The Infant Henrique Bridge over the River Douro, in Porto, Portugal

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1. INTRODUCTION

The public call for tenders for the Design and Build contract of the Infant Henrique Bridge, connecting the cities of Porto and Gaia and located halfway between the Luiz I Bridge and the Maria Pia Bridge, demanded a solution that would have to match the technical and aesthetic qualities of those two bridges, which are both considered great works of structural engineering (Fig. 1).
The responsibility in designing such a bridge was raised further by naming the bridge after the Infant Dom Henrique, the Portuguese Prince who is one of the most distinguished figures of the city of Porto and Portugal and who led Europe on the maritime adventure to meet other civilisations.
The project designers understood that these qualities would have to appear in a discrete manner, without fanfare and embellishment. A bridge that, without supports on the riverbed, without supports even on the banks of the river, would fly as if it were a bird over the noble waters of the river Douro, with great transparency and expressing itself in the purest possible way. This bridge does not contain any decoration. It does not contain anything that does not comply with the functional requirements. Everything in the bridge has a purpose that is both structural and functional. For this reason, it has the virtue of simplicity, structural purity, and geometric regularity.

Fig. 1. Aerial view of Maria Pia, Infant Henrique and Luiz I Bridges.

Keywords: bridge, shallow arch, slender arch, concrete

2. HISTORY OF THE PROJECT

2.1. The city of Porto and its bridges

2.1.1. Porto

“Granitic, baroque, romantic, mirrored in the river ... This is OPORTO”.

CALE means place, where a river PORT developed; the PORT of CALE, that is, PORTCALE, which gave the name to PORTUGAL.

2.1.2. World Heritage

The city of Porto, built along the hillsides overlooking the mouth of the Douro River, is an outstanding urban landscape with a 1,000-year history. Its development on the north bank facing the sun left the hill slopes on the south bank free to accommodate the amphitheatre of Port Wine cellars. Wines that still carry the perfume of Gaia, the beautiful Moorish princess that lived in the castle facing Porto and that gave name to the left bank.

2.1.3. Bridges

Crossing the river Douro from Porto to Gaia has been always a very special experience and an inspiration for the construction of outstanding bridges with the highest regard to the power of the river underneath.

BRIDGE OF BOATS

Provisional boat bridges were assembled for very special occasions since the 10th Century, but the first built to last the entire dry season, from April to October, was open to pedestrian and animals in 1806.

SUSPENSION BRIDGE

The first permanent bridge was a suspension bridge. Its span of 170 m was almost a world record at the time. Designed by engineer Stanislas Bigot, construction finished in 1843 but the bridge was demolished after 44 years only.

BRIDGE MARIA PIA

This work of art is a fundamental mark in the history of railway bridge design and construction. Built by engineer Gustave Eiffel, it is the most famous bridge in Porto. The lightness of the Maria Pia Bridge is extraordinary, with a hinged arch spanning 160 m and setting a *world record* at the time. The opening ceremony took place on the 4th of November of 1877.

BRIDGE LUIZ I

This double deck bridge for trams and motorcars sits splendidly in the local topography. The design of engineer Théophile Seyrig set a *world record* at the time with the two decks supported by the arch spanning 172 m. Construction started in 1881 and it was open to traffic on the 31st of October of 1886.

ARRABIDA BRIDGE

This bridge is an impressive work of art. The double arch spans 272 m and for a while set a *world record* for reinforced concrete bridges. Designed by engineer Edgar Cardoso and built with innovative procedures, the opening ceremony on the 22nd of June of 1963 was an enthusiastic popular event.

SAINT JOHN BRIDGE

Engineer Edgar Cardoso was the designer of this majestic railway bridge over the Douro, taking the trains off the old Maria Pia Bridge. It was open to traffic on the 24th of June of 1991. This bridge is still the *world record* in portal prestressed concrete railway bridges, with a central span 250 m long.

INFANT BRIDGE

A light metro network is under construction in the metropolitan area of Porto, and the central line connecting the commercial and administrative centres of Porto and Gaia was installed in the upper deck of the King Luiz Bridge. A new bridge for the displaced road traffic had to be built 500 m to the East, half way in between the Maria Pia Bridge and the Luiz I Bridge. Therefore, the Infant Bridge takes the centre position between the two masterpieces of the 19th Century.

Evidently, it is a bridge inspired by the works of art designed by the Swiss engineers Robert Maillart and Christian Menn. From the former, is mentioned the Bridge over the Schwandbach stream, built in 1933 and having a span of 37.4 m. From the latter, are referenced the Hinterrhine Bridge, in the Viamala Gorge, and the two bridges with a span of 112 m, built in the second half of the twentieth century, over the Moesa stream on the south slope of the San Bernardino Pass.

3. DESCRIPTION OF THE STRUCTURE

3.1. Conception of the structure

The demand was for a 21st Century Bridge between two bridges of the 19th Century. A bridge with the following fundamental conceptual features:

- High respect for the river underneath and to the magnificent historic bridges in Porto; it does not compete with them; it only tries to come up with a new solution that is discreet in the form and elegant, with the highest technical purity and advanced both in its design and in its construction;
- High respect towards the city of Porto and to its particular profile drawn in the blue or misty sky, with no structural elements above the deck of the Bridge.

The Bridge is located in a well defined urban space that is full of character and personality; this Bridge intends to avoid any conflict with the consolidated outline of the city, adding no new elements that might change it.

The solution for the Bridge is very simple and neutral towards the city, at the same time calling for an advanced technology in its construction. A Bridge that stays handsomely in its place, showing up very cautiously with no will to form either a new image or a new urban deco.

This Bridge flies from Gaia to Porto as a bird, in a clean and sensible way and expressing itself in the purest manner, with no supports in the river Douro, not even in its banks. This structure flies musically, away from the conventional and from the ornamental.

A singular and highly slender arch lands with a natural and harmonious movement in the high rocky slopes up in the hills, and this arch supports the deck of the bridge with a profile that is more powerful in its drawing than that of the arch.

This Bridge has a peculiar geometric character. It is formed by grand planes, both the arch and columns, and by the powerful box-beam of constant high of the deck. The structure is made up of straight lines and planes, not of curved elements. That corresponds better to the anti-funicular of the loading and eases the construction process. This aspect slightly broken is more functional and gives a very special personality to the Bridge [1, 2, 3].

3.2. Design of the structure

The Infant Dom Henrique Bridge is composed of two mutually interacting fundamental elements: a very rigid prestressed reinforced concrete box beam, 4.50 m in height, supported on a very flexible reinforced concrete arch, 1.50 m thick. The span between abutments of the arch is 280 m and the rise until the crown of the arch is 25 m, thus with a shallowness ratio greater than 11/1.

In the 70 m central segment of the bridge, the arch combines with the deck to form a box section that is 6 m in height. The lateral faces of this section are recessed to give the impression of continuity of both the deck and the arch. The arch has a constant thickness and a width that increases linearly from 10 m at the central span segment up to 20 m at the abutments [4].

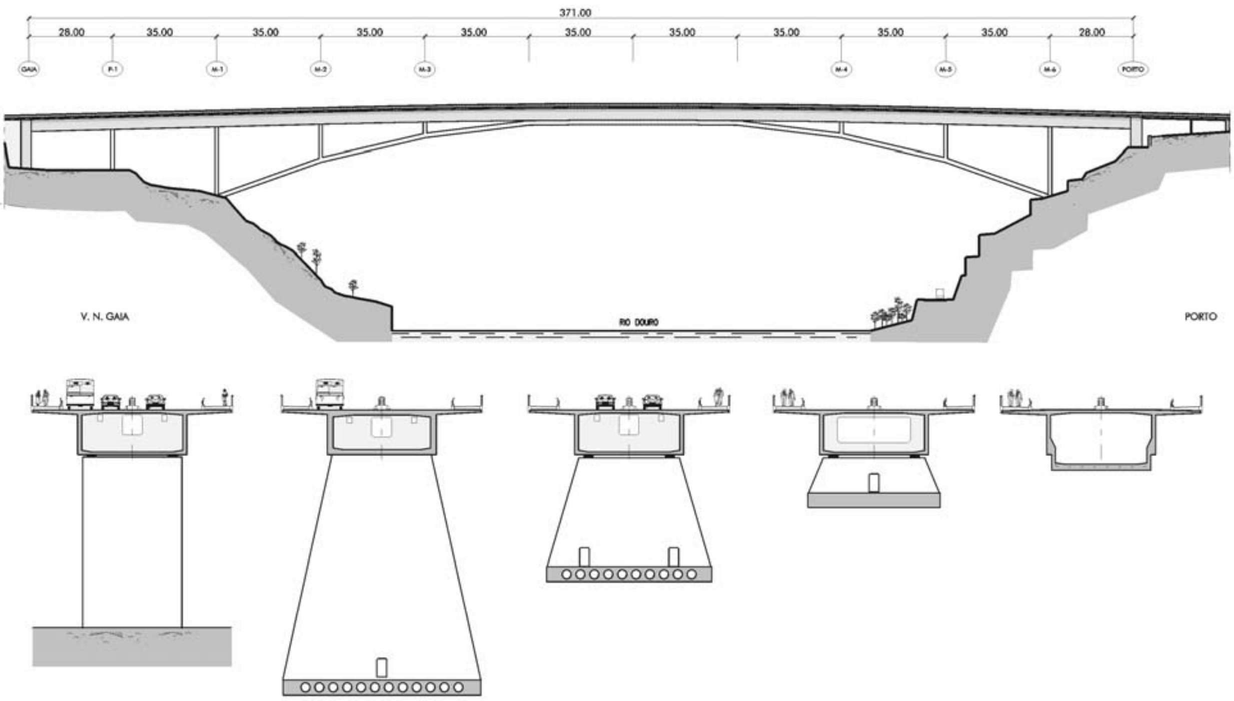


Fig. 2. Elevation and cross-sections of the bridge.

3.3. Structural behaviour

The structural behaviour of the flexible arch – rigid deck combination has the following basic features:

- Absence of important bending moments in the arch except at its fixed ends;
- Axial force variations carried by the arch are relatively moderate; the tendency of the arch rise to decrease due to thermal actions and creep and shrinkage deformations is hindered by the rigidity of the deck;
- The deck behaves as if it were a continuous beam on elastic supports provided by columns spaced 35 m apart (in fact, the contribution of the deck towards resisting the applied vertical loads is around 15% for permanent actions and symmetrical live loads; this percentage increases to 20% in the case of asymmetrical live loads, which means that the usual high bending moments in the arch under live loads with a pressure line not matching the arch shape are avoided);
- Where the arch and deck combine to form the 70 m long central span segment, the eccentricity between the centroid of the arch and the centroid of the box-beam of the deck lets the high compression force arising from the arch to generate localised high negative bending moments that eliminate the positive bending moments along that central span (Fig. 3); thus, a convex curvature in that span that counteracts the deformations that occur in the rest of the structure is guaranteed; however, there is an increase of positive bending moments in the spans preceding the central span segment;
- The high compression force introduced by the arch in the central span segment of the deck allows that no prestressing is required in that span after the bridge is finished.

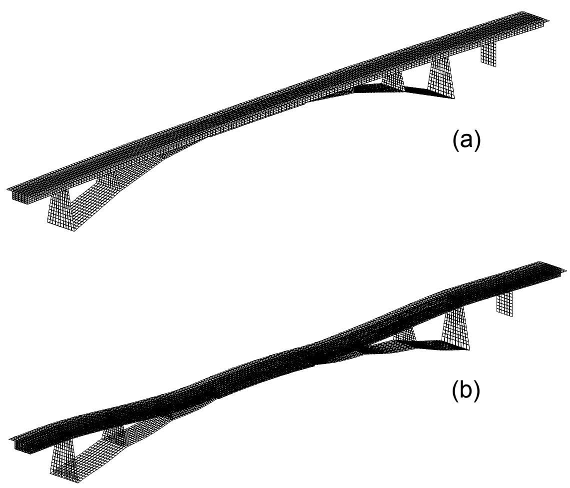


Fig. 3. Three-dimensional shell finite element model unloaded (a) and loaded with permanent actions (b).

The option for a single box-beam in the 70 m central span, where the arch and deck combine into one single element, was also an important factor in the optimisation of the structure. In effect, the dead weight of the structure per metre length in this span is close to half of the weight per metre of the structure anywhere else on the bridge, where the arch and deck are separated.

4. PARTICULARITIES OF ITS REALIZATION

4.1. Construction method

A shallow and slender arch can only function structurally if in conjunction with the deck. The construction method was to progress by cantilevering the deck and the arch from each side of the river. Two temporary pillars were built first in order to reduce the span from 280 m to 210 m, during construction, and trusses were created by adding tensile diagonal bars (provided by temporary stays) and vertical compression bars (provided by the reinforced concrete columns and temporary steel struts) between the arch and the deck [5]. Therefore, two cantilever trusses of considerable height were constructed until the deck and arch met. The 70 m central span was built by typical cast-in-place segmental box-beam construction methods (Fig. 4).

Fig. 4. Three phases of the construction method

Trusses were created similarly in the slopes outside the arch (Fig. 5). They were defined by the deck, abutments, column on the Gaia side of the river, reinforced concrete struts built on the ground and working integrally with the rock foundation, and diagonals provided by temporary stays. These diagonals worked as backstays and ensured that the two bridge halves were tied back to the deck abutments until they were united at the centre.

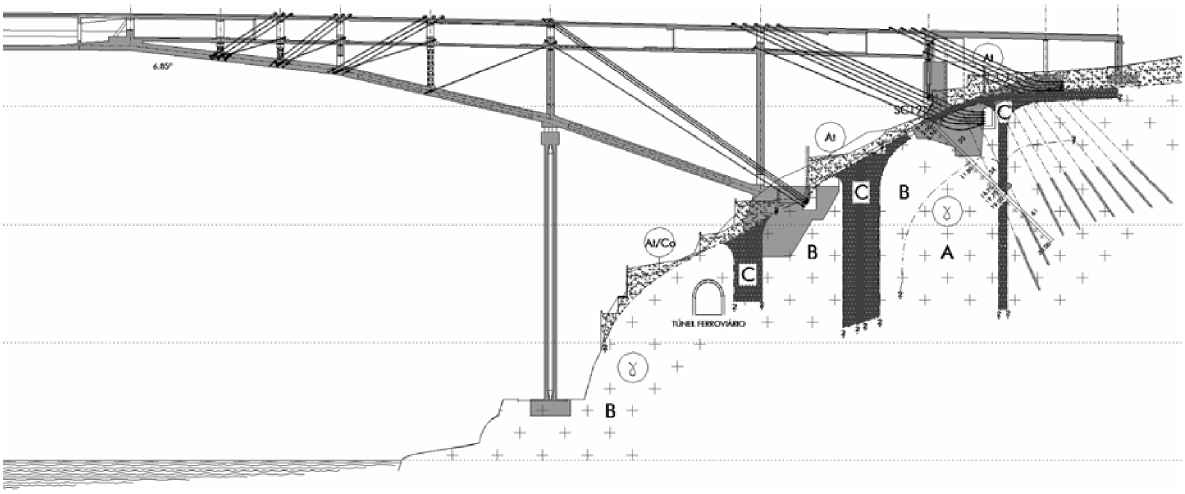


Fig. 5. Construction structural system on the side of Porto

Tensile forces in all diagonals were applied and regulated in a predefined order to control the structural response of the two cantilever trusses.
Equilibrium of the advancing cantilevers was secured by inclined ground anchorages and by footings connected together by reinforced concrete struts. Geometry of these footings was optimized in order to mobilize the rock foundations in resisting the horizontal components of the construction forces, which meant that forces generated in footing struts were kept under control and stability of the rock slopes was ensured. After the two bridge halves were united by the crown segment, backstays, diagonals, temporary struts and pillars were all dismantled following to a very detailed sequence (Fig. 6).

Fig. 6. View of the bridge before temporary elements were dismantled.

Two independent evolutive calculations were performed, both considering the time dependent behaviour of concrete through the modelling of the viscous-elastic properties of materials. These mathematical models were coded into the DIFEV [6] and FASES [7] softwares and both confirm the adjustment criterion of forces installed in the “active diagonals”, which were first determined by a linear elastic model.

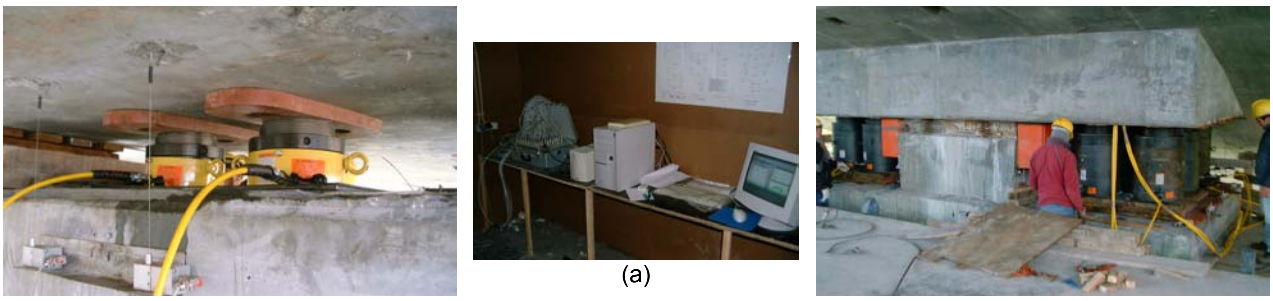
4.2. Construction innovation

Several techniques and procedures used in the construction of the Infant Henrique Bridge were highly innovative. Moreover, to build a large bridge subject to a geometrical precision criteria never before demanded was, in itself, an enormous challenge for the contractor. Also, the erection of an extremely slender and shallow arch over the distance of 280 m lead to the construction of the deck ahead of the “suspended” arch, which is a method that had been used only once before, with the Nakatanigawa Bridge in Japan, where the arch spans 100 m and rises 19 m.

From the construction of the Infant Henrique Bridge, the following application examples are noted:
- The positioning of the support platform for the arch formwork was adjusted to the millimetre, before the concrete of each segment of the arch was poured, and was carried out using two automatic and computerized hydraulic systems (Fig. 7);

Fig. 7. Double formwork traveller and automatic computerized system

- The monitoring of the structural behaviour of the bridge during construction was carried out by centralized computer systems (Fig. 8a) that collected data from relevant structural elements of the bridge and that automatically stored, managed, and processed these data in order to interpret readings supplied by the internal monitoring devices;
- The special operations of predefined upwards and downwards settlements (Figs 8b and 8c) on top of the temporary pillars, in order to move the internal forces along the deck, as well as the release of the bridge from those temporary pillars, were controlled by those computer systems, with on-line follow up of readings in the internal monitoring devices;



(b) (a) (c)

Fig. 8. Centralized computer system (a) and jacks on top of provisional pillars (b) and (c)

- The removal of the temporary pillars weighing 8000 kN was achieved by means of a rotation and transfer system with on-line control and adjustment of forces in the hydraulic jacks that suspended the rotation axis located halfway up the pillar (Fig. 9).

Fig. 9. Removal of the temporary pillar on the Porto side of the bridge.

4.3. Construction control

Construction of this bridge was a major achievement requiring a highly efficient monitoring system, capable of assessing physical quantities of different types, namely support reactions, axial forces, bending moments, rotations and temperatures at particular sections of the arch, deck and temporary struts and pillars, and axial forces in the temporary stay cables (backstays and diagonals).

The monitoring of the construction of the bridge was performed by three separate instrumentation systems, one for the granite slopes and the foundations on each side of the river, another for the concrete elements and another for the temporary stay cables [8]. Fig. 10 shows an example of readings from the monitoring system that prompted a “structural correction”. Graphs show the development of stresses in the upper and lower fibres of the spring cross section of the arch on the Porto side. The arch is clamped to the abutment and the progressive “gap” between the readings on the two fibres signifies negative bending moment at that section was increasing, because of insufficient tension applied to the suspension stay cables during the construction of the first span of the arch. This situation was corrected by re-tensioning the stays before the provisional pillar became a support for the advancing structure.

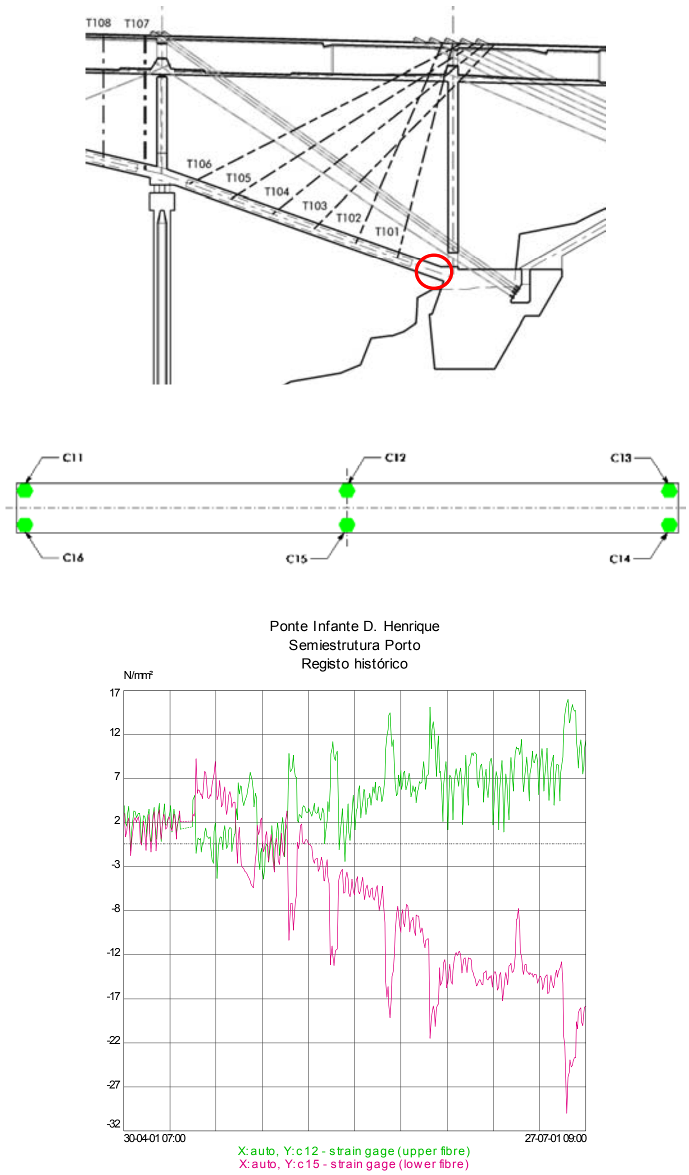
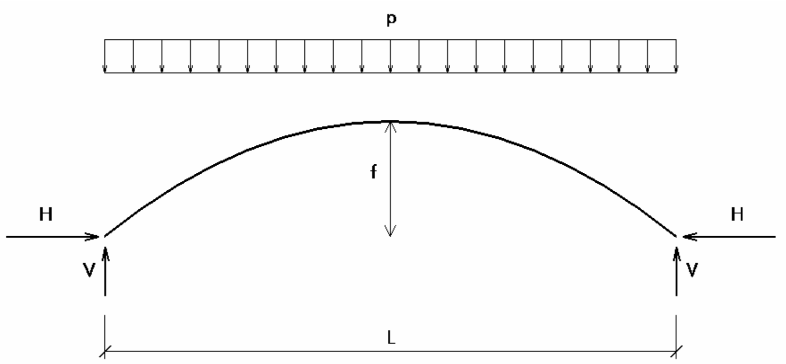


Fig. 10. Development of stresses in the upper and lower fibres at cross section of the spring of the arch

5. CONCLUSION

The Infant Dom Henrique Bridge exhibits high technical and aesthetic qualities and represents an important technological advance in construction, both because of the magnitude of its dimensions and because of the following set of relevant facts (Fig. 11):



$$H = \frac{p}{8} \times \left(\frac{L^2}{f} \right)$$

Fig. 11. Structural response of a "perfect arch"

- It is the second largest concrete arch in Europe; with a span L = 280 m, it is only surpassed by the Krk Bridge, in Croatia, constructed in 1979 and which, with a 390 m span, held the world record for 18 years, up to 1997
- It holds the world record for shallow deck stiffened arches; with a constant thickness of 1,50 m (approximately L/187), it stands out for being extremely slender in relation to the usual thicknesses used in conventional rigid arch solutions (between L/40 and L/60)
- The rise of f = 25 m means a shallowness (L/f = 11,2) for the arch that has n*o* parallel in the field of large span arch bridges
- Its "static coefficient" (L^2/f > 3000), which is directly proportional to the axial force existing at the crown of the arch, is the largest of any concrete arch built to date.

In fact, this arch is the most loaded and the most "delicate" in the world. Notwithstanding the fact that it is a world record holder for slenderness, it possesses the greatest axial force of any concrete arch.

Fig. 12. Aerial view of Maria Pia, Infant Henrique and Luiz I Bridges

6. ACKNOWLEDGEMENTS

Acknowledgements are due to our colleagues at AFAssociados and at IDEAM for their contributions to the discussions in which many of the final solutions were found.

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