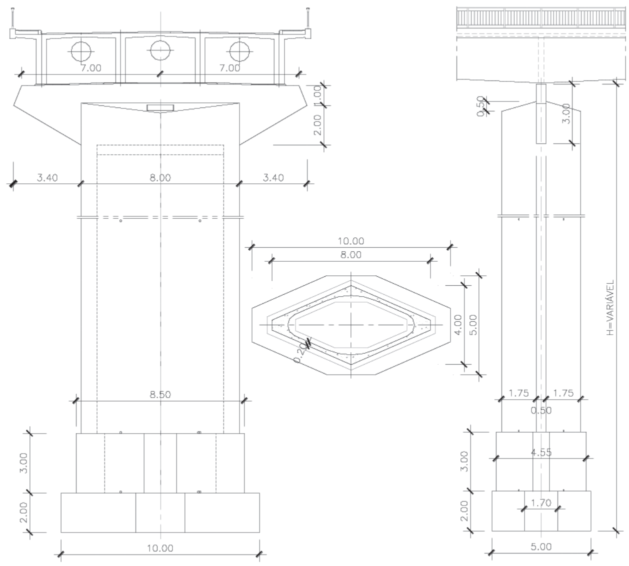
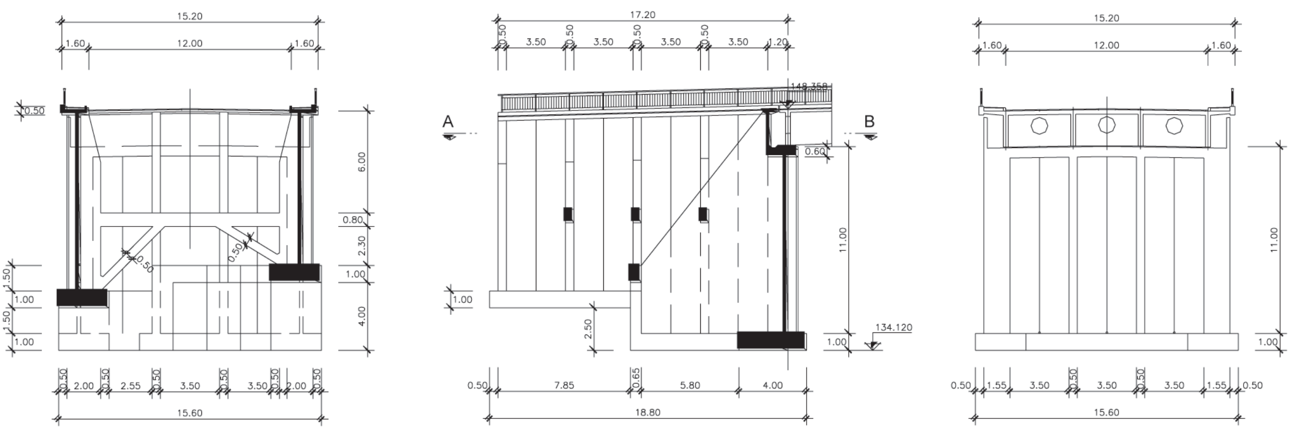


Figure 10 Foz do Dão, Criz I, Criz II and São João de Areias Bridge piers [1]



a) b) c)

Figure 11 Abutments vertical cross section a), longitudinal section b) and frontal elevation c) [1]

3 Detected deteriorations

3.1 Underwater inspections

Through the underwater inspections carried out on the bridges, a set of several deteriorations were observed, as follows:

- Several cracks in piers foundation, particularly at the basement level, with random orientation, typical of swelling reactions;
- Vertical cracking, mainly in the pier/basement connection, over all the piers perimeter, with uniform spacing;
- Vertical cracking in the piers shaft, with some spot zones with steel corrosion and deficient concrete joints.

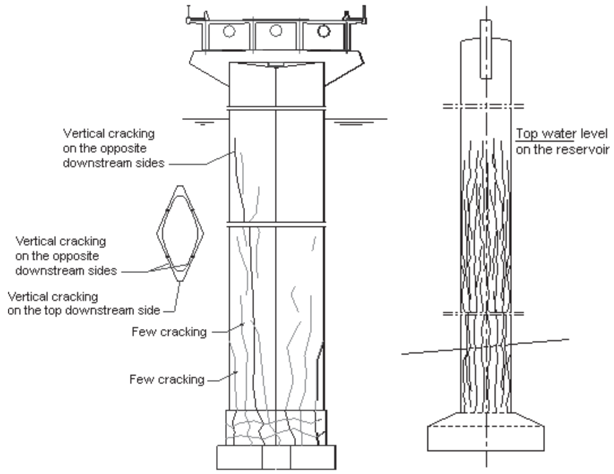


Figure 12 Cracking observed on Foz Dão Bridge piers [1]

3.2 Tests

To better understand the damage process that occurs on the bridges and the potential evolution of the deteriorations that were found, a set of laboratory and "in situ" measurements and tests were carried out, which allowed IP, S.A to promote some corrective measures and define structural rehabilitation and reinforcement strategies.

3.2.1 Assessment of concrete degradation

To characterize the concrete condition, some laboratory tests were carried out on the structural elements of the bridges, in order to assess the causes of concrete deterioration and to evaluate the potential of evolution in a near future, namely:

- Mineralogical analysis by X-ray diffractometry;
- Petrographic characterization;
- Determination of soluble alkalis content;
- Determination of cement content;
- Determination of sulfate content;
- Potential residual expansion due to ASR;
- Potential residual expansion due to DEF;
- Microstructural analysis by SEM (electronic scanning microscopy);
- Evaluation of compressive strength;
- Evaluation of the elasticity modulus;
- Determination of stiffness degradation.

The results of the studies developed by LNEC on these bridges have concluded the presence of internal swelling reactions, namely alkali-silica reaction (ASR) and internal sulphate reaction (DEF). These reactions were manifested through the cracking and deterioration of the superficial layer of the concrete, with more expression in the structural elements in contact with permanent water or water-flow.

The cracking that occurred in some sections of the pier shafts immersed on the reservoir, was predominantly oriented along the vertical direction. This situation was related to the confinement effect in this direction provided by the axial compression to which they are subjected. The development of cracking was in all submerged pier height, sometimes increasing their expression in depth.

The cracking process was more expressive in the pier basements and particularly in areas where tensile stresses or low compressive stresses occur for structural reasons.

According to the LNEC results, the swelling process that occurred was classified as moderate to high, regarding the remaining potential of alkalis (P6 pier of the Criz II Bridge), and low, regarding the internal sulfates, which conducted into a reduction of the concrete elasticity modulus (with greater relevance in P6 pier of Criz II Bridge, P2 and P3 piers on Foz Dão Bridge, P1 and P3 piers on Santa Comba Dão Bridge), being therefore expected the concrete deterioration to worsen over time.

The results of the tests performed by LNEC showed that the deterioration mechanism, due to swelling reactions, led to a significant change in the concrete mechanical properties, particularly the elasticity modulus, which conducted to the structural rehabilitation and reinforcement of 6 bridges and the replacement of Foz do Dão Bridge.

3.2.2 Precision levelling

Several precision levelling surveys were carried out on the bridges deck, with the main objective of detecting possible vertical displacements in the piers, as consequence of the pathologies that were found. The survey results were satisfactory.

3.2.3 Dynamic characterization tests

Dynamic tests were carried out periodically in some bridges in order to identify changes in the dynamic characteristics of the structure, namely the natural frequencies and damping coefficients of their main vibration modes. Since the dynamic characteristics depend on the stiffness and bridge mass, any change in these parameters could indicate an evolution of the structural damage.

The results of these tests allowed to complement the assessment of the structural conditions of the bridges, leading to the implementation of traffic constraints (vehicle weight and speed) in Criz I, Criz II, Foz do Dão and São João de Areias Bridges.

3.3 Structural monitoring

As a complement to visual and underwater inspections that were carried out periodically, a set of monitoring campaigns was also implemented, which allowed assessing the structural behaviour of bridges in the period between the project development and the rehabilitation works.

3.3.1 Before rehabilitation works

For the Criz I and II, Foz do Dão and S. João de Areias Bridges, a structural health monitoring system was implemented, which consisted in the installation of the following equipment:

- Inclinometers, for measuring rotations at the top of the piers;
- LVDT transducers, to measure the movements of the expansion joints;
- Thermometers, to measure the temperature of the deck, bridge piers and air.

This system was operating until the end of rehabilitation works in the structures and the replacement of the Foz do Dão Bridge.

3.3.2 Post-rehabilitation works

During the piers and foundations rehabilitation works on Criz II and S. João de Areias Bridges, it was installed a monitoring system to evaluate its structural integrity, which allows to collect information related to the performance and durability of the rehabilitation and reinforcement systems that were implemented.

The concrete deterioration that resulted from the development of swelling reactions will origin a loss of stiffness in the structures that, according to the structural system that was designed and implemented, will result in a load transfer to the reinforced structural elements.

The structural health monitoring system installed by LNEC [6] comprises the following equipment:

- Extensometers, to measure strains inside the foundations concrete, particularly in the reinforcement elements (piles), as well as on the piers shafts concrete surface, in the lower section of the pile cap;
- Strain-gauges, to measure strains in the jacketing, in the higher section of the pile cap, in order to detect the eventual contribution of this concrete to support the loads;
- Moisture sensors, to measure the original piers shaft permeability, in order to monitoring the possible water access to the original concrete, now covered by the jacketing, finishing mortar and coating applied in the intervention;
- Moisture sensors, inside the piers jacketing concrete, in order to monitoring the evolution of the water conductive conditions to develop rebar corrosion;
- Thermometers, to measure the concrete temperature, inside and on the surfaces.

4 Interventions

4.1 First phase: deck and abutments

The first structural reinforcement and rehabilitation works were carried out on the decks and abutments of all bridges, apart from Foz do Dão Bridge, in order to repair the anomalies and to suppress the structural deteriorations.

4.1.1 Main anomalies

The most common anomalies detected on the decks and abutments were generically of the following types:

- Excessive deflection of the deck, easily observable, with values greater than 5 cm;
- Areas with concrete poorly vibrated or with poor connection between different age concrete at construction joints, with honeycombs;
- Vertical cracks on the longitudinal girders, associated with bending, resulting from the reduced compression introduced by the applied prestress;
- Some transversal cracks on the deck slabs, next to the transversal girders located above the piers;
- Concrete degradation, such as delamination and rebar corrosion, associated to carbonatation effects;
- Crushed or damaged lead bearings;
- Cracks on the transversal girders located above the piers, next to the external longitudinal girders;
- Cracks on the abutments, due to the swelling reactions, and structural defects.

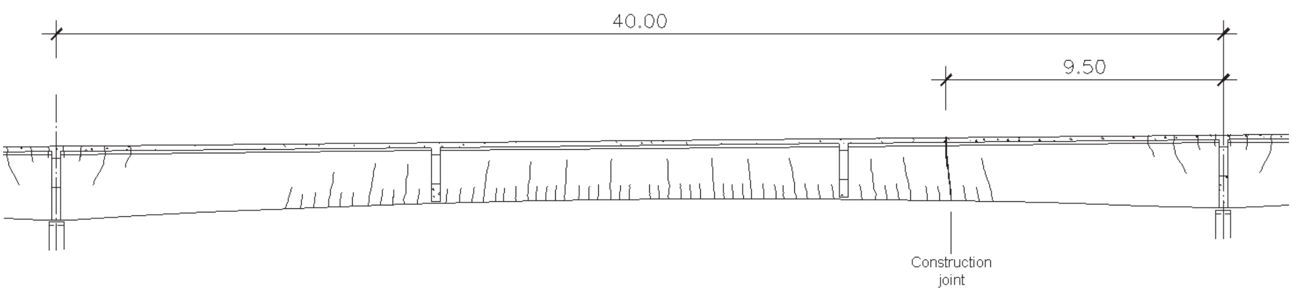


Figure 13 Cracks distribution on the girders [1]

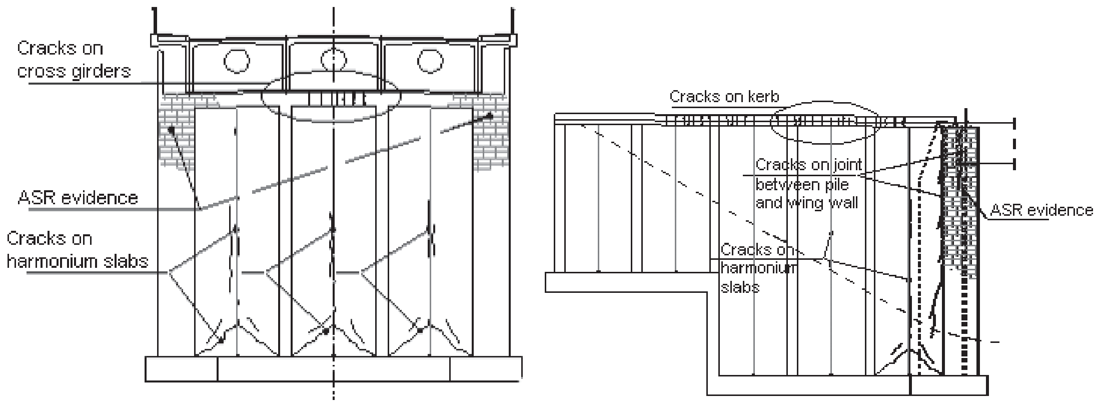


Figure 14 Anomalies detected on the front walls and wing walls of abutments [1]

4.1.2 Structural evaluation

From the limit state verification for the current regulations, resulted de following main conclusions:

- Non-verification of the serviceability limit state (SLS) (deflection and cracking) on the decks and piers shaft, and safety factors for the ultimate limit state (ULS) lower than the prescribed on the regulations;
- Insufficient shear rebar;
- Lack of resistance in some of the piers when subjected to the seismic action.

4.1.3 General description of rehabilitation and reinforcement works

Considering the poor performance of the existing prestress, the deck was reinforced through external prestressing in the four longitudinal girders of the deck. This measure improved the service behaviour of these elements, resulting in an important increase in their performance.

In addition to this measure, the following interventions were also implemented, to reinforce the deck and abutments:

- Abutments reinforcement, through the placing of a slab on the wing walls and counterforts of the existing wing walls and on an alignment of piles built along the road axis;
- Removal of the abutments interior fill until the ground level, in order to reduce the soil pressure;
- Reinforcement of the abutment bearing beams, piers and abutments transversal girders, through jacketing with new elements of reinforced concrete and prestressing application;
- Piers cap beam reinforcement through the adoption of prestressing and jacketing, in order to allow the load transfer from the bearings to the piers;
- Concrete rehabilitation and cracks injection, including coating;
- Expansion joints replacement;
- Structural bearings replacement;
- Drainage systems repair and relocation.

4.2 Second phase: bridge piers and foundations

The second phase corresponded to the rehabilitation and reinforcement works on the piers and foundations, which were carried out in order to repair and correct the deteriorations, after assessing the concrete degradation and residual swelling.

4.2.1 Conditionings

The proposed solutions were conditioned by a set of several aspects that required a sophisticated, highly conceptual and technical reinforcement solutions, as follows:

- Bridges location in the Aguieira dam reservoir, with a level variation around 10 m. The piers shaft have a variable immersed length, about 20 to 30 m, and more than 60 m in the maximum zone;
- Several difficulties on access to the piers shaft and footings;
- The repair process of the piers shaft was not enough to solve the existing deterioration, since the swelling reactions that were observed would be expected on spread footings;
- Proximity of the existing foundation elements (footings and piers basement) to the reinforcement elements;
- Repair works had to be carried out without road traffic interdiction;
- In the case of the Foz Dão Bridge, there are very steep slopes, forming a "V" shape.

4.2.2 General description of rehabilitation and reinforcement works

4.2.2.1 Cunhedo, Mortágua and Santa Comba Dão Bridges

The rehabilitation solution designed for these bridges consisted on the execution of a single shaft, on each pier, keeping the existing cap beam. The shaft cross-section geometry is a ring, which involves the existing one, founded with micro piles. The new shaft walls have a thickness of 0,30 m and an outer diameter of 3,40 m, ensuring a

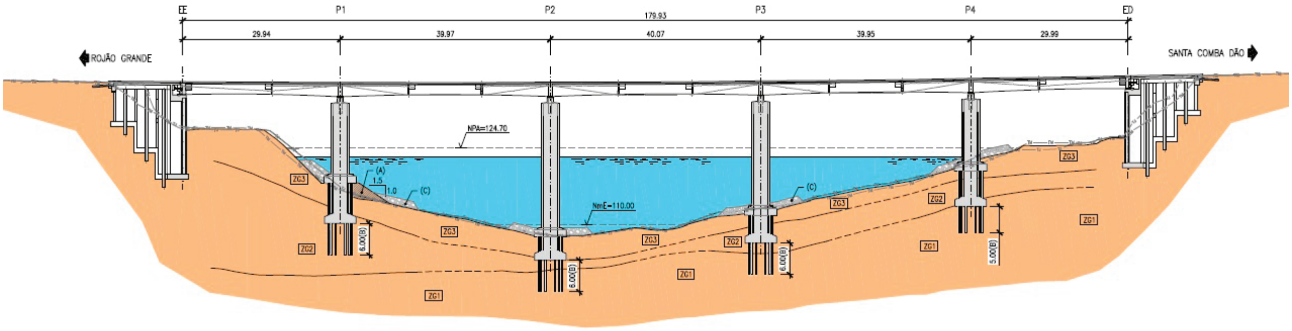


Figure 15 Intervention solution in the foundations of Santa Comba Dão Bridge [3]

clearance of 0,10 m throughout the perimeter of the existing piers, in order to allow its expansion without restrictions, due to the swelling reactions that will continue to take place.

The foundation consists in a set of twelve micro piles with high load capacity, headed by a circle pile cap with an outer diameter of 6,20 m, built, as the shaft, around the existing pier. The micro piles were built from the surface, intersecting the existing footings. At the top (cap beam), the new shaft is connected to the existing one through bolts, throughout the perimeter of the shaft and at a height of about 2,0 m.

It was generally preserved the structural equipment as bearings, expansion joints and oil-dynamic devices, installed during the deck rehabilitation and reinforcement, except in the P7 pier of the Cunhedo Bridge, where it was necessary to change the bearings, from the fixed type to the longitudinal free guided type.

4.2.2.2 Criz I and Criz II Bridges

Structural solutions

The structural solution designed for these bridges consisted of the deactivation of existing foundations and shaft pier sections that are immersed in the reservoir, through the execution of a set of several piles with ϕ1,50 m, headed by a prestressed pile cap in reinforced concrete, transferring the load from the shafts to the new foundation.

The main difficulty of these solutions was related to the execution of the piles and their caps with the use of aquatic and underwater resources, in order to ensure the perfect embedding on the bed rock. To minimize the identified difficulties, during the construction phase a system to guide and fix pile tubes was performed near the bottom, around the shaft and pier basement which also served as pier base confinement.

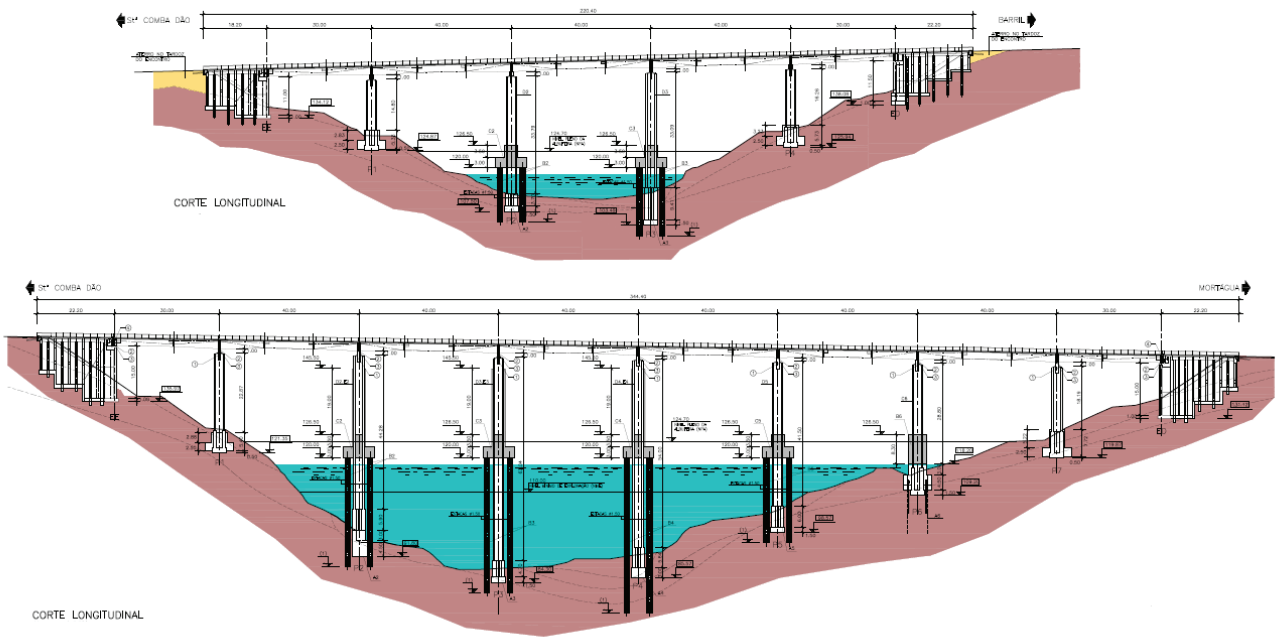


Figure 16 Intervention solution in the foundations of Criz I and Criz II Bridges [4]

Additionally, in P2, P3 and P4 piers of the Criz II Bridge, it was designed the strengthening of the shaft through jacketing with reinforced concrete, above the top of the pile cap. This reinforcement was necessary due to the high stresses in the existing shaft, resulting from local vibration modes associated with the high mass of the pier and water, which exceed their resistant capacity.

The reinforcement of pier basements located outside the reservoir was designed through external and internal jacketing with reinforced concrete, in order to protect these elements against water, and through prestress to confine and to able the load transfer between the pier and the new concrete element.

After finishing the new foundations and the piers jacketing, a set of works were foreseen to repair and reinforce the piers shafts and beam caps, including coating and an application of water-leaking impregnation.

Finally, was also designed the replacement of Criz II Bridge bearings, which included the construction of a new concrete element on the pier cap beams to support the deck during this work.

All solutions presented above allowed to preserve the abutments and deck rehabilitation and reinforcement solutions that were implemented in the first phase, presented in 4.1.

Monitoring during the works

Due the proximity execution of the new piles to the existing pier basements and foundations, and degradation of these elements, LNEC [7] developed a vibration monitoring system to reduce the dynamic impact of works on the piers and foundations, as also to prevent possible dynamic resonance phenomena resulting from the core drill works.

Thus, the implemented procedures above distinguished, allowed to conduct the structural reinforcement of the bridge piers, with a reliable degree of assurance to guarantee the safety of the workers, the road users as also the structures performance.

The monitoring procedure that was developed to assess the dynamic impact of the foundations and bridge piers structural reinforcement, had the following specific objectives:

- Establishing the vibration level limits induced by rock drilling equipment in order to mitigate the risk of increasing the bridge piers deterioration, based on dynamic response simulation models of the structures;
- Definition of procedures to demonstrate the equipment suitability to those vibration limits requirements;
- Assessment and implementation of construction process monitoring measures, as preliminary tests to evaluate the drilling process system, vibrations induced in the structures and observation of the cracking process development.

4.2.2.3 São João de Areias Bridge

The solution designed in this bridge is similar to the one developed to the Criz I and Criz II Bridges. The structural intervention was planned in the submerged areas of the piers below the reservoir top operation level.

This solution has been designed in order to create a redundant system that ensures the structural stability and good performance in service, if the internal swelling reactions continue to occur in the original concrete elements.

The P2 to P4 piers reinforcement consisted on the execution of a

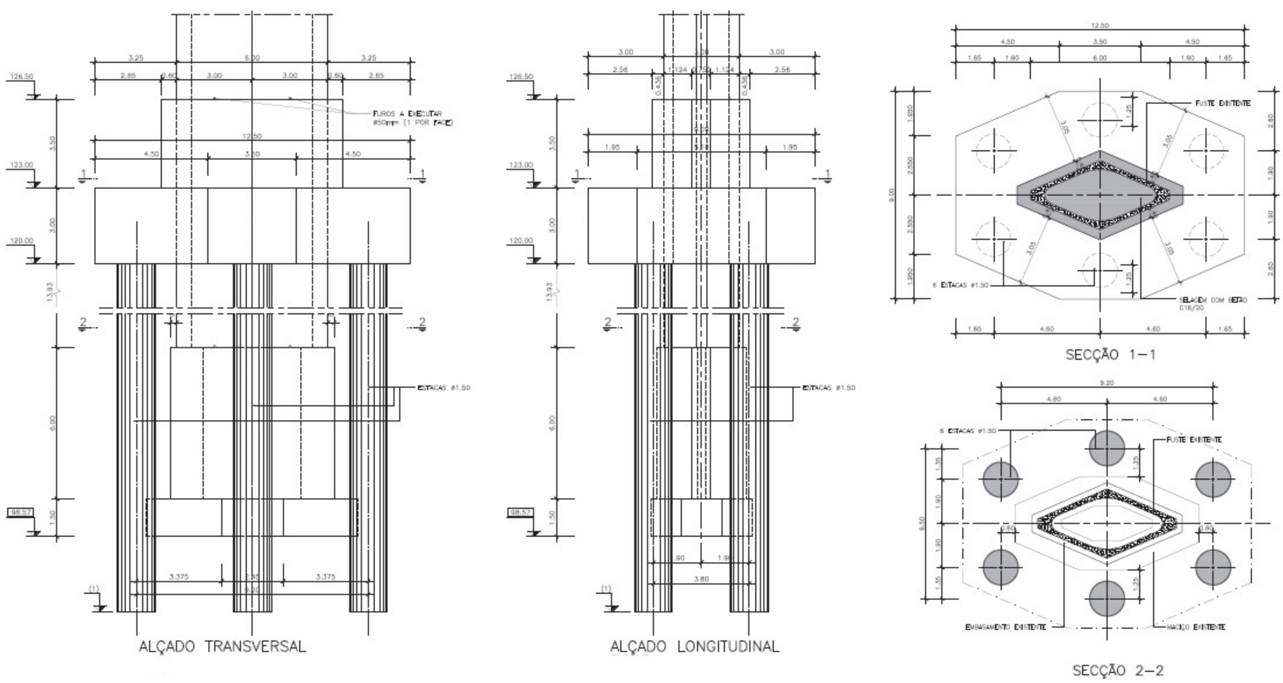


Figure 17 Solution type for the piers in the reservoir [4]

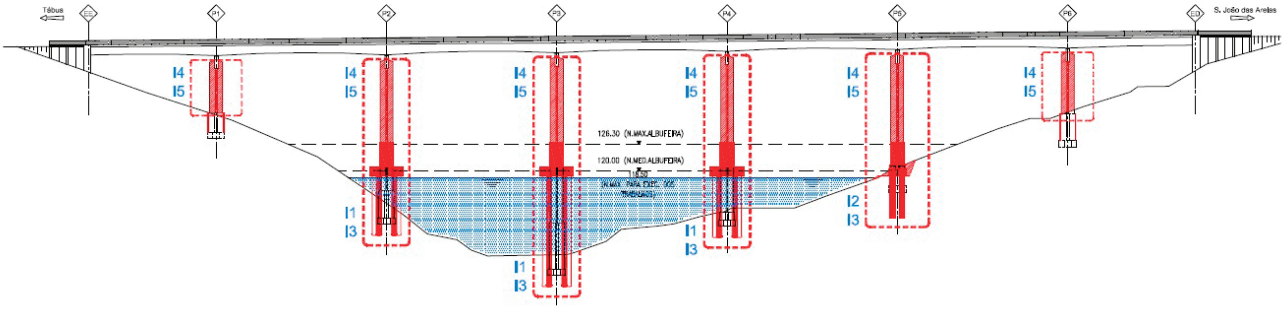


Figure 18 Intervention solution in the foundations of São João de Areias Bridge [5]

set of 6 piles, with ϕ1,20 m, embedding on the bed rock, around the piers, linked to it through a prestressed pile cap in reinforced concrete, where the load will be transferred from the pier shaft to the new foundation in case of deterioration of the existing ones.

In the case of P5 pier, near the river bank, the reinforcement solution was carried out with micropiles around the pier, linked to it through a prestressed pile cap in reinforced concrete with 1,50 m thickness, built at the same height as the others pile cap.

Thereby, it was carried out an external jacketing solution with reinforced concrete around the pier shaft between the upper face of the prestressed pile cap and the maximum level of the reservoir, plus 0,50 m, in order to protect these elements against water and to confine them as well.

Regarding P1 and P6 piers, a reinforcement concrete jacketing of 0,14 m thickness was applied on the outer perimeter of the basement, in order to avoid the contact of the concrete with the underground water.

After finishing the new foundations and the piers jacketing, a set of works were foreseen to repair and reinforce the piers shafts and cap beams, including coating and an application of water-leaking impregnation.

As in Criz II Bridge, due the proximity execution of the new piles to the existing pier basements and foundations, a vibration monitoring system was implemented.

4.2.2.4 Foz do Dão Bridge

The Foz do Dão Bridge piers reinforce and rehabilitation was found to be unfeasible during the intervention design development.

Currently, 3 of the 8 piers that support the deck structure have a permanently submerged height of more than 50 m (the P5 pier is 60 m height), making it very difficult to work at these depths. It is important to underline that the elements with more evident deteriorations, caused by the swelling reactions, are the pier basements, the elements at the bottom of the piers where the shaft becomes larger. Therefore, it wasn't possible to make any reinforcement solution along the piers height (like the ones of Cunhedo, Mortágua and Santa Comba Dão Bridges), once it wasn't possible to use technical and human means to execute correctly these kind of works at the mentioned depths. Another solution would be to execute the reinforcement by jacketing in half of each pier height, supported by a reinforced concrete pile cap located at the medium height of the reservoir, which in turn would be supported by a set of piles, executed with a tube, that would work like piers. This solution was also implemented on the Criz I, Criz II and São João de Areias bridge piers, and showed to be adequate where the reinforcement by jacketing along all the pier height is costly and complex because of the piers submerge height. However, given some of Foz do Rio Dão bridge foundations were very deep, it wasn't possible to guarantee the piles verticality, which makes this solution extremely complex and extremely difficult to perform.

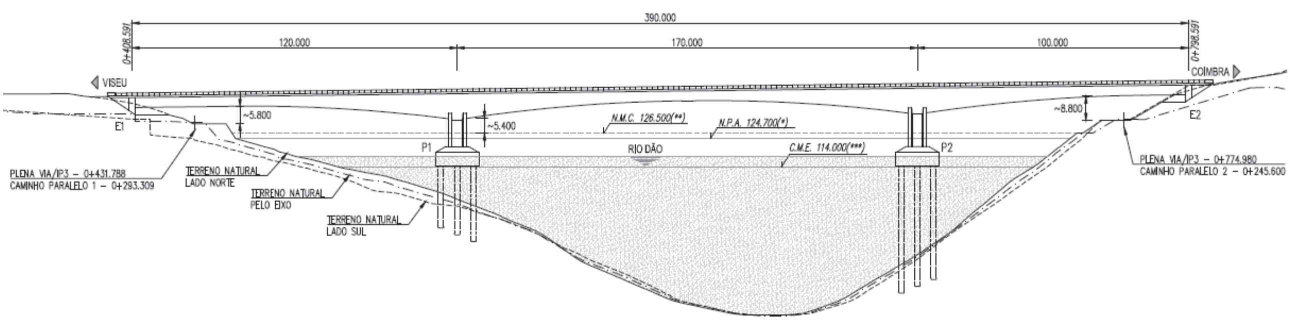


Figure 19 New Foz do Dão Bridge [8]

Thus, the studied solutions included the piers replacement or the full bridge replacement. At the end, the full bridge replacement was proved to be the better solution.

The new bridge deck has a 15 m wide platform, with 3 spans of 120 m + 170 m + 100 m length, performing a 390 m total bridge length.

The deck consists of a monocellular box girder with variable height cross-section, made of prestressed and reinforced concrete. It was cast-in-place using the balanced cantilever method.

The deck/piers connection is monolithic, while the deck is supported on the abutments through bearings.

The piers are made of prestressed reinforced concrete, which cross-section consisting of two parallel walls of constant geometry, with 5,80 m x 1,40 m envelope dimensions.

The pile cap heads a set of 9 piles, with 2 m diameter each, executed using a lost metallic tube, fixed in the bed rock.

Both abutments are made of reinforced concrete and consists on a bearing beam supported on footings, placed on top of jet-grouting columns.

Due to the necessity of using a guide metallic tube to execute the piles, their execution was particularly difficult because of the reservoir depth (30-40 m submerged) and the significant river bank slope. It´s also important to highlight that this was the first time in Portugal where submerged piles were executed at this depth.

5 Final considerations

The results of the inspections and tests performed on this set of bridges confirmed the existence of degradation process resulting from swelling reactions of the ASR and the DEF type. Given the implications on the resistant capacity of the structural elements, mainly piers and foundations, proven by the low value of the concrete compressive strength and elasticity modulus, Infraestruturas de Portugal, S.A., with the support of LNEC, outlined a strategy to rehabilitate and strengthening these bridges.

The design of piers and foundations strengthening was based on the assumption that was possible to maintain the decks, and that this approach was more competitive, in economic terms, than the integral replacement of the bridges. Indeed, during the project development was verified that the applied methodology was appropriate for 6 bridges. Only for the Foz do Dão Bridge was verified to be more advantageous, in technical and economic terms, the integral bridge replacement solution.

The intervention in these bridges consisted of a set of processes that allowed to maintain the bridges safety during the projects development until the structural safety levels reestablishment. For this purpose, specific emergency interventions were adopted over the years, which were not addressed in this paper, but allowed to maintain temporary structural safety levels for the most damaged elements, until the global intervention.

Despite specific evidence in some bridges throughout the country, whose punctual repair/reinforcement and monitoring has been effective, the intervention in the bridges of Aguieira's road network, due to its size, scope and cost, represented the first major challenge to Infraestruturas de Portugal, S.A. regarding to swelling reactions in concrete.

The total investment cost in these bridges, including studies, design, monitoring and execution, was about 33 M€.

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