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Design and execution of restoration work on a low-water crossing platform with a reinforced concrete structure

Projeto e execução da obra de restauração de uma plataforma de travessia em nível com estrutura de concreto armado

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ABSTRACT

Low-water crossings are special structures that play a role similar to bridges, differing mainly in that they are less expensive, as well as in the fact that water can pass partially and temporarily over the roadway. These structures are very common in rural areas, which is why they suffer from a lack of preventive maintenance. This type of structure is often neglected, compromising its quality and causing low-water crossings to have reduced durability and compromised performance. The objective of this study is to examine the design and execution of a low-water crossing built in the 1970s in the Pau Ferro district of in the municipality of Salgueiro-PE, Brazil. It can be concluded that it was built under conditions that limited its durability, and that, with the lack of periodic maintenance, it eventually reached the limit of its usability. With this new restoration, it is hoped that the low-water crossing will be able to withstand the increased flow of heavy vehicles in the region, have a longer service life, and that public authorities will carry out proper maintenance.

Keywords: Low-water crossing, Restoration, Strengthening, Recuperation, Performance.

RESUMO

As passagens molhadas são obras de arte especiais que desempenham papel semelhante ao das pontes, se diferenciam principalmente por serem menos onerosas, como também pelo que lhe caracteriza que é a passagem de água ocorrer parcial e temporariamente sobre a pista de rolamento. Estas obras são muito comuns em zonas rurais, e por este motivo sofrem por falta de manutenções preventivas. Muitas vezes esse tipo de obra é negligenciado, comprometendo a qualidade, fazendo que as passagens molhadas tenham durabilidade reduzida e desempenho questionado. O objetivo deste trabalho é tratar de um projeto e da execução relativo a recuperação e reforço de uma passagem molhada construída na década de 1970, no distrito do Pau Ferro localizada no Município de Salgueiro-PE, Brasil. Pode-se concluir que ela foi executada com condições que limitaram sua durabilidade, e que com a ausência de manutenções periódicas acabou chegando ao limite de utilização. Com esta nova restauração, se espera que a Passagem Molhada suporte o aumento de fluxo de veículos pesados na região, tenha um ganho maior de vida útil e que o poder público realize manutenções.

Palavras-chave: Passagem molhada, Restauração, Reforço, Recuperação, Desempenho.

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Introduction

A low-water crossing is a structure that is part of the group of special engineering structures, since it is based on the principle that these constructions have a purpose of providing continuity to the normal roadbed by overcoming obstacles such as rivers, streams, and other perennial or non-perennial watercourses.

This type of crossing is an alternative with reduced costs compared to bridges, because the roadway (also called a platform in this case), is built on a continuous base of granular material (soil or stone), which is often available from nearby quarries, so that a rockfill can be built to provide continuity for traffic. These structures can include "caissons," which are longitudinal structural walls made of cyclopean concrete or stone masonry, with granular material deposited between them, as well as drainage made up of pipes or cells that cross the longitudinal axis of the road, so as not to interrupt the natural flow of water

An important characteristic of this type of structure is that it has a low height, which reduces the cost of earthworks, walls, and/or rockfill. In times of flooding, the water will therefore flow over the roadway following its natural course, which is its main characteristic and gives it its name. Therefore, the way it works will depend on the level of the water that passes through it.

The superstructure of these crossings is similar to that of bridges, since longitudinal and transverse beams must be provided, as well as central slabs (these being the superstructure of the deck, called a platform). Abutments must also be provided, but due to the low height of these structures, they are smaller. The rockfill low-water crossings do not have structural walls or structured platforms (a superstructure made up of beams and slabs), so their use is more limited to smaller spans with low traffic and less intense flow.

Low-water crossings have a social purpose, because, along with bringing development to a region, they improve the quality of life of the local population and create a leisure space for users. This type of structure, when well designed and executed, is praised by the population of the Northeast region of Brazil, which has major issues linked to droughts.

This study aims to take a descriptive approach to the entire process involved in restoring the Pau Ferro District Low-Water Crossing, located in Salgueiro,

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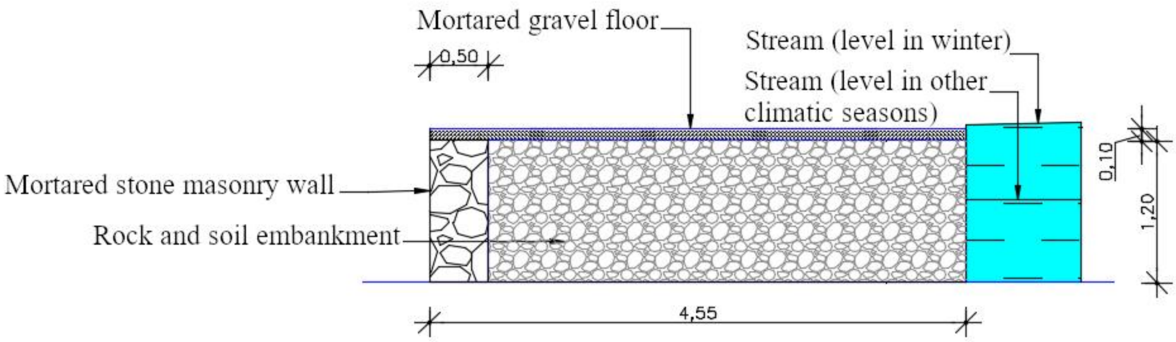
Pernambuco, Brazil. The case study in question deals with a public project located on a state highway, which is a secondary unpaved road called the Estrada do Pau Ferro. The restoration was carried out on a structure characterized as being part of the special projects group, which includes bridges, viaducts, and footbridges, for example.

History and inspection

The low-water crossing was built in the mid-1970s. It was constructed using a simple method that consisted of a rock and soil embankment, with a mortared stone masonry retaining wall, and a layer of compacted and mortared gravel that would serve as a floor, as shown in Figure 1.

The project was designed to make it easier for residents of the Sítio Pau Ferro community to travel to the municipality of Salgueiro, as it would help contain the waters from the Riacho Grande. Agriculture had been developing in the community and this project would make it possible for products to be more easily transported.

Figure 1 - Detail of a cross-section (at meter 41) of the Pau Ferro low-water crossing during its construction in the 1970s, measurements in meters.



Source: Own authorship (2024).

During the 1980s and 1990s, in addition to periodic maintenance, the crossing underwent more extensive repairs, including the addition of buttresses every 4 four meters, to the existing structural wall, as well as the installation of a simple concrete floor to replace the mortared gravel, as can be seen in Figure 2. This configuration of the low-water crossing remained in place until 2021, with only periodic maintenance.

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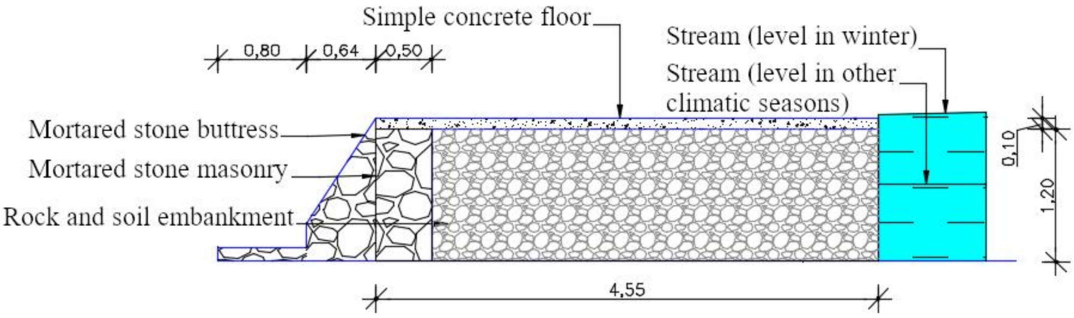
Figure 2 - Detail of a cross-section (at meter 41) of the Pau Ferro low-water crossing after renovations in the 1980s and 1990s, up to the year 2021, measurements in meters.



Source: Own authorship (2024).

In the last five years, the area has received a greater contribution of water from the São Francisco River Transposition Project. The Negreiros dam, located in the rural area of the municipality of Salgueiro, is integrated with the São Francisco River. A failure in the dam occurred, which was repaired. However, it left some openings that allowed water to reach the Riacho Grande.

As a result, the low-water crossing, which previously only had its roadway submerged during floods, is now in use practically all year round. This situation affected agriculture positively and led to further development, with the municipality becoming a major passion fruit and onion producer in the Central Sertão region of Pernambuco, and consequently the flow of heavy vehicles on the highway increased.

Furthermore, the low-water crossing, whose structure was less than robust, suffered more severe damage, compromising the entire simple concrete floor, wearing down the buttresses, and breaking part of the soil and stone rockfill.

Inspection Methodology

For the case study, an on-site inspection was carried out, involving a detailed examination of the condition of the building and its structure. This inspection was classified as a “level 01 inspection,” which consists of an expedited analysis of the facts and of the construction systems inspected, according to the IBAPE Building Inspection Standard (2012). It was also classified as an extraordinary inspection in accordance with the inspection standard for concrete bridges, viaducts, and footbridges, ABNT NBR 9452 (2023), because the damage was caused by natural events.

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According to the criteria of SAMCO (2006) F08a (Guideline for the Assessment of Existing Structures), this assessment is characterized as “non-formal,” a category based on visual inspections, in which the damage assessment routines are based on the experience and judgment of the inspecting engineer, which are more or less subjective.

In this regard, the structural assessment is classified as qualitative (level 0) and based on the engineer's experience, making use of visual signs such as deterioration of structural elements, pathological manifestations, and structural damage.

The inspection was carried out by the Urban Development and Works Department on January 20th, 2021 at 9:00 a.m. It was during flood season, so the water level was higher than the level of the roadway, which made it difficult to work.

The road was highly deteriorated, making it difficult for motorcycles and pedestrians to pass. Accidents had already been reported at the site. The simple concrete floor had been worn down, mainly due to the high traffic of heavy vehicles and the constant flow of water, which had damaged it through the abrasion effect.

Part of the rockfill located between meters 60 and 64 had collapsed and, in some stretches along the roadway, slumping had occurred. The absence of a structural wall on the left-hand side, in the direction of Pau Ferro, was something notable, as it could not have been in full working order due to its size, being a rockfill, or partially rockfill, low-water crossing (since there was only one wall). Figure 3 shows a schematic of the crossing’s sections and the situation observed during the inspection on January 20th, 2021.

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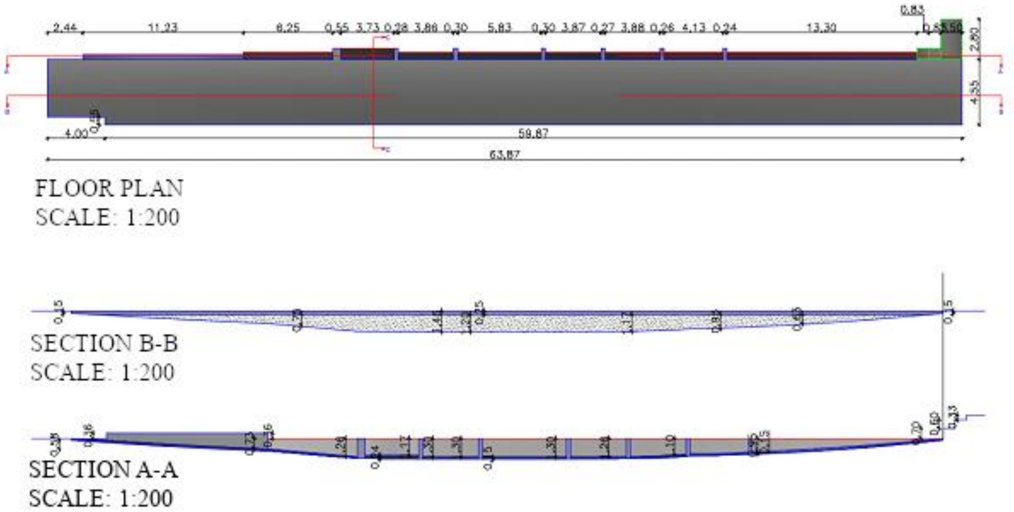
Figure 3 - Floor plan and sections as collected during the inspection, measurements in meters.



Source: Department of Urban Development and Structures, Salgueiro City Hall, Salgueiro-PE (2021).

Projects to restore the low-water crossing

After the completion of the inspection and analysis of what was observed on site and the history of the structure, it was found that immediate intervention was necessary. This time the renovation would require a more severe intervention compared to the maintenance that had been done over the years.

As a result, it was necessary to carry out a drainage study on the site, considering current contributions, and reinforce the structure according to current standards of durability, because the roadway platform has seen a significant increase in traffic and in the number of heavy vehicles that use it.

Drainage Project

The low-water crossing is located in the Terra Nova River basin. This is one of the main tributaries of the São Francisco River and is in the semi-arid region of Pernambuco. According to Padilha, Zanghetin and Ortega (2004), the rainfall regime in this region is characterized by prolonged periods of drought. According to the Ana (2002), the basin has a reasonable volume of water during the region's rainy season, and it has an area of 4909 km². The area of influence for the Pau Ferro low-water crossing is estimated at 98.18 km².

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The following morphometric characteristics were determined: Drainage area (A) and Perimeter (P). The drainage area covers the entire river system delimited by its water divides, projected horizontally, while the perimeter represents an imaginary line formed by the topographic water divide that surrounds the entire river basin. In addition to these, the shape factor (F), compactness coefficient (K_c), circularity index (I_c), drainage density (D_d), and the order of the watercourses were calculated. These formulas are shown below:

$$F = \frac{A}{L^2} \quad (1)$$

$$K_c = 0{,}28 \frac{P}{\sqrt{A}} \quad (2)$$

$$I_c = \frac{12{,}57 * A}{P^2} \quad (3)$$

$$D_d = \frac{Lt}{A} \quad (4)$$

Where A is the drainage area (m²), L is the length of the basin axis (m), P is the basin perimeter (m), the K_c value is a dimensionless number, and L_t is the total length of all the channels (km). The values found were F = 0.036, K_c = 2.54, I_c = 0.152 and D_d = 2.24.

According to Schumm (1956), an I_c equal to 0.51 indicates moderate surface runoff and a low probability of rapid flooding; I_c greater than 0.51 indicates a more circular basin, which favors flooding; and an I_c less than 0.51 characterizes a more elongated basin, which contributes to surface runoff, which was the case found for the site under study.

With regard to the other morphological parameters of the basin, the shape factor found was 0.036. The compactness coefficient of 2.54 shows that the basin is not subject to major flooding under normal rainfall conditions, excluding events of abnormal intensity (CARDOSO et al., 2006). The larger the perimeter, the more irregular the basin and the higher the compactness coefficient (K_c), suggesting that the basin is elongated and not very susceptible to peaks of flooding.

Flow rates are used for various purposes during the design of low-water crossings. The high design flow determines the maximum expected water level and the length of the road that will require surface shielding for cleaning and protection. In relation to recurrence time and low flow rates, they help in designing drainage systems made up of concrete pipes.

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According to Clarkin et al. (2006), in the U.S. Department of Agriculture's official publication on low-water crossings in low-risk situations, designs are generally based on local information, such as rough estimates or field observations of annual flow levels, full flow estimates, high water marks, and estimated traffic delays.

The project under study had a flood area of 98.18 km² with numerous rocky outcrops, shallow soils, thin vegetation cover, and little urbanization. In these situations, low-water crossings without pipes are recommended, with water passing over the platform itself.

Two quantitative approaches need to be considered in the hydrological study of the design of low-water crossings. The first approach involves the use of flow duration data to estimate the typical annual delay time at a crossing and the required capacity of the drainage system. The second approach involves the use of flood frequency data to estimate peak flow values for the design of the total capacity of the structure, and local knowledge of low flow characteristics to determine structural walls, vent size, and estimated delay times.

In low-risk situations, designs are usually based on local information, such as rough estimates or field observations of annual flow levels, full flow estimates, high water marks, and estimated traffic delays (Clarkin et al., 2006). However, it is worth noting that, if this information has been collected over a very short observation period, it may be inadequate for most projects and can lead to failures.

The simplest and most common approach to designing low-water crossings, particularly according to the USDA Forest Service, involves the use of flood frequency analysis. In this approach, the peak flow likely to occur or be exceeded every 'x' year on average (the recurrence interval for that flow) is estimated. This method identifies the probability of exceeding different levels of peak flow, but does not estimate the timeframe in which the road may be closed due to flooding. Crossings are generally designed for flood levels of 50 or 100 years.

With regard to the calculations for defining the length of the platform, the 100-year maximum discharge flow was calculated using the following equation:

$$Q_s = 1150 \cdot \frac{A}{\sqrt{(L \cdot C)} \cdot (120 + K \cdot L \cdot C)} \quad (5)$$

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Where:

Q_s: 100-year maximum discharge flow (m^3/s);

A: Area of the local contributing basin (km^2);

L: Length of the baseline (km);

L_S: Maximum discharge width adopted (m);

C_S: Maximum platform elevation (m);

ME: Maximum flood level (m);

Type of basin (according to Aguiar, 1939) → K = 0,30

→ C = 1,05

Given that:

A = 98.18 km^2

L = 52 km

L_S = 1.00 m (normal design value)

C_S = 1.95 m

ME = 2.95 m

Using this method, the value found for Q_s was 112.04 m^3/s, however, two batteries of three 0.80 m diameter concrete pipes had been allocated, with unit flow rates of 1.15 m^3/s, totaling 6.90 m^3/s. The Q_s value therefore became 105.14 m^3/s.

The following equation is used to determine the length of the platform (width of the spillway):

$$EP = \frac{Qs}{1{,}77\ .\ LS\ .\sqrt{LS}} \tag{6}$$

The value found for EP was 59.40 m with the concrete pipes fully functioning. However, as described, the flow through the pipes will be controlled by representatives of the local community, with the aim of damming water upstream. In this situation, the most unfavorable flow would be one that disregards the concrete pipes, requiring in a platform length of 63.30 m. This demonstrates that the value used for the platform length of 64 meters meets the project's design requirements.

In the low-water crossing under study, the width of the spillway is considered to be 64 m. In addition, it will be equipped with two batteries of three 600 mm diameter culverts that have a total flow of 6.90 m^3/s, which can handle small floods during the winter season. At times of peak flow, the structure itself will function as a spillway.

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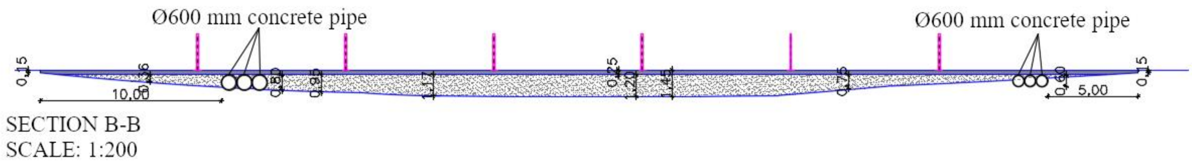
For the drainage project, concrete pipes having a diameter of 600 mm will be laid across the roadbed near the banks, located as shown in Figure 4.

Figure 4 - Location of drainage pipes in the Pau Ferro Low-Water Crossing, measurements in meters.



Source: Department of Urban Development and Structures, Salgueiro City Hall, Salgueiro-PE (2021).

Recovery and Reinforcement Project

After carrying out the inspection and analysis of what was observed on site and the history of the structure, it was determined that immediate intervention should be performed, and that this reform would need to be more extensive compared to the simple maintenance that had been carried out over its lifespan.

The intervention selected would be a recovery and reinforcement project, in which the rockfill on one side would be removed, giving way to another structural wall of mortared stone masonry, forming a caisson with granular material in the middle. The ends would be blocked off with stones in the transverse direction, with mortared stone abutments having entrances that follow the tangent of the roadbed.

The deteriorated concrete floor would be completely removed, along with the layer of gravel still present from other renovations. The rockfill would be excavated to a certain depth, replacing some of the material with compacted sand to allow for the inclusion of a structured platform or superstructure of longitudinal and transverse beams and central slabs.

The conditions taken into account for the project would make the low-water crossing safer, with the addition of the second structural wall and abutments giving the structure greater rigidity and guaranteeing its stability. The superstructure, made up of beams and slabs, would be built on a more solid base. In addition to the same benefits mentioned above for the structural wall, it would complete the caisson system, making it a structured low-water crossing with a rigid floor and guaranteed durability. Figures 5, 6, and 7 show the proposal for the recovery and reinforcement project.

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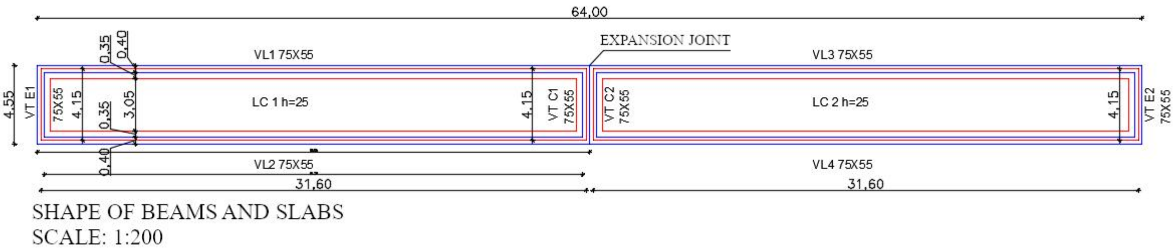
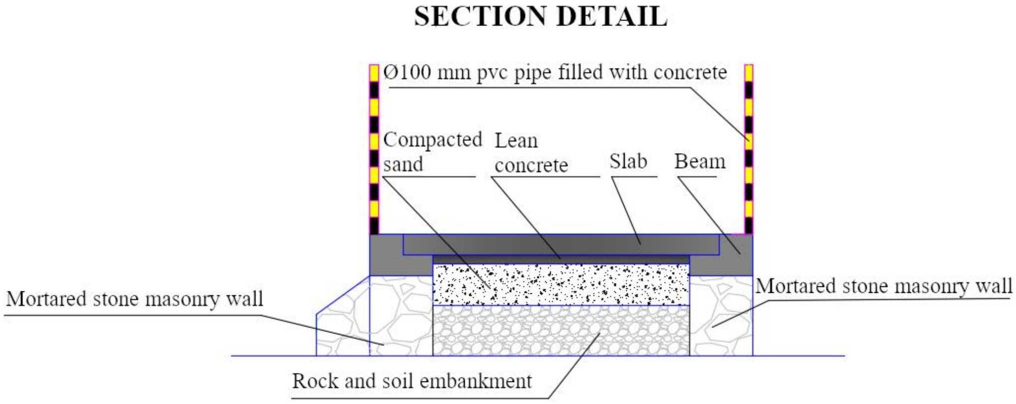
Figure 5 - Blueprint of the superstructure (platform), measurements in meters.



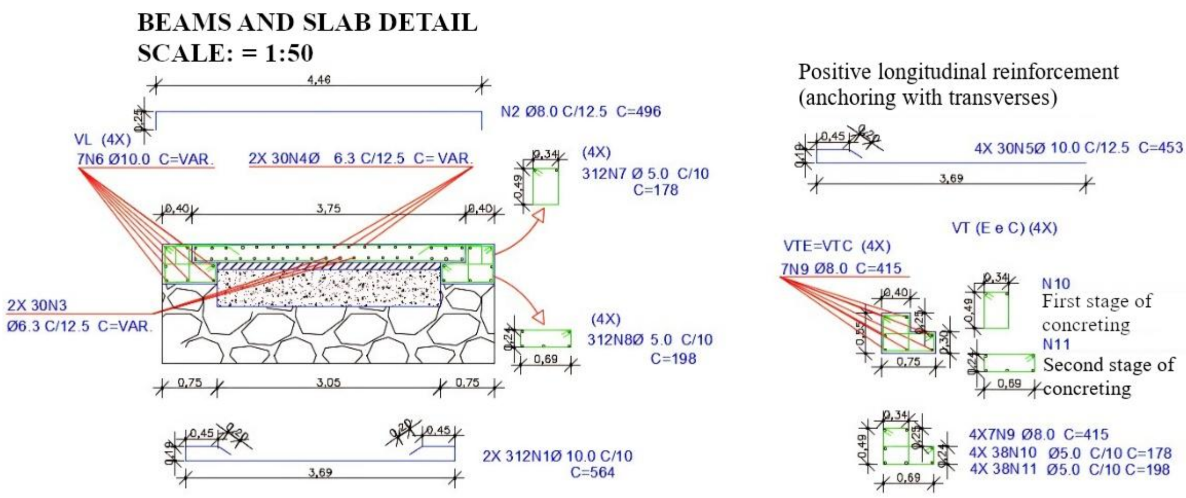
Source: Department of Urban Development and Structures, Salgueiro City Hall, Salgueiro-PE (2021).

Figure 6 - Schematic cross-section detail of the project to restore and reinforce the Pau Ferro Low-water Crossing.



Source: Department of Urban Development and Structures, Salgueiro City Hall, Salgueiro-PE (2021).

Figure 7 - Detail of schematic cross-section of reinforcements for the project to restore and reinforce the Pau Ferro Low-water Crossing, measurements in meters.



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Source: Department of Urban Development and Structures, Salgueiro City Hall, Salgueiro-PE (2021).

Calculation process

The structural elements to be dimensioned and verified belonged to the superstructure (slabs and beams), along with the load-bearing walls (old and new), located in the mesostructure.

For the structural design, criteria were adopted in accordance with the prescriptions established in current norms and standards. It is known that, when it comes to reinforcement and recovery, some factors end up differing from the design due to the conditions in which the project's construction was conceived and financial limitations, however the conditions relating to stability and safety must be respected.

According to the requirements of ABNT NBR 6118:2023, the concrete structure can be considered to be in aggressivity class I, as it fits into the situations indicated in the standard: rural or submerged. The construction site is located in the rural area of the municipality of Salgueiro, and at certain times of the year it is submerged. The risk of deterioration of the structure can therefore be considered low.

For aggressivity class I, the same standard limits the use of concrete to that having a characteristic compressive strength (f_{ck}) of no less than 20 MPa and a water cement ratio (w/c) of no more than 0.6. For this project, values were set higher than the minimum established by the standard, using concrete with f_{ck} of 25 MPa and w/c of 0.55. Values of 3.0 cm were used for overlaps of both the slabs and the beams.

The use of values higher than the minimum indicated by the standard was justified, not only for the increase in structural performance, but also for the gain in useful life of the structure, as the Riacho Grande today receives water from various sources and may have a small amount of sulfates, which are capable of contributing to the degradation of concrete.

The mobile load defined for this project was the TB-240 Brazilian road unit, as it meets the following conditions established by ABNT NBR 7188:2024:

> For projects on one-lane municipal roads and private projects, at the discretion of the competent authority, the mobile load is equal to the TB-240 type, at least, which is defined by a 240 kN type vehicle having six wheels, P = 40 kN, with three load axles 1.5 m apart and a footprint of 18.0

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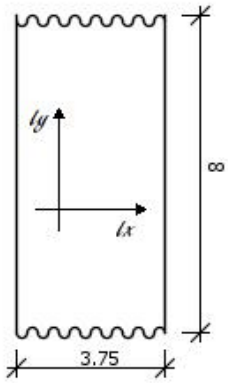
m², surrounded by a constant uniformly distributed load of p = 4.0 kN/m² (ABNT, 2024, p. 4).

Because the project is located on a side road and has a width of less than 7.0 meters (using the criterion of 3.5 m for lane width), it can be considered a narrow single-lane road. Therefore, TB-240 can be adopted for this case.

The structural system to be adopted will be a slab supported by beams, which are directly supported by the load-bearing walls. The slab is the main component of the low-water crossing, as it receives the direct vehicle load and will be the element with the highest steel content. It will be solid, 25 cm thick, and designed using the methodology of the Rüsch Tables (1965) for calculating rectangular slab bridges. Two calculation situations were checked:

- **Situation 1**: Considers a slab simply supported on the beams and with infinite edges at the ends in the direction of traffic (since the ratio $\lambda = l_x/l_y$ is much greater than 2.0). In this situation, the positive bending moments M_{xm} and M_{ym} would have higher values. Table 1 (RÜSCH, 1965) was used, with the face-to-face width measurement equal to 3.75 (l_x):

Figure 8 - Table used for Situation 1.



Source: Adapted from Rüsch (1965).

- **Situation 2**: Considers the slab fixed to the longitudinal and transverse beams. It is known that the design situation does not generate a perfect fixed support, but in order to increase the rigidity of the structural system, especially to avoid excessive deformations in the slab, reinforcement N2 was used for this purpose in the longitudinal beams, and N4 in the

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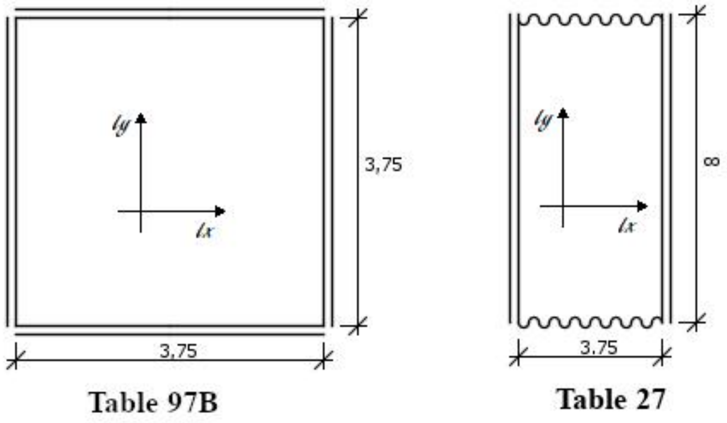
transverse beams (see figure 7). In this way, negative bending moments are formed at the edges of the slab, which will be resisted by the reinforcements described above. Reinforcements N1 and N5 have upper bends which will also reinforce these areas. For this situation, table 27 (considering the ends in the direction of traffic as infinite) and table 97B were used, simulating the regions connected with the transversals, as shown in figure 9:

Figure 9 - Tables used for Situation 2.



Source: Adapted from Rüsch (1965).

The permanent load that the slab will bear is only its own weight, since it will have no upper surface layer. Even though no asphalt layer has been laid on the surface of the low-water crossing, a resurfacing load of 2.0 kN/m² has been taken into account, as the slab could be resurfaced in the future, and this resurfacing will be carried out with cementitious material, mainly because of abrasion. This value is defined in ABNT NBR 7187:2021.

The longitudinal and transverse beams for this project play a fundamental role in the functioning of the structural system. They ensure that the slab does not come into direct contact with the stone walls and will also allow for a significant gain in rigidity as a whole. The beams have an "L" shape (Figure 10) and will therefore have satisfactory rigidity to handle the stresses they will be subjected to.

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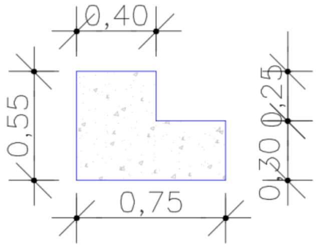
Figure 10 - Cross-section of longitudinal and transverse beams, measurements in meters.



Source: Department of Urban Development and Structures, Salgueiro City Hall, Salgueiro-PE (2021).

In addition to its mechanical performance, the shape is also suitable for construction reasons, as it can serve as a template for making a sand base with the regularization of lean concrete, and later, in the second stage of concreting, it can make it easier to cast the forms for concreting beams and slabs together.

It is important to note that the “L” shape of the beams, together with their construction procedures, allows the element to function both as a brace (in direct contact with the walls, with a larger horizontal dimension) and as a beam itself in the part that will be concreted together with the slabs. These elements can be calculated as beams supported on an elastic base.

An expansion joint was designed in the central region of the platform, making the superstructure work as two independent platforms.

For structural walls in mortared stone masonry, the calculation is similar to that of a retaining wall, which has to withstand the stresses due to the pressure of the earth (internal rockfill), the pressure of the water (Riacho Grande), and the vertical and horizontal stresses coming from the beams. The cross-section of the new wall is shown in Figure 11. Because there were no geotechnical tests for this project, empirical formulations were used. Minimum values were used for stability checks, as prescribed in the ABNT NBR 11682:2009 and ABNT NBR 6122:2022 standards. For the combination of loads, items from ABNT NBR 6118:2023 were used. Figure 12 shows the final state of the structure, which is now functioning.

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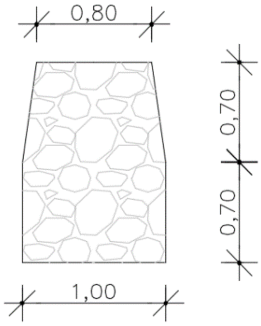
Figure 11 - Cross-section of the new low-water crossing wall, measurements in meters.



Source: Department of Urban Development and Structures, Salgueiro City Hall, Salgueiro-PE (2021).

Figure 12 - Low-water crossing inaugurated and fully operational.

Source: Salgueiro City Hall, Salgueiro-PE (2022).

Conclusions

The aim of this study was to present a case study in which an existing structure was not achieving the level of operation for which it was designed, with unsatisfactory performance that compromised its useful life. This structure had undergone interventions over the years which were merely palliative and the gain in residual useful life was minimal. Following the restoration, it had a significant gain in useful life, though it is clear that preventive maintenance is always necessary.

The intervention featured in this study was practically an entirely new structure for the low-water crossing, which underwent restoration with reinforcement and structural recovery procedures. The ford, which until then had no structured platform, was given a reinforced concrete superstructure, as well as an additional structural wall to form a "caisson," making the system much more rigid

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than the previous one. The existing wall was also recovered and reinforced in some areas.

Although the low-water crossing is a simpler project than a bridge, it is cheaper and provides gains not only structurally, but also in terms of a better drainage system than the previous structure. It also included signage, which is often lacking in this type of project.

Low-water crossings are very common in rural areas and small towns in Brazil, as they are a less expensive option for roads that need to pass over water obstacles. It is worth pointing out that an important stage is that of understanding the needs of the community where the project will be carried out, in order to design functionality that meets local demands. It is therefore very important to calculate the maximum water level and how it will be controlled in the drainage system.

It frequently happens that these projects are neglected, having been carried out with a partial or total lack of a structural system. This type of economy ends up producing user dissatisfaction and generating accident liabilities. Another factor is that if a low-water crossing is executed in a structured way, maintenance will need to be less frequent, and in the long term, the cost-benefit will be greater.

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