THE VIADUCT OF THE GRANDE RAVINE:
A BRIDGE WITH A LIMITED AND CONTROLLED ARCH EFFECT

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Summary. The viaduct of the Grande Ravine is part of the future Route des Tamarins, a high-speed road with 2 x 2 lanes connecting the towns of Saint Paul and Etang Salé. The owner is the Reunion Region. The work for building the bridge will start in 2005. The structure is exceptional for the dimensions of the breach: 320 metres wide at natural ground level and 170 metres deep. The principal constraints of the project are environmental (protected fauna and flora), topographical (very steep slopes on the flanks and very great depth ruling out any construction from the bottom of the ravine) and climatic (risk of cyclones both during construction and in service). The structure consists of a 288 m long metal deck with orthotropic slab, hinged on two high performance prestressed concrete braces inclined at 20° to the horizontal. The deck is launched from both sides of the ravine. The braces are cantilevered from counterweight abutments and maintained at their heads by external prestressing cables situated inside the deck. The abutments are founded on superficial footings at the rear under the counterweight and on a large diameter concrete pile at the front. The phasing of construction and the different structural behaviour before and after midspan connection, as well as the role of the provisional and final stays make it a very special structure, which may be defined as a bridge with a limited and controlled arch effect.
1 PRESENTATION OF THE PROJECT

The viaduct of the Grande Ravine is on the future Route des Tamarins, an express road with 2 x 2 lanes connecting the towns of Saint Paul and Etang Salé on Reunion Island. The Route des Tamarins crosses about a hundred ravines, some of which are very deep and inaccessible from below. This therefore requires the construction of about twenty standard structures, about twenty non-standard structures, a 300 m twin tube tunnel, two cut and cover structures and four exceptional bridges, including the viaduct of the Grande Ravine. The owner is the Reunion Region, assisted by the Major Public Works Department of the DDE of Reunion Island.

The contract for the design and construction of the exceptional bridge over the Grande Ravine has been awarded after competition between several design firms. The permanent commission of the Regional Council, at a session on 29\textsuperscript{th} March 2002, nominated the SETEC TPI / SPIELMANN grouping as winner of the competition.

The pre-project and project studies were carried out between 2002 and 2004, with a control by the SETRA (Department of Technical Studies of Roads and Motorways in France). The construction work on the structure will begin in 2005.

2 PROJECT CONSTRAINTS

2.1 Functional constraints

The longitudinal profile of the structure has a single slope of 0.5 %, down from the right bank to the left bank. The alignment is a straight line. The cross-sectional profile is roof shaped, with an inclination of 2.5 %, and the single deck has a roadway width of 18.60 m.
2.2 Natural data

The structure is exceptional because of the dimensions of the breach: a width of 320 m at natural ground level and depth of 170 m. The very steep slopes of the flanks and the very great depth prohibit any construction starting from the bottom of the ravine.

The sides of the Grande Ravine are made up of alternating metric banks of basalt and volcanic slag of average quality. The general dip of these banks is about 15° in the downstream direction. The admissible stress of the foundation terrain depends on the horizon involved: from strong on the basalt banks to average or even weak for the volcanic slag.

This data, together with the geometrical data, led to the design of a “light” structure with foundations at a distance of about 25 m from the cliffs of the ravine.

Because of its situation in the South West of the Indian Ocean, Reunion Island is on the trajectory of climatic phenomena such as tropical depressions and cyclones. It is therefore essential to take into account the risk of cyclones, both during construction and during the operation phases.

2.3 Environmental constraints

The bottom of the Ravine is home to sensitive fauna and flora that must imperatively be protected. In particular, the Grande Ravine has nesting sites for Baillon’s Puffins, protected indigenous birds. It is estimated that the risks of collisions by Baillon’s Puffins with the elements of the structure that cross the ravine are higher if these elements have small dimensions. As a result of this, the specifications established by the owner stated that, as a precaution, all suspension bridge solutions (involving stays, cables and suspending rods) are forbidden. On the other hand, temporary systems of suspension or bracing are authorised, provided that their dispositions are examined with regard to collisions by Baillon’s Puffins and their time of use is limited.

3 GENERAL DESIGN OF THE STRUCTURE

![Figure 2: Elevation of the structure](image-url)
The structure consists of a 288 m long steel box girder with orthotropic plate, launched from both extremities and then connected at midspan. Intermediate supports are provided by two high performance prestressed concrete braces inclined at 20° to the horizontal. The braces are rigidly fixed at base into counterweight abutments at their feet and maintained at their heads by stays made up of external pre-stressing cables situated inside the deck. The abutments are founded on superficial footings at the rear under the counterweight and on a large diameter concrete pile at the front.

4 THE ARCHITECTURAL CHOICE

The program of the competition required a discreet structure that blends into the site, that is remarkable and that will fit into the Grande Ravine without “disturbing either the fauna or the flora”. It seemed highly desirable to propose a structure with a light deck, easy to launch, made of metal, with a constant height that appears like a blade in the countryside. The structure is supported by braces built into foundations that are themselves buried in the rock of the two banks. This proposal with highly inclined braces is derived from braced bridges, but with proportions that are more slendered. In this way it has a dynamic aspect while “consuming” little space. This solution enables the environment and the site to be preserved. The height of the deck is minimal. The impact in terms of area on the two cliffs has been reduced so as not to disturb the cliffs and leave them with their character.

The structure is flat, very fine and very slendered, and it vigorously expresses the dynamism and new strength of 21st century techniques: high technology allows new progress and generates new shapes. The inclination of the braces and the horizontal deck will symbolise the structure and its modernity:

- a metal deck that can be launched, “a blade in the countryside”, “a blade in the sky”, 4.00 metres thick, or 1/70 of the total width of the breach (1/35 of the span between supports), which gives this bridge an exceptional appearance,
- two concrete braces, one at each end, which support the forces, with a width that is identical to the bottom slab of the deck, about 6 metres, to ensure the visual continuity of the drawings, which “support the blade” like “a finger that is carrying the blade”,
- a protruding ribbed abutment whose width is equal to that of the brace,
- an abutment with two lateral walls concealed in the terrain to limit the impact on the environment,
- a structure that gives the impression of having been placed in contrast with the site of cliffs and canyons,
- a very streamlined, metal, sober structure that seeks the extreme simplicity of its lines and elegance.

5 THE CONSTRUCTION PROCESS

5.1 Execution of the abutments and braces

The general earthmoving and abutment foundations are executed first. The braces are then built by cantilevering out from the abutments.

5.2 Installation of a temporary stay connecting the head of the brace to the abutment and launching of the deck

This stay is intended to ease the bending moment of the brace, thus limiting the quantity of prestressing to be implemented in the brace. The total half-length of the deck is assembled on the bank, and then launched up to a position slightly beyond the brace, at which position devices are installed on the abutment to ensure static equilibrium at the end of launching. The second launching phase is then carried out up to the keying up position, and this phase must be quick and under weather forecast, as the structure is then very sensitive to violent winds. Both half-decks are launched simultaneously and temporarily connected together once the final position is reached, this connection being able to withstand a ten year wind outside the cyclone season. The tension in the temporary stay at the head of the brace is adjusted in accordance with the progressive increase of the deck support reaction. Sliding supports mounted on a temporary structure at the head of the brace make up the upstream temporary support. The final hinge at the head of the brace is installed during the launching operations using the partially launched deck for transporting it. The structure of the hinge is then welded to the deck at the end of launching. At the end of launching, the deck is vertically connected to the abutment.
5.3 Transfer of the stays and unjacking of the launching support

On each bank in succession, the hinges at the head of the brace that were installed during launching and welded from under the deck will be progressively loaded in the course of an operation that combines in phases the partial tensioning of the final stay cables, the partial unjacking of the launch support and the partial detensioning of the temporary stay cables.

At the end of this operation, the temporary stay will have been transferred from the head of the brace to the interior of the deck as a final stay, thus preserving the limitation of the bending moment of the brace.

5.4 Central keying up of the deck, jacking and placing of the superstructures

After this keying up, the ends of the deck are jacked up vertically by 50 cm. The final supports of the deck on the abutments, as well as the final transversal abutments, are then installed. The twin objective of this jacking up is to ease the moment in the deck at the braces and increase the positive reaction of the deck on the abutments under permanent load.

From the time the structure is keyed up, it operates like a braced bridge.

6 DESCRIPTION OF THE STRUCTURE

6.1 The deck

The deck is a metal multi-tubular streamlined box girder with an orthotropic slab that:
- is straight with a constant slope of 0.5%,
- has a constant height of 4.00 m, except at the support shoes of the hinges,
- is 19.90 m wide (excluding the cornices),
- has a total length of 288 m,
- distances: 73.25 m - 140 m - 73.25 m between the intersection points of the median lines of the deck and the braces,
- uses S355 steel for the normal zones and S460 steel for the reinforced zones near the hinges.

The deck rests on the braces by means of the hinges. At the abutments it rests on classic sliding supports with transversal immobilisation abutments. The final stays run along the interior of the caisson from the reinforcement zones around the hinges to the abutments. They are only connected to the deck at the hinges, as the sheet metal panels they then pass through.
(reinforced frames and closure of the deck) allow the cables to pass without deviating them. In this way the cables are only deviated inside the abutments.

![Figure 4: Transversal cross section of the deck](image)

The transmission of force from the deck to the hinges is done by means of two side plates, which enter the caisson and are attached to its upper and lower slabs. These side plates are about 14 m long. They go from the final position of the launch support up to beyond the anchorages of the final stays, reinforcing the deck both in construction (including launching) and in service. The force of each hinge acts on a 2 m x 2.5 m plate stiffened by four stiffeners welded to two side plates. Transversally, four special reinforced frames stiffen the assembly and allow the transmission of the vertical force of the webs of the caisson to the central side plates. Two frames are located opposite the plates of the hinge and its external stiffener. The two others are placed so as to be equidistant from the first two. The final stay is supported by shuttering attached to the webs of the central caisson on one hand and the two internal side plates of the hinge on the other.

6.2 The braces

The braces are made up of a box girder in prestressed high performance concrete, inclined at 20° to the horizontal, with a constant width of 7 m, a height that varies from 6 m to 3.50 m and a length of about 50 m. Construction is by cantilever method with post-tensionning, distributed in the top slab, made up of 32 x 12T15S cables with two in each 3 m segment. To limit the effects of creep that increase the bending moments, and for resistance to buckling, it was decided to use a B60 high performance concrete with silica slag.

6.3 The abutments and earthworks

The abutments are made up of a partially prestressed box in B40 with variable height founded on a superficial footing at the rear under the counterweight and on a large diameter pile at the front:

- width between the main walls 12 m,
- height varying from 11.50 m (at the back) to 24.50 m (at the front),
- a 13 m x 16 m rear footing,
- a prestressed slope at the front of the abutment (10 x 12T15S cables),
- front pile about 10 m in diameter and 19 m deep.
The role of these abutments is to transfer the various forces to the foundations, mainly by means of the longitudinal walls. The forces are due to:

- the fixing of the brace,
- the ballast at the back and the weight of the earth on the edges of the rear footing,
- the forces of anchorage and deviation of the temporary and final stay cables,
- the supports of the end of the deck,
- the end wall, the fill and the roadway above the upper slab,
- the earth pressure on the lateral walls.

### 6.4 The stays

The stays are broken down into two families:

- temporary stays outside the deck during construction, made up on each side of 10 x 31T15S cables and anchored into the abutment at the back end and in the head of the brace,
- final stays inside the deck for service, made up on each side of 10 x 31T15S cables anchored into the reinforcement provided at the point of the hinge and at the end of the abutment.

### 7 PROJECT STUDIES

The calculations carried out in the project phase were based on a certain number of models: with bars or with finite elements.

The principal model for calculating the structure is a bar model with rigid abutments based on stiff supports, for which SETEC TPI used its PYTHAGORE software, which is specialised in the calculation of structures, and which enabled:

- the total spatial modelling of the structure from beam elements,
- the taking into account of the detailed phasing of construction, with the short term and long term behaviour of the concrete, including scientifically calculated shrinkage.
and creep,

- the modelling of turbulent cyclonic wind (with maximum values of average wind of up to 52 m/s) and the calculation of the dynamic effects of wind on the structure,
- the calculation in large displacements of the structure with counterdeflections and defects of shape in the braces to check them against buckling,
- the checking of the sections in concrete, taking account of cracked concrete,
- the checking of buckling in the thin sections of the metal deck.

It was from this model that the structure in construction and in service was dimensioned, except for the abutments and the ground. The dimensioning of the abutments was the subject of a special model, established from the preceding model by adding elements of plates for the abutments and springs for the ground. A check of the influence on the dimensioning of ground parameters varying within a range of values was also carried out.

![Figure 6: Calculation model by PYTHAGORE software](image)

The distribution of forces in the zone of the shoe and the anchorage of the final stays and the checking of the stiffening of the deck during launching (calculation in large displacements including defects of shape in the principal modes of buckling) were subjected to finite element modelling using the ANSYS software package.

A special model of the ground was carried out by the TERRASOL Company using the CESAR software package to check that the interaction of the structure and the ground was in conformity with the results observed in the PYTHAGORE model.

### 8 THE LIMITED AND CONTROLLED ARCH EFFECT

The behaviour of the structure during construction and in service is based on very different modes of structural operation, whose central element is the stay, whether temporary or final.

During construction, that is to say before keying up, each half structure is built as a cantilever. The use of the temporary stay enables the bending moment in the brace during the launching of the deck to be limited. The whole is balanced by means of the counterweight at the rear of the abutment. During the transfer of the stay, the structural behaviour remains the
same, as the final stay is the equivalent of the temporary stay, but it is protected inside the deck. Furthermore, the eccentricity of the final stay in relation to the hinge enables the deck to be vertically connected to its support on the abutment. During keying up, the loads due to the weight of the structure do not create any force through the keying up joint. Once the structure is keyed up, the forces due to the weight of the superstructure and the loads in use (wind, road and thermal loads) create a normal force in the structure due to the arch effect. Because of the low inclination of the braces and the conditions of support (foot of the brace, hinge at the head and sliding support on the abutment), part of the force goes in bending, with the bending of the braces being transmitted into a rocking moment in the abutments.

The limited and controlled arch effect is therefore explained by the presence of the stays, which enable the horizontal thrust to the ground to be limited by replacing the loads due to the weight of the structure by a rocking moment in the abutments, the said moment being balanced by the counterweight. The loads due to operation and the superstructures create a normal force in the structure and a horizontal thrust to the ground, these forces being much less than they would be if the whole of the structure were to function as an arch, which satisfies a requirement of the program to limit the forces in the terrain by avoiding structures that function entirely as arches. The maximum horizontal force in SLS is 5,900 t. If we relax the final stays after keying up to make the structure function completely as an arch, this maximum horizontal force would then be 10,700 t. The main deformations due to the loading of the abutments are produced under loads due to the weight of the structure during construction. The installation of the final stays enables no major new deformations to be introduced under these same permanent loads after keying up.

The adjustment of the tension in the final stay therefore makes it possible to act separately on the brace and the abutment, deconnecting two major elements of the structure. Before keying up, the moment in the brace is adjusted in order to have admissible stress in the prestressed concrete in service. After keying up, a horizontal force is transferred to the abutment due to a function as an arch and a rocking moment taken up by the counterweight at the back of the abutment, without changing the functioning of the brace.

These effects may be reversed by relaxing the stay.

9 CONCLUSION

The viaduct of the Grande Ravine is a structure that appears like a blade in the countryside, with a thin deck supported by very inclined braces. It will present to the observer a totally new image, a new drawing of structure, derived from braced bridge or arch bridge. The thickness of the deck, the incline of the braces and the simplicity of its decorations, as well as the structural behaviour with the limited and controlled arch effect based on the role of the stays give this bridge a unique character.