THE VIADUCTS OF THE NEW COASTAL ROAD

Thierry DUCLOS - VINCI Construction Grands Projets

Brahim DJESSAS - Bouygues TP

Fahed CHEBBI - Dodin Campenon Bernard

Romain LEONARD - Demathieu Bard

Table of Contents :

1 INTRODUCTION

The New Coastal Road (NRL) will allow the inhabitants of the Reunion Island, in the Indian Ocean, to connect quickly and in complete safety Saint-Denis, the capital in the East, with its commercial harbor situated about twenty kilometers further west. It will replace the current coast road with 4 lanes at the foot of the cliff.

Figure 1 : the current road at the foot of cliff

Figure 2 : fall of a 15 tons of rocks on 03/03/2016

This dangerous road exposes its users to two types of risks:

- *on sea side, exposure to breakers in case of strong swell, which happens frequently because of the absence of continental shelf;*
- *on cliff side, exposure to falling rocks, in spite of the presence of safety nets.*

So two months per year in average, the authorities close one or two traffic lanes thus generating heavy traffic jam to protect the users.

The project of the New Coastal Road (NRL) stretches over a length of 12.5km between the West of Saint Denis city and La Possession city. It is almost completely situated at sea

The future road, parallel to the coast, will allow to free from falling rocks but also from the swell, because it will be situated between 20 and 30 m over the sea level. The road will be clearly wider because it will allow an operation with twice 3 lanes at first, with the addition of the soft traffic (pedestrians and cyclists). Later on a trolley line will be set on the deck.

The link will mainly consist of a 5,4 km viaduct (it will be the longest viaduct of France on ground or at sea), of the Grande Chaloupe Viaduct and a series of dikes of a total length of 6,7 km.

The construction joint venture in charge of the viaduct (contract n°3 (MT3): 715 million euros value) combines VINCI Construction Major Projects (Leader), Dodin Campenon Bernard (two entities of the Division of the Major projects of VINCI Construction), Bouygues Public works and Demathieu Bard

The tender established by EGIS Engineer of La Réunion Région (Owner) featured two technical basic solutions:

- *A deck of variable depth and 120m long spans designed with a mono-cellular box girder with two webs; transverse ribs allowing a 0.22m thickness of the overhang,*
- *A deck of constant depth and 100m long spans designed with multi-cellular box girders with four webs.*

The foundations of the bridge were spread foundations for one half of the piers. For the others, the piers were founded on four deep piles, 4 m in diameter.

During the Tender stage, our construction joint venture established an alternate, the main technical characteristics of which were the following:

- *Prefabrication of all the elements of the project*
- *A deck of variable depth and 120m long spans designed with a mono-cellular box girder with two webs; overhangs with transverse post-tensioning but without transverse ribs, in order to simplify the prefabrication of segments,*
- *Elimination of piles (except for the two abutments at each extremity of the viaducts), subject to confirmation by additional geotechnical investigation, with the possibility of local soil improvement on a case-by-case basis.*

This technical alternate developed by the construction joint venture provided substantial savings thanks to the elimination of the deep foundations. It was therefore was developed after contract award.

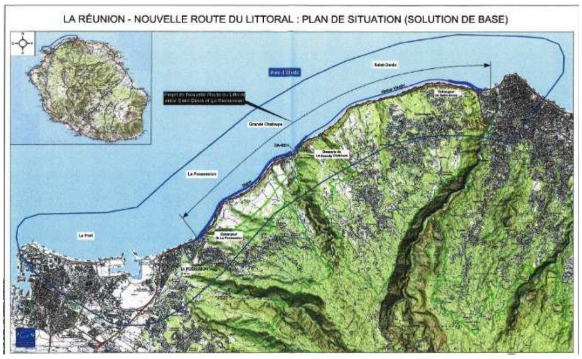


Figure 3 : site plan

2 PROJECT DESCRIPTION

The contract number 3 concerns only the Viaduct at sea (5409m long viaduct). This contract covers all the elements of this viaduct, foundations, piers, abutments and the prestressed concrete decks.

Essentially laying in the sea, far away from the cliff, this part of the New Coastal Road is designed for a working life of one hundred years, especially for the maritime constraint (cyclonic swell). It is also designed to integrate in future public transport, called mode 2, a trolley line.

This structure will experience during its construction and also its operation several climatic hazard events such as swell, cyclones, trade winds, and also seismic hazards and ships collision.

The project is constituted of seven independent viaducts with a length varying from 771,285m for the end viaducts (viaducts 1 and 7) and of 773,286m for the standard viaducts (viaducts 2 to 6), length defined between bearing center lines at the extremities of each viaduct.

For these 7 viaducts, the main spans are equal and 120m long. All the side spans have also the same 84,643m length.

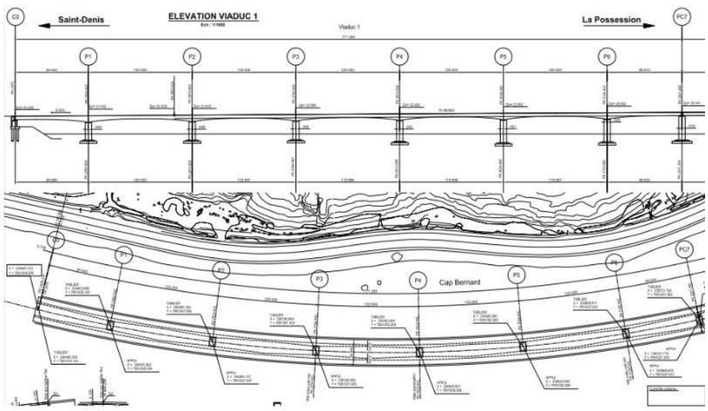


Figure 4 : layout and plane view of the viaduct 1 on East

The bearings at each extremity of contiguous viaducts are 4m away on the shared pier-abutments. The total length of the project with its 7 viaducts, between the support center lines at its extremities is then given by:

$$2*769.285+5*769.286+6*4 = 5409.000 \text{ m}$$

The project lays between the kilometric point (PK) 2470 (center line of supports of the C0 abutment, on St Denis side) and PK 7879 (center line of supports of the C49 abutment on The Possession side)

The longitudinal profile is defined on the axis of the viaduct. The alignment consists of a series of curves, the shortest radius of curvature being 1500m.

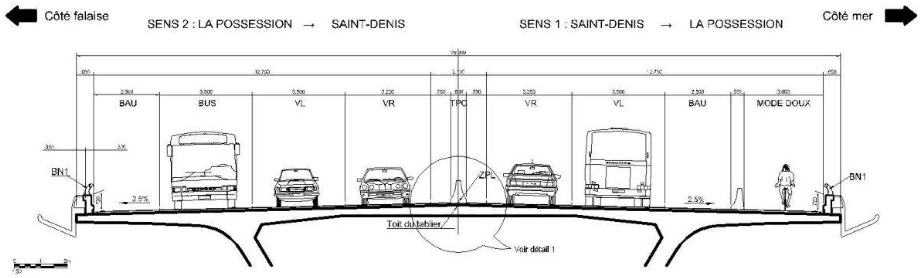
The reference line chosen to define the longitudinal profile is set at the finished level of the pavement.

The road surface and the deck slab are of centerline crown type centered on the reference line, with a constant cross-slope of 2,5%.

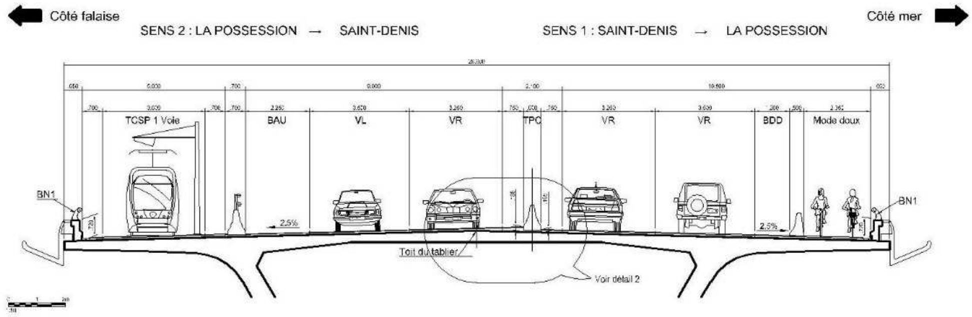
During the service life, the Owner has defined 3 successive types of operation modes. The last one will see the trolley line in operation.

These 3 functional types are figured below. The first mode is only a road operation with a dedicated car line on cliff side of the transverse cross section.

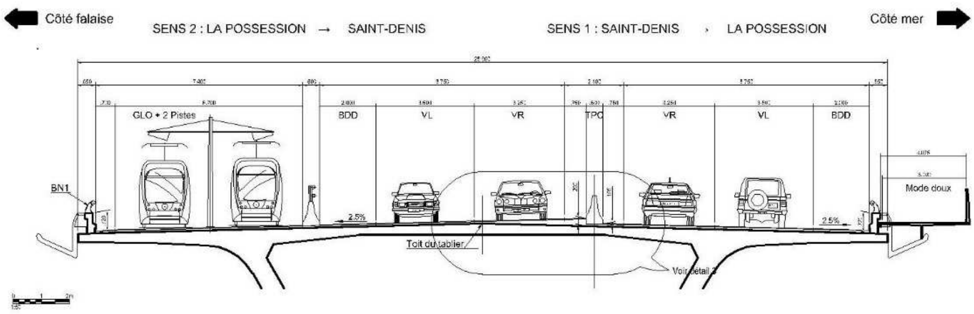
Mode 1 - Figure 5 : functional cross section at opening



Mode 2a (1 voies TCSP Tramway) : Figure 6 : functional cross section with one trolley line with alternated traffic



Mode 2b (2 voies TCSP Tramway) : Figure 7 : functional cross section with 2 trolley lines**.**



The mode 2b with its reserved 2 trolley lines will correspond to the final stage of the deck arrangement with the installation on the sea side of a lateral walkway for the pedestrian and the cycles.

2.1 DECK

Each deck is a prestressed concrete box girder with 2 webs. It is totally precast and its segments are match cast. It is assembled following the cantilever construction method with a 278m long launching beam supported by two lattice towers and a front leg. During a typical sequence of cantilever construction, one of the lattice towers rests on the cantilever under construction, the second is on the previous cantilever already built and the front leg is on the next pier.

The deck has a variable depth from 7,3 m on pier (segment on pier) to 3,8m at mid span following a polynomial law in the power of 2,5.

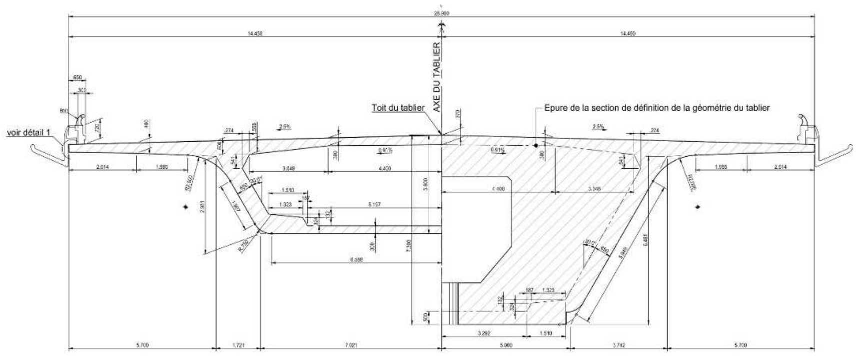


Figure 8 : half cross section of the deck at middle span and on pier

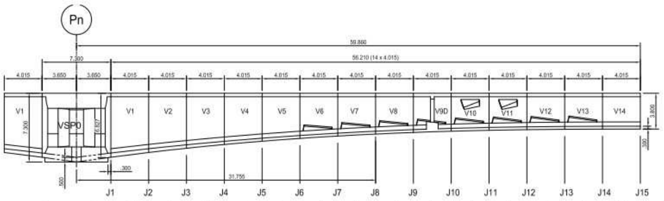
The deck slab has a variable thickness from 0,3m at the overhang extremity to 0,6m at the embedment in the gusset of the web, then from 0,558m to 0,3m at the end of the gusset between the webs, to finish at 0,37m in the middle of the central slab.

The thickness of the web is 0,65m. The webs are inclined with an angle of 30° to the vertical which is not common for this type of deck. It involves significant variation of the bottom slab width from 14,024 m at the mid span to 10m on the pier segment.

The bottom gussets are designed to avoid the intrusion in the webs of internal continuity prestressing tendons. Also this principle is applied at the top of the webs where the ducts don't go through the webs stirrups. So all the stirrups have a regular shape subjected only to the web height variation.

The design of the prestressing is typically a mixed prestressing technology. A part of prestressing is internal to the concrete for stability during construction, and external to the concrete in the box girder to complete the internal for the operation stages. So for this last technology two intermediate cross beam (deviators) are introduced for each interior span as well as each side span.

All sizing for operation phase include the described modes, 1, 2a and 2b.

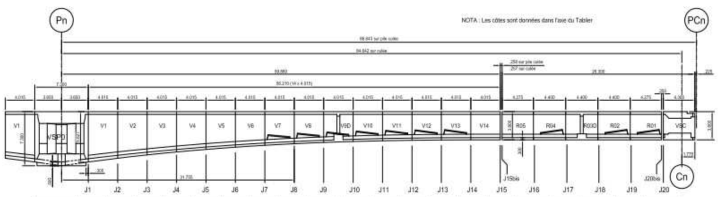


FLÉAU COURANT

	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12	J13	J14	J15
Ht	6.791	6.285	5.834	5.437	5.090	4.791	4.538	4.329	4.160	4.028	3.930	3.864	3.823	3.804	3.800
Ep	0.447	0.400	0.364	0.336	0.318	0.306	0.301	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300
Lb	10.566	11.172	11.693	12.152	12.553	12.897	13.189	13.431	13.626	13.778	13.891	13.968	14.015	14.037	14.041

Ht (x)= 3.800 + (7.300 - 3.800) * (L travée - x)^2.5 / (L travée)^2.5 — L travée = 59.860
Ep (x)= 0.300 + (0.500 - 0.300) * (L joint v7.v8 - x)^2.5 / (L joint v7.v8)^2.5 — L joint v7.v8 = 31.755
Lb (x)= (ya - (Ht (x) - za) * tan 30°)) * 2 — ya = 8.742 za = 0.819

Figure 9 : breakdown into segments on standard span



FLÉAU DE RIVE

	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12	J13	J14	J15	J16	J17	J18	J19	J20
Ht	6.791	6.285	5.834	5.437	5.090	4.791	4.538	4.329	4.160	4.028	3.930	3.864	3.823	3.804	3.800	3.800	3.800	3.800	3.800	3.800
Ep	0.447	0.400	0.364	0.336	0.318	0.306	0.301	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300	0.300
Lb	10.566	11.172	11.693	12.152	12.553	12.897	13.189	13.431	13.626	13.778	13.891	13.968	14.015	14.037	14.041	14.041	14.041	14.041	14.041	14.041

Figure 10 : breakdown into segments on side span

The breakdown into segments relates to the lifting and erection capacities both on the precast yard and on the site. The standard length of the 14 segments is 4,105m. The pier segment with a length of 7,3m was segmented in 3 parts. This partition is guided by the lifting capacity on the casting yard to allow match-casting the first segment against the lateral elements of the pier segment. The three parts of the pier segment are assembled after beginning the prefabrication of the cantilever segments on the casting yard. Each half cantilever is 59,86m long. The cast-in-situ stitch is 28cm thick.

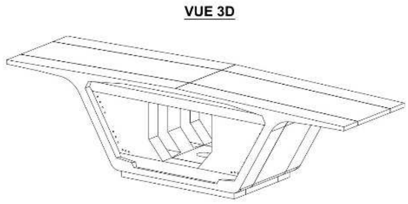


Figure 11 : 3D view of pier segment

At each extremity of the side span, the segment on shared pier-abutment or on abutment is 4,30m long and is built in a single element. It is linked with a 0,25m thick stitch to the last five segments of the side span, the length of which is respectively 4,275m, 3 x 4,400m and 4,275m, resulting in a total length of 26,30m. This group is linked to the last cantilever of each deck by a 0,258m thick stitch.

Before being transported to the site, the pier segment is completed on each side with the two first segments V1 and V2 to constitute the mega VSP which we will discuss in the construction methods chapter.

The cantilever prestressing consists of 20-31T15S type tendons stressed per web completed with 2 empty ducts to potentially correct greater-than-expected losses in stressed tendons.

The bottom internal continuity tendons at mid-span are of 37T15S type. There are 7 tendons per web in typical span anchored between segments V7 and V13. During construction stages they are completed with a pair of continuity top tendons anchored in segment V11. Each of these tendon families includes an empty duct per web. (See sketches 10, 8, 9).

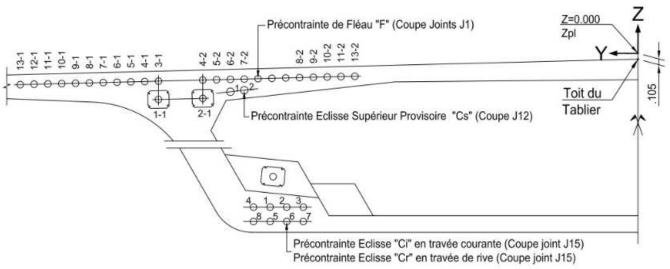


Figure 12 : general principle of ducts layout in segment bulkhead

The external tendons are also of 37T15S type. There are 6 tendons per web in each span, including the side spans.

There is transverse prestressing with mono-strands grouped in 4T15S units. This prestressing is installed and staged in the yard on the precast unit before pouring the next match-cast segment so as to limit the differential deflections between segments and therefore keep the segments compatibility for the installation on site.

Shear keys are provided for each segment, distributed essentially along the webs.

There are also shear keys in the bottom and top slabs. However their density is a low, so as to ease the assembly on site. A higher density of shear keys in the bottom and top slabs may induce high local loads when assembling adjacent segments with small geometrical differences, without bringing a noticeable contribution to the accuracy of the operation.

Figure 13 : distribution of keys along a web

2.2 PIERS AND ABUTMENTS

Only the extremity abutments, C0 and C49 are standard abutments, poured-in-situ. All substructures located in the sea, foundations, piers and pier-abutments are precast off-site in reinforced concrete, then installed on site with an off-shore barge. The transport and lifting capacity of this barge is 4800 tons.

2.2.1 Piers and pier-abutments

The piers and pier-abutment are founded on circular spread footing 20m or 23m in diameter depending of the deck-bearing condition.

Each viaduct has only one longitudinally fixed pier. The fixed piers distribution is determined by the same number of spans on each side of this pier so as to obtain similar movements at expansion joints, but not exactly the same movements because of the difference in foundation stiffness between each pier. All piers with longitudinally fixed bearings have 23m diameter spread footings, the same for the pier-abutments where the bearing reaction of viaducts are smaller whereas the applied loads (boat impact, swell) are the same as for the standard piers.

These foundations are bearing on sand or rock. A few of the sandy zones show some weakness. So they have to be strengthened with the vibro-flotation method.

All the piers with their foundations are precast in two parts. The first part called "base" includes the spread footing and the lower part of the pier shaft extending 3m above the water level. The second part called "pier head" includes the upper part of the pier shaft and the pier cap.

These two parts are connected on site with a 1,5m high cast-in-situ stitch.

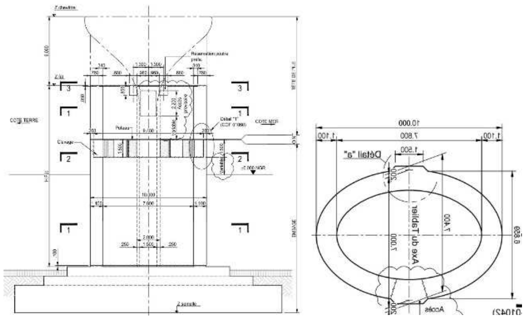


Figure 14 transverse layout of piers and foundations, and typical section 1-1

The circular spread footings are 2,4m thick. They are covered with 2 octagonal stools, 0,8m in thickness. The pier shaft is hollow and its shape is elliptic, the long dimension is 10m long, and the short dimension is 7,4m. The thickness of the wall is 1,1m. A vertical external protrusion is provided along the shaft on each side of the long dimension of the ellipse to respect the architectural concept.

The stitch between the two parts of the precast pier includes a 26 cm thick peripheral wall built on the first part with supports plinths to allow for the adjustment of the second part during assembly.

On top, the precast pier cap shows a surface under the pier segment which is a shortened ellipse with a 7,4m short dimension of and an 11m long dimension resting on an arc of 50m radius. The transition between the ellipsoidal shapes of the shaft to the pier cap is done through the enlarging of the groove which varies from 1,5m to 11m. The construction cycle includes a construction joint within the pier head. A precast floor is used to pour the pier cap in the precast yard.

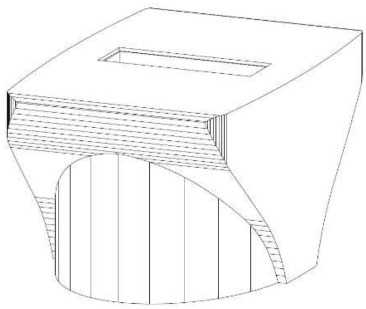


Figure 15 : fixed pier pier cap axonometry, without bearing plinths

The pier cap accommodates the bearings, recesses required for the construction stages (temporary bearing areas, ducts for the tie down cables and provisions for lifting). A 4,6m long and 1,6m wide recess is located at the center of the pier cap to allow for inspection and maintenance.

The bearings are pot bearings. The first part ("base"), of the precast pier weighs 4500 t maximum and the upper part ('pier head"), 2500 t maximum.

2.2.2 Abutments

The abutments are founded on 26 piles, 1m in diameter which experience significant ground displacement due to the size of the backfill installed after their construction. The so called g(z) efforts create displacement in the order of 1cm and downdrag around 1 MN.

Their design includes the drainage system for the water coming from the channel parapets and the recesses for the utilities.

2.3 Construction methods

The construction methods, lifting and assembly will be described in a future article because the design of the construction equipment is still in progress.

At Tender stage, the construction joint venture proposed a fully precast solution. Transport and lifting equipment (barge), have been studied as well as a launching beam.

Viaducts are constructed with the precast segmental balanced cantilever method. Segments are tied with PT bars during erection then prestressed with the cantilever tendons.

In order to achieve this assembling on site, all viaduct segments are precast.

The precast yards are already in operation and spread over over a few sites of the town named Le Port.

Figure 16 : precast yard for piers

After drying in a storage area, segments are transported on a tyre-mounted low-bed semi-trailer. The launching beam will then handle the segments.

This launching beam is 278m long and allows for balanced cantilever erection of the segments. It is built in Italy by Cimolai. The launching beam is assembled near the precast yard for segments.

The segments supply will be done from the C49 abutment on La Possession side. The sketch below shows the launching beam seen from the old coast road at the beginning of a cantilever construction.

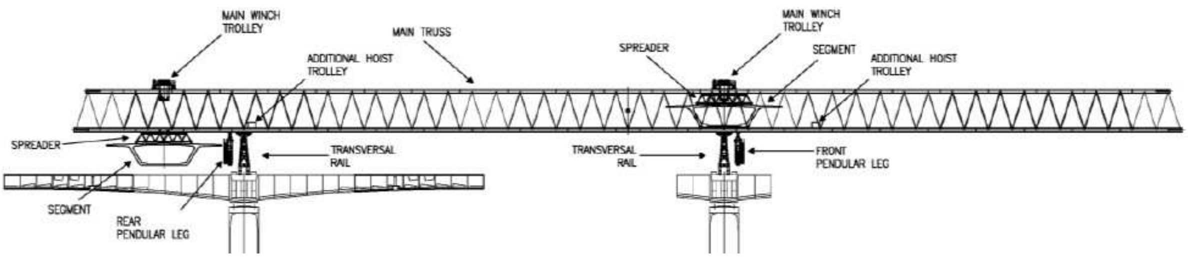


Figure 17 : launching beam principle

Segments are supplied from the trailer driving on the already built part of the deck. The construction will begin from pier P48.

3 CHALLENGES OF THE DETAILED DESIGN

3.1 PRODUCTION OF THE DESIGN

The construction joint venture selected an organization for the structural studies of the viaducts which put together the resources of the contractors' own structural design offices instead of subcontracting the design work. The latter was not retained for efficiency reasons. Having at our disposal the in-house resources of the contractors allows achieving a perfect continuity of the studies together with the greatest reactivity for the work site during the preparation of the construction stages.

This structural design team was located in a dedicated open space office with about 20 persons composed for a quarter of cad engineers and three quarters of confirmed and senior engineers.

All calculations were performed with a single Finite Element Analysis software (Sofistik) for all models, so as to secure production and achieve the best quality of the studies.

3.2 STRUCTURAL ISSUES

3.2.1 Foundations

The spread foundations sizes were a critical issue because these sizes impacted the barge design, the construction of which required a period of 2 years.

The start of the project is a period when optimization concerning the structure can impact the loads on foundations. It is also the time for setting the design assumptions, in particular the soil parameters and calculation methods.

So, based on the initial set of data provided in the Tender documentation, the vertical loads at each viaducts piers were calculated to perform the geotechnical verifications of all the foundations in order to confirm as quickly as possible the sizes of the spread foundations.

3.2.2 Distribution of the fixed supports

At the beginning of the studies, the supports conditions at pier head were discussed with experts of the construction joint venture. The significant loads from the swell as well as the collision loads due to ship traffic could justify to set more than one fixed support in the longitudinal direction. The distribution of these severe load effects on several piers could be beneficial.

However, the geotechnical conditions for foundations were heterogeneous between zones of viaducts and created a great variability of pier stiffness. Moreover, each viaduct was founded in a zone with specific soil stiffness. So it was likely that this design with more than one fixed support per viaduct would lead to a specific design per viaduct. This alternative was dropped and a design with a single fixed support per viaduct was adopted.

4 GOVERNING LOADS

4.1 SWELL LOADS

The swell load is defined by 2 distinct actions, on one hand the swell with a height over 2m called cyclonic swell with an horizontal load of 1631 tons applied at the sea water level, on the other hand the swell with a height less than 2m called frequent swell with an horizontal load of 353 tons at the same level, which can be concomitant with the ship collision.

4.2 SHIP COLLISION LOADS

The ship collision defined in the Tender documentation is a horizontal static equivalent force of 3000 tons in any direction applied on the pier shaft 4,2m above the sea level.

4.3 TRAFFIC LOADS

The particularity of the analysis of the operation phase comes from the previously defined two modes, which involves the addition of prestressing before the implementation of phase 2.

Indeed, the transition from mode 1 to mode 2 modifies operational conditions from road to mixed traffic, road and trolley. The road traffic loads are those of Eurocode 1 part 2: LM1, LM2 pedestrians completed with special vehicles, wide load C2. The trolley taken into account for the mode 2 is of Alstom Citadis type with a weight of 123 tons per convoy composed of 2 trains. Then the sum of breaking load from trolley and road loads gives a load of 1,17 MN.

The others operation loads are the temperature with a uniform temperature variation equal to -15°C or 17°C around an average temperature of 22°C, and the thermal gradient with a variation of -6°C and 9,6°C.

4.4 WIND LOADS

La Réunion Island is situated in a tropical zone subject to cyclons, so the project has to withstand the cyclonic wind.

This load is significant during the operation phase, however it has the greatest effects during construction, when the bridge is not in its final configuration yet. The calibration of this load was elaborated with the help of CSTB with physical and numerical models.

4.5 CONSTRUCTION LOADS

The construction loads are principally governed by the construction equipment:

- *The tyre-mounted low-bed semi-trailer carries the segments from the abutment to the launching beam. It has a weight of 414 tons spread on 18 axles and moves on the deck under construction.*

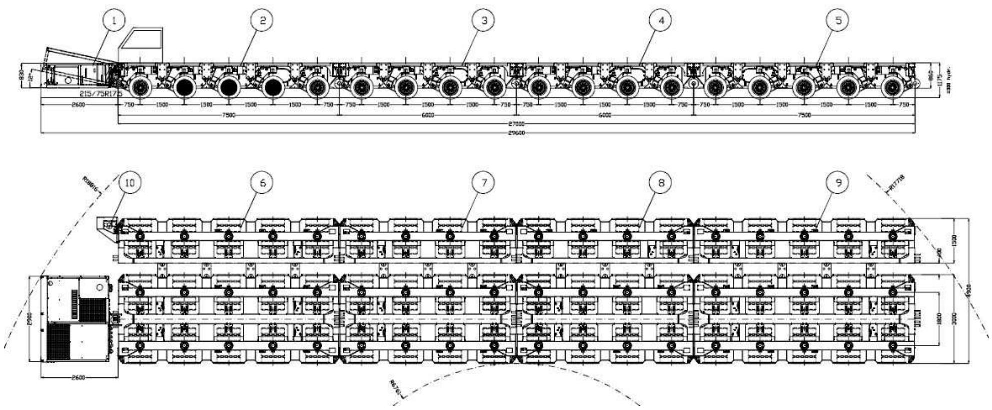


Figure 18 : trailer representation

- *The launching beam is 278 m long and weighs 2400 tons. The girder overhangs the deck by11 m and is 11 m tall. It is supported by two lattice towers and it has two additional lattice legs to allow for its movement along the viaduct. It produces significant loads applied directly on pier segments with a transverse eccentricity up to 5m. It also transmits through its two towers, a significant load on the piers during temporary stages due to wind drag on its large surface exposed to the wind.*
- *The barge which is used for the transport to the site generates specific loads on the precast elements: pier segments, pier caps or spread foundations due to lifting from the yard or on site, and due to fixing on the barge during transport until the site.*

5 TRANSVERSE ANALYSIS

Due to the great width of the deck, the transverse analysis of the deck required specific calculations to resolve the following technical issues:

- *The distribution of transverse load effects in the box girder working as a frame,*
- *The significant interaction between longitudinal and transversal bending,*
- *The shear lag effects and spreading of prestressing in the wide deck*

In order to do so, a 3D shell Finite Element model with was created with the Sofistik software. Three spans of 120 m length were modeled. A detailed analysis of the nodes connecting webs and slabs allowed finding a coherent behavior between them.

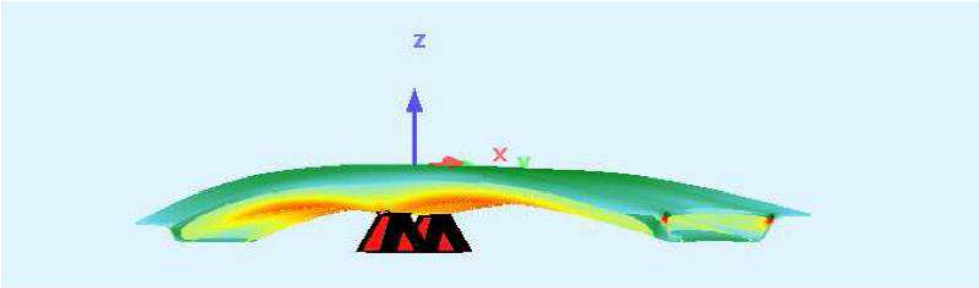


Figure 19 : 3D FEM view of cantilever - longitudinal compressive stress

As the construction sequence is not taken into account in this 3D model, the effect of the dead load needed a very precise analysis in order to process the results from the analysis of spatial behavior. This work allowed to highlight the coupling between longitudinal and transverse behavior of the deck particularly due to the variation of the bottom slab thickness and outward pressure from compression stress in the bottom slab.

Moreover transverse normal forces due to the frame behavior of the box girder were highlighted in the slabs

At last, due to the great width of the deck, the shear lag leads to uneven repartition of normal stresses in the deck. This phenomenon was evaluated thanks to a comparison between a one-dimensional Finite Element model and a shell Finite Element model, both loaded with the dead load and longitudinal prestressing.

Differences between the normal stresses especially in the top and bottom slabs at the intersection with webs allowed to define margins to take into account regarding the criteria of verifications of normal stresses in the one-dimensional Finite Element model.

6 LONGITUDINAL ANALYSIS

6.1 DESIGN METHODOLOGY

The longitudinal analyses have been performed for the operation phases of mode 1 and 2 and for the construction stages.

In that purpose, some specific models have been created in order to study these stages. Although these models are distinct, all the geometry, the numbering, signs conventions and prestressing are the same. Two different models were compulsory to make them easier and more convenient to use.

The design team has first focused on the operation phases. For this model, we used some simplified constructions stages to get the right repartition of dead loads of self-weight without getting overwhelmed by too many phases.

A more detailed model has been done for the study of construction phases.

6.2 SPECIFIC DESIGN ISSUES

Some specific issues have been analyzed for the longitudinal flexure during the construction of the bridge.

- *Traffic of the tyre-mounted low-bed semi-trailer on already constructed sections of the deck.*
- *Suspended end spans*

  The end spans of the NRL, made of 5 segments, will be suspended to the launching beam during construction.

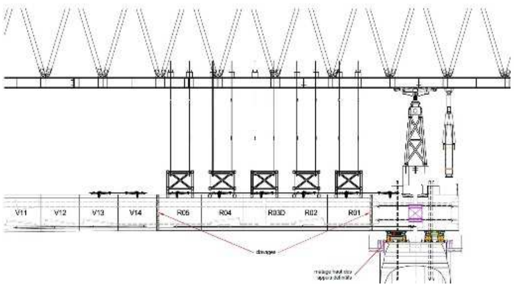


Figure 20 : construction phase of the side span end – hanging segments

Some prestressing cables are stressed during the suspension of these segments. The phases of cables stressing and of hangers releasing are alternated in order to avoid tensions in the concrete in the upper and lower fibers of the suspended segments.

- *Double stitches in the end spans*

  The end spans are linked to the bridge by two stitches. The first stitch is located between the existing cantilever and the first suspended segment of the end span and the second one is between these segments and the segment on abutment or segment on abutment pier. This second stitch is used to adjust the geometry of the deck.

- *Upper continuity prestressing at mid span*

  The passage of the tyre-mounted low-bed semi-trailer which brings the segments onto the deck during construction creates some tension on the upper fiber on the adjacent span. This implied the addition of one pair of temporary upper continuity prestressing cables (37T15) in the top slab.

- *Construction sequence of a typical span*

  In this chapter we describe the sequence of a typical span closure:

1) *Erection of segments V7 to V14*

   Temporary bottom and top PT tie bars (bottom PT bars on V11/12, V12/V13 and V13/V14 kept, top PT bars on V13/V14 kept)

   Tensioning of cantilever prestressing for V7 to V13 (no cantilever prestressing on the last segment)

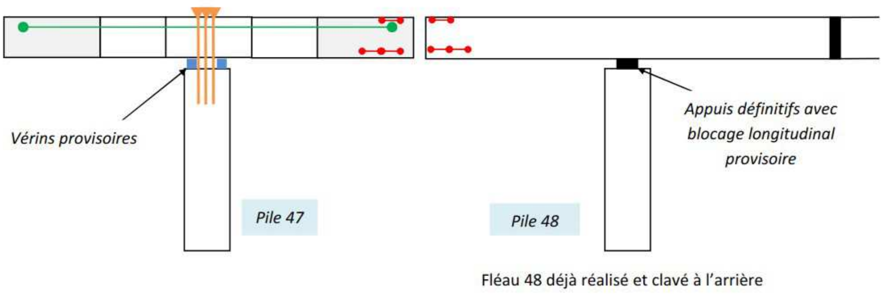


Figure 21 : closure sequence between P47 and P48

2) *Installation of the closure steel frame between cantilevers before stitching at mid span*

   2 pairs of tie down cables removed on pier (2 out of 3) to allow for the adjustment of each cantilever (X, Y, Z and rotations).

   The cantilever stays on temporary bearings and keeps its remains restrained on the top of the pier.

3) *Pouring of the diaphragm of the deviator segment V9D, then closure at mid span*
4) *Tensioning of the continuity cable Ci4*
5) *Tensioning of the temporary upper continuity cable Cs1*
6) *Tensioning of the continuity cable Ci5*
7) *Removal of the closure steel frame of the cantilevers*
8) *Installation of permanent bearings on P47*
   Removal of the last part of the tie down cables on pier and removal of the temporary PT tie bars on the segments V11/V12, V12/V13 and V13/V14.
9) *Tensioning of the remaining continuity cables Ci6 and Ci7.*
10) *Tensioning of one pair of external cables to allow for the passage of the trailer.*

7 PARTICULAR ANALYSIS

7.1 SHEAR STRESS

The analysis of the longitudinal shear and torsion loads of the precast deck was done following the philosophy of the Eurocode 2 part 2. The effect of the joint opening during ultimate limit state (corresponding to cracking) was taken into account. The shear strength of the deck is obtained with a strut and tie model constituted of tensioned and compressed elements due to the longitudinal flexure (N,My) and of the inclined strut in the webs and slabs due to shear and torsion.

The longitudinal component of these struts involves additional longitudinal tension in the members to those generated by bending. From this analysis, all the elements of the strut and tie model were justified using the variable strut inclination method.

The presence of grouted cantilever tendons allowed taking into account their additional strength beyond prestressing to find an equilibrium state under normal loads effects (N,M) and under shear and torsional load effects (V, $M^t_{torsion}$)

The EN1992-2 allows a maximum additional strength over prestressing of 500 MPa in the grouted tendons. So the coherence of the global over tension due to bending and shear loads was verified regarding the actual state of tendon tension. Of course the more bending mobilizes this additional strength over prestressing, the lesser it is available for shear, which involves reducing the struts angle to the vertical and increasing the quantity of stirrups.

7.2 SPECIAL SEGMENTS

Special segments (pier segments and abutment segments) are major elements of the prestressed concrete deck. Each of these segments is used to introduce and transfer concentrated loads (prestressing anchorages for example) and to ensure the global longitudinal shear and bending behavior of the deck on its supports.

7.2.1 Pier segment

The pier segment is used to introduce concentrated forces from the longitudinal prestressing system. It is also the support segment during the construction stages and the service phase. This element of the deck is also the first segment which is launched and placed during the balanced cantilever construction of the deck. The fine tuning of its geometry and position is a critical issue for the geometry control of the bridge.

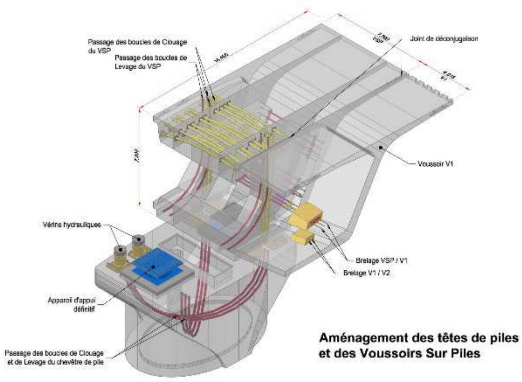


Figure 22 : exploded view of the pier segment – view of tie down tendons

Because of the limitation of the lifting equipment and of the weight of these massive elements, the pier segment has been segmented into three pieces during prefabrication.

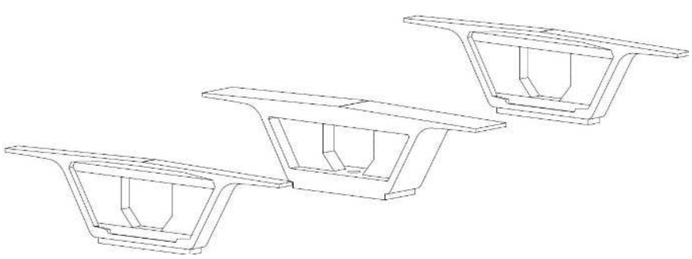


Figure 23 : elementary parts of pier segment

During the launching phase of the deck, the three th of the pier segment are assembled with the segments V1 and V2 in order to create an element of the deck called "MEGA-VSP".

The design of the pier segment is based on a Finite Element analysis. The whole MEGA-VSP is modeled, including the regular segments V1 and V2. All construction stages have been studied in order to produce a complete design of the pier segments, including the launching and lifting phases.

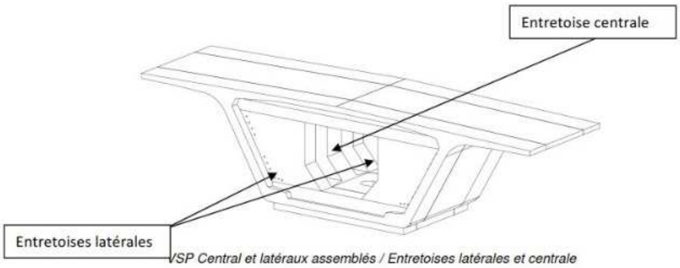


Figure 24 : assembled pier segment

The external prestressing system of the deck passes through the top of the pier segment. The upper crossbeam is designed (thickness and reinforcement) so as to transfer the anchorage forces of this prestressing system.

For the global longitudinal bending of the deck, the static scheme differs between the construction phase and the service phase. During construction of the balanced cantilevers, the deck is supported on the pier cap with two lines of temporary jacks. By using this scheme, a rotational restraint is created in order to ensure the stability of the cantilevers.

During service phase, the deck is supported on the pier cap one one line of permanent pot bearings (considered as hinges for the design calculations).

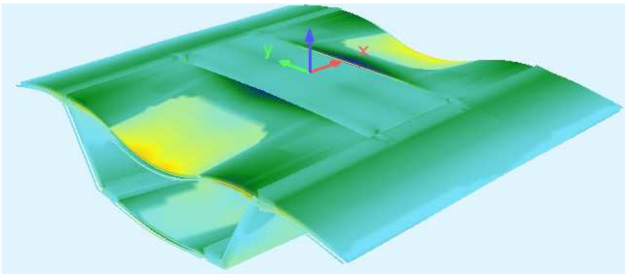


Figure 25 : deflections under dead load

The pier segment is constituted of thick members but also includes three pairs of walls in the transverse direction: one central pair of central walls designed for the service phase at the location of the permanent bearings and two lateral pairs of walls designed for the construction stages at the location of the temporary bearings. The stiffness of these elements creates a transverse diaphragm behavior which is studied with a full Finite Element model of the pier segment. This model is used in particular to study the transmission of the longitudinal bending internal forces to the bearings through the struts and also to justify the local stability of the elements constituting the MEGA-VSP.

The longitudinal internal forces have been introduced into the model in the form of regularized stresses at the edges of each segment V2. This model type is used in order to replenish the global longitudinal bending behavior of the deck.

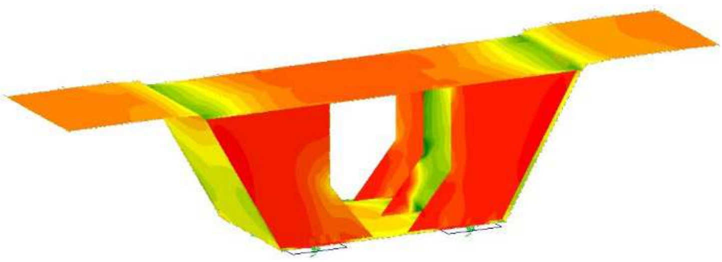


Figure 26 : FE model – iso area of shells principal loads

The rest of the loads applied between both J3 sections are directly introduced and applied to the Finite Element model.

7.2.2 Abutment segment

The abutment segment is the place where a lot of concentrated forces from the prestressing system are introduced and applied (9 pairs of 37T15S external prestressing cables, 4 pairs of 37T15S internal prestressing cables). This segment has also to be designed to resist the internal forces due to the anchorage of the end strut. Numerous particular temporary construction stages have to be taken into consideration for the final design of this concrete element.

This segment is precast and is constituted of one single 4.0m long concrete element. Depending on the final position of this segment (abutment or abutment-pier), the static scheme during construction stages will be different. On the abutment, the abutment segment is tied down with tensioned bars during a short time. Once this segment is assembled to the already built part of the deck through the stitch, the tie down is eliminated and the abutment segment laid on pot bearings. On an abutment-pier, the two adjacent abutment segments are maintained by a temporary beam and tensioned bars, and each segment is tied downwith tendons to the pier-abutment cap. Then each segment is connected to its respective deck, when the temporary beam and the bars are released. Then the tie downs are eliminated and each segment is laid on pot bearings.

The abutment segment is composed of a thickened transverse section with thicker web and slabs. A three meter wide transverse diaphragm stiffens the segment in order to transform the torsional moment into vertical reactions on the pot bearings. The presence of the launching beam towers and legs is another reason for increasing the stiffness of this segment.

The central cross beam is used to introduce and transfer prestressing anchorage forces. The design rules summarized in the SETRA guideline book "Diffusion des efforts concentrés" have been chosen to design its reinforcement. This method is based on the evaluation of the passive reinforcement by creating sections through the segment. For each section, the slip force is evaluated and the reinforcement required to counteract this force is calculated and placed through the proper section. The shear stress is also controlled within the concrete in order to check the crack opening in the segment. All these calculations are performed at both ultimate limit state and serviceability limit state with a 300 MPa working stress for the reinforcement.

These calculation have been completed with a 3D Finite Element model created with the Sofistik design software. This model allows identifying the principal stresses and their directions under the effect of prestressing forces.

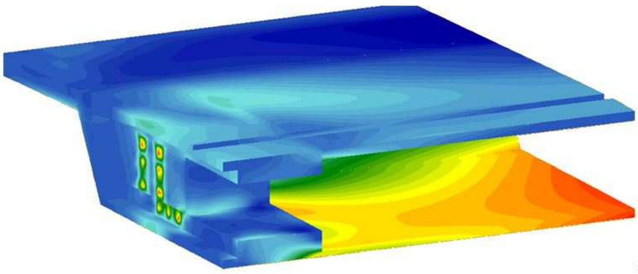


Figure 27 : External prestressing load – iso area of longitudinal stesses

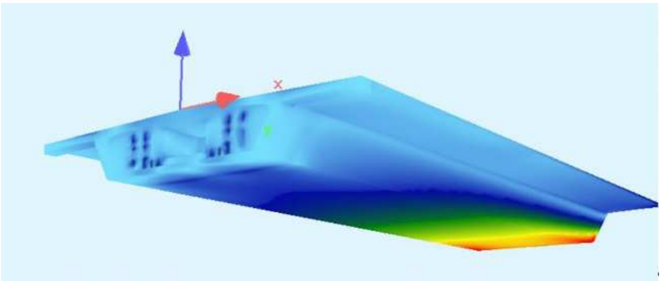


Figure 28 : iso area of stresse in the cross-beam – horizontal cross section

The design of the end strut anchorage has been optimized by fine-tuning the tensioning sequence of external prestressing cables and continuity cables.

Finally, as the abutment segment is placed at the end of the deck, it is very sensitive to the edge effects and to the dynamic effects generated by the trolley. The presence of the roadway expansion joint has also contributed to the difficulty of designing and detailing this segment. The expansion joint reduced the space available to place the reinforcement.

The presence of sensitive equipment on the abutment segment imposes the respect of displacement criteria.

7.3 PIERS

The design of piers was subject to a detailed analysis to take into account significant loads applied directly onto the pier shaft, in particular the ship collision load.

The pier shaft, a hollow elliptical cross-section made of reinforced concrete, can be studied considering two different deformation systems. This is similar to what is usually done for deck slabs:

- *One deformation system referred as "global deformation" in which the cross-section is assumed to remain un-deformed according to the Navier-Bernoulli principle.*
- *One deformation system referred as "local deformation" in which we evaluate the deformation of the walls of the hollow cross-section.*

The global deformation of the pier shaft is studied with the general model of the bridge used for the longitudinal analysis. A specific 3D model with shell elements was implemented to study the local deformation of the pier shaft.

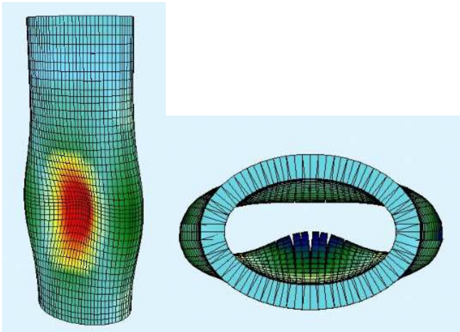


Figure 29 : Shell FEM for local bending

The combination of flexural and shear reinforcement resulting from the global deformation model, with the bending reinforcement resulting from the local deformation model has been determined in accordance with the Eurodode 2 rules usually applied to the deck slabs. According to these rules, global longitudinal bending effects are fully cumulated with local bending effects occurring in the same direction. However shear effects of the global system are considered either 100%, or 50% cumulated with the transverse local bending effects.

7.4 PRECAST-SPECIFIC STUDIES

7.4.1 Bases and pier heads

The bases are precast in one piece. The pier heads constitute the second precast part of the piers. The particular studies of these elements focus, on one hand, on assembly phases on site, and on the other hand, on the stability during assembly stages, including the installation of the MEGA-VSP.

7.4.2 Segments

The prefabrication of the match-cast segments required particular deformation studies at different construction stages to verify that the deformations which could be detrimental to achieving the full contact between adjacent segments, would not exceed the commonly accepted values. The effects of transverse prestressing as well as creep and shrinkage, have been analyzed throughout prefabrication and storage stages.

These calculations required a significant amount of time and were iterative so as to adjust the transverse tendons tensioning stages.

8 CONCLUSION

This short description of the detailed design of the New coastal Road viaducts shows that precast segmental construction for viaduct can't allow amateurism as highlighted by Jean Armand Calgaro and Jacques Combault in their lectures.

The main items were mentioned. Other studies were performed, a few concerning construction alternates, others concerning more detailed studies of the mentioned points. The great width of the box girder led the design team to carry out in-depth-analyses of certain items to evaluate the risks but also to secure the construction process. In this respect, the design team approach can be assimilated to the Safety in Design approach which is being implemented by VINCI as well as other major contractors in their projects.

***Owner**: La Réunion Region*

***Owner's Engineer**: EGIS*

***Contractors**: VINCI Construction Grands Projets (leader) –Bouygues TP – Dodin Campenon Bernard (VINCI Construction) – Demathieu Bard*