ACHIEVING HIGH PRODUCTIVITY IN BRIDGE CONSTRUCTION – THE ORGANIC PRESTRESSING IMPACT

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ABSTRACT

The demand for productivity is a common requirement of bridge construction process nowadays. Focusing on span by span concrete bridges, different solutions have proved to be efficient. Besides cost efficiency, the choice for the most adequate solution is not linear and depends on several factors of quite different nature, such as bridge geometry (curvature, transversal slope, longitudinal slope), deck section (weight, shape), span length and bridge total length, environmental conditions, site logistics, local construction and design traditions and constructor experience and preferences.
Independently of the chosen solution, a fundamental factor for achieving a cost and time-efficient construction process is a timely cooperation between the bridge designer and the construction process developer, making key adaptions in bridge design in order to make it easier for construction. In this specific case, details do matter and a judicious choice may have a significant impact in construction times.
In this paper, 3 different span by span concrete bridge deck construction processes are presented, ranging from segmental pre-cast to cast in situ solutions for one or two spans at a time. The different solutions have a common denominator – the demand for productivity.
The presentation is based on real examples. Throughout the text, a brief reference is made to Organic Prestressing System (OPS), an actively controlled prestressing system that increases structural efficiency. In its recent applications to bridge construction equipment, OPS confirmed a positive impact in productivity.

Key words: Bridge Construction, Productivity, Movable Scaffolding Systems, Launching Gantries, Organic Prestressing System (OPS)

1. INTRODUCTION

Usually the demand for productivity in bridge construction has some very distinct causes:

- The operation and construction yard costs have a very important component of variable cost due to time;
- Nowadays bridge construction financing relies frequently on private investment by concession and therefore the concessionaire has a strong interest in opening the bridge to traffic to start the capital return period as soon as possible;
- Focussing only on bridge design often leads to a limited preparation time for construction process caused by disregard and undervaluing of the latter. This incurs in a very narrow chance to make key adaptations in bridge design in due time;
- The impact of bridge construction on existing roads by limiting their traffic;
- Political promises.

Despite the fact that causes are different in nature, the general approach to achieve higher productivity on bridge construction should generally follow the guidelines:

- Preparing the bridge construction process right from the beginning of bridge design. The development of bridge design in parallel with bridge construction process usually implies a better design for both

bridge and bridge construction equipment and often leads to more productive and less expensive solution;

- The bridge construction process analysis shall include all operations to be done on site. The productivity on bridge construction strongly depends on adequate preparation and simplification of each task to be done on site;
- The use of specialized labor force for all stages: bridge design, bridge construction process design and also bridge construction – sometimes the labor force during bridge construction is disregarded and consequently the productivity is much smaller;
- The bridge construction process shall include risk analysis for all tasks to be done on site. All tasks shall be designed to have an acceptable risk level. Usually a safe task is also a more productive one.

2. ORGANIC PRESTRESSING SYSTEM (OPS)

Using as inspiration the behaviour of nature structures (biomimetics), more specifically the muscle behaviour, Organic Prestressing System (OPS) is an automatically adaptive prestressing system which has the ability to increase or decrease prestressing forces according to live load variation. It is no more than a prestressing system in which the tension applied is automatically adjusted to the actuating loads, through a control system, in order to reduce the structural deformations and minimize tensions due to live loading (Pacheco, P. 1999).
Centering on bridge construction equipment, the OPS main elements are 1) the actuator in the active anchorage, 2) the unbonded cables, 3) the sensors, 4) the electronic controller in the girder control unit, 5) passive anchorage and 6) deviation shores (please see Figure 1).

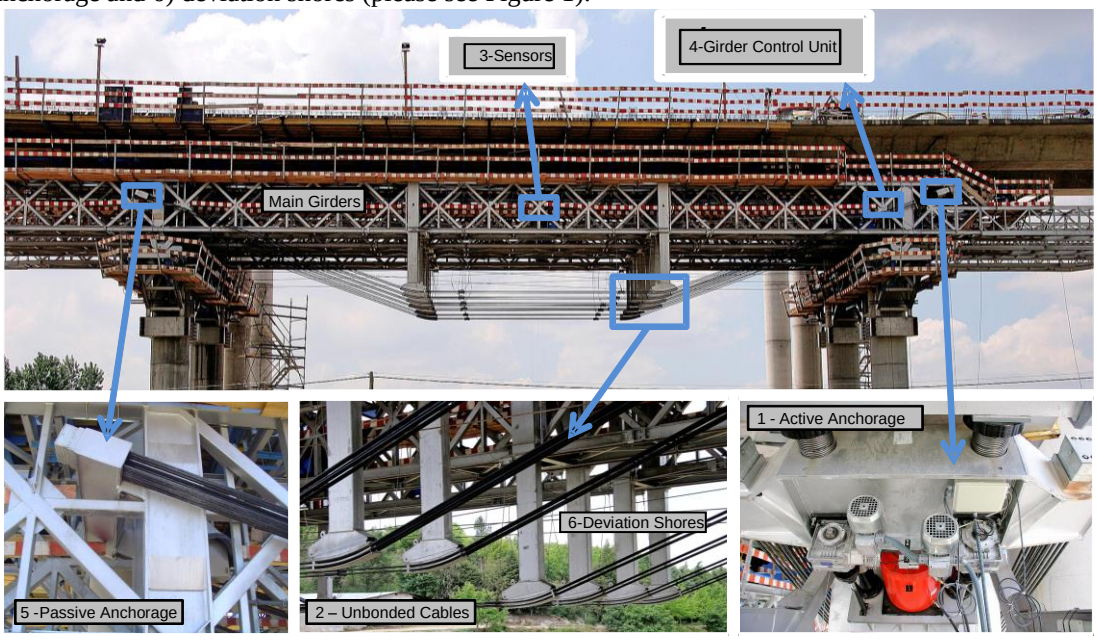

Figure 1 – OPS Main Elements and layout

The OPS control system is based on mid span deflection continuous measuring and analysing. The information from the sensors is transmitted to the girder control unit that based on a simple algorithm decides on stroke variations on hydraulic cylinder on active anchorage and consequently tension change on unbonded cables. The decision is based on mid span deflection changing tendency and not on instantaneous deflection noise due to vibration.
To ensure reliability, OPS is provided with several sensors with measures that are permanently compared to guarantee that the algorithm decision is always based on accurate information.
However, if the OPS detects any inconsistent or incoherent data there are several alarm combinations (buzzer and color light) to warn the operator to check the data – always available on real time on intuitive touch screen interface (on girder control unit), to confirm if the data is correct and take immediate action to prevent accidents if that is the case. Granting information to the operator about the bridge construction equipment behavior, the OPS system increases the safety factor of the structure.
On bridge construction equipment, the OPS allows the design of lighter and more efficient structures. An important indirect impact on productivity and operational costs is due through considerable weight reduction and load capacity increase, especially since these equipments have to endure frequent launching, assembly, disassembly and transport operations.

3. CASE STUDY 1 – BERD M60-I CORGO

3.1. Bridge overview

The bridge over Corgo river in Vila Real (Portugal) is a cable stayed concrete bridge with a total length of 2796 m. At this time this the 2nd highest cable stayed bridge in Europe. The East viaduct was built with M60-I performing 22 spans with a maximum length of 60 m accomplishing a total length of 1278 m (please see Figure 2).

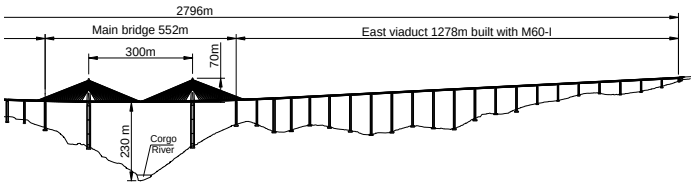

Figure 2 – Bridge over Corgo river elevation

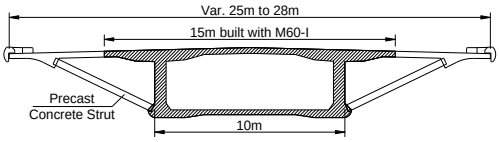

Figure 3 – Deck cross section

Figure 4 – M60-I on concrete pouring phase

The deck cross section is a single box with 10 m width. The total width of the crossing platform – 25 m in access viaducts and 28 m in cable stayed bridge – is reached through continuous cantilever and is supported by precast concrete struts positioned every 3 m (please see Figure 3).

3.2. Project challenges

There were some important challenges to develop a solution for the construction of the East viaduct:

- When M60-I design started the bridge design was almost finished and the construction works had already started – there were piers partially constructed. To fulfill Contractor's schedule the M60-I had to be prepared to build one 60m span every 10 calendar days (9 working days) and the assembly had to start in less than 10 months. Furthermore, the interfaces between bridge piers and M60-I had to be defined 4 weeks later to avoid interruption of bridge piers construction;
- The Contractor required that M60-I should be prepared to work under wind velocities greater than usual (launching operation with wind velocity up to 70 km/h). To accomplish Contractor's schedule it was necessary to work even in adverse climatic situations (usual at Winter time in that region);
- Due to the significant height from the deck to the ground and also the irregular orography it was not possible to have auxiliary equipment – mobile cranes – to assembly the machine supports. This means that the M60-I needed to be prepared to assembly its own supports;
- The orography was very difficult for assembly operation (there was only 18m of free space behind the abutment) and also for disassembly operation (on last span the MSS was around 75m from the ground).

3.3. Equipment description

The solution developed by BERD to build the East viaduct was an underslung movable scaffolding system (MSS) – M60-I. The main components of the M60-I are: (1) Main Girder and Noses; (2) Rear Support Ring; (3) Support Brackets; (4) Transversal Structures; (5) Bogies; (6) OPS Elements and (7) Front Support Ring (please see Figure 5).

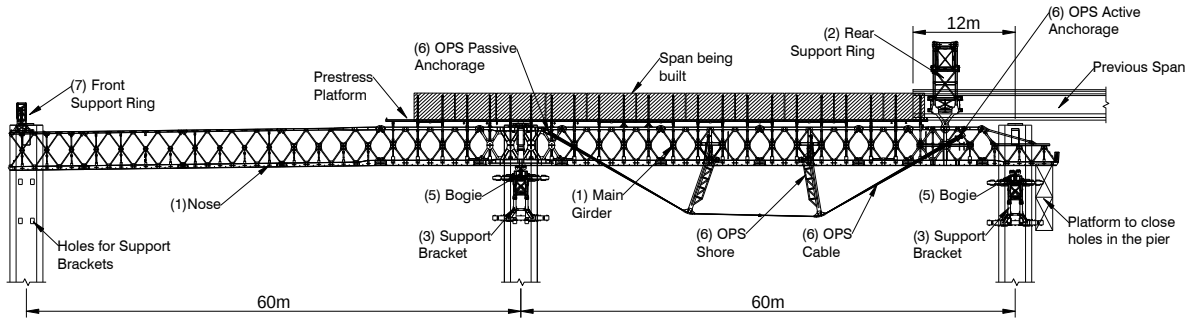

Figure 5 – M60-I Elevation and components identification

Basically the M60-I has 2 different phases: 1) Fixed Phase and 2) Launching Phase. The Fixed Phase includes all operations of span (n) deck construction and the Launching Phase comprises all operations in-between the M60-I fixed on span (n) and fixed on span (n+1).
During Fixed Phase the MSS Front Support is performed directly on the pier and is done by a hydraulic cylinder placed inside a recess in the pier (please see Figure 6). The MSS Rear Support is the rear support ring which suspends both girders and transfers the loads to the previously built deck cantilever by metallic shims (please see Figure 7).

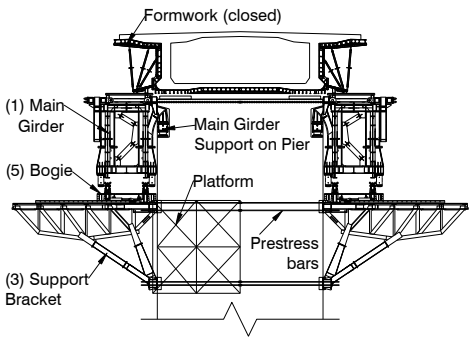

Figure 6 – M60-I Front Support on Fixed Phase

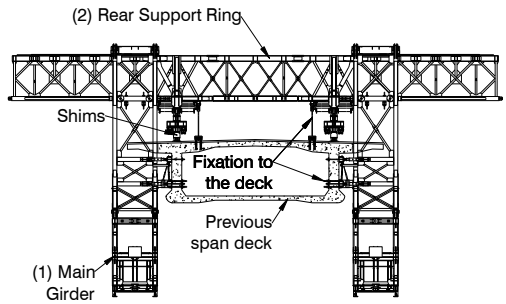

Figure 7 – M60-I Rear Support on Fixed Phase

During Launching Phase the MSS Front Support changes from the hydraulic cylinder positioned in the pier recess to bogies' wheels positioned over support brackets fixed to the pier by prestress bars (please see Figure 8). The MSS Rear Support changes from the metallic shims to wheels on metallic rails previously assembled over the deck (please see Figure 9).

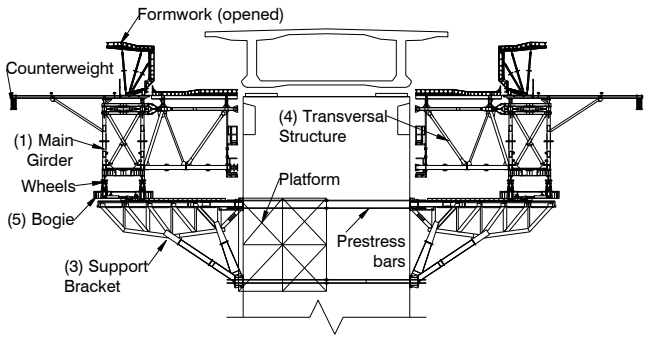

Figure 8 – M60-I Front Support on Launching Phase

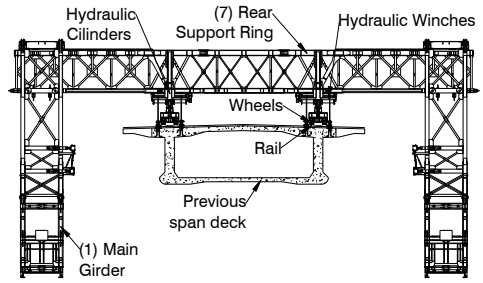

Figure 9 – M60-I Rear Support on Launching Phase

3.4. Working Cycle

The Contractor demand for 10 days working cycle was very important to define M60-I from design to operation. Working cycle operations were designed to guarantee the predefined schedule while regarding all safety measures.

Table 1 – M60-I working cycle

Tasks	Day 1	Day 2	Day 3		Day 4	Day 5	Day 6	Day 7	Day 8		Day 9	Day 10
			Day shift	Night shift	Day shift				Day shift	Night shift		
Deck Prestressing Operation												
Opening Formwork and Launching												
External Formwork Closure												
Support Brackets Relocation*												
Reinforcement Steel Placement on bottom slab and Webs												
Prestressing steel and ducts placing												
Internal Formwork Assembly												
Concrete pouring (1st Stage)												
Internal Formwork Disassembly												
Top slab Formwork Assembly												
Reinforcement Steel on the top slab												
Prestressing cables installation												
Concrete pouring (2nd Stage)												
Concrete couring												

* Note: The duration of the brackets relocation operation is about 5 hours. In the table is represented the time when this operation can be carried out.

The construction of deck central box was performed in two stages. The first stage comprises the construction of the bottom slab and the vertical webs ("U" section) and the second stage the superior slab. This decision simplified the inner formwork and the reinforcement steel preassembly, increasing concrete pouring productivity and deck prestressing productivity as well – deck prestressing operations could be started 15 to 20 hours after finishing concrete pouring (starting on "U" section cables).

Figure 10 – Auxiliary Cranes for rebar placement

Like many *in situ* span by span deck construction, the most consuming task is reinforcement steel assembly and placement. The M60-I was equipped with two movable cranes specially designed for the rebar operations (cages preassembled on construction yard).

Brackets relocation operations include Brackets disassembly, transport to next pier and reassembly procedures. The climatic conditions – mainly the wind velocity – had a great impact on the safety of this operation. Having the M60-I supports for Fixed Phase directly on the pier and on the deck cantilever (front and rear support, respectively) has two main advantages: (1) avoiding concrete loads on brackets allows to significantly reduce their weight and consequently the weight and complexity of all equipment and auxiliary structures used to relocation operation (2) Given that the Brackets are unloaded during almost the entire cycle is possible to perform the relocation with good climatic conditions and also avoid working cycle critical path.

When the concrete of both stages reaches a predefined hardness the deck is prestressed allowing the MSS to move forward to the next span.

Prior to the M60-I longitudinal movement it was necessary to unfold the formwork and move transversally the girders. In this particular project the deck inferior corner demanded the lateral formwork panels to unfold through transversal movement before lowering the girders. After transversal movement of the formwork lateral panels the girders are lowered and moved outside to guarantee compatibility with bridge pier position and geometry (please see Figure 8).

The M60-I longitudinal movement relies on gravity, as the deck longitudinal slope is -5,0%, and its duration is around 1 hour. The movement is controlled by 4 hydraulic winches on the rear support ring. During the launching operation the MSS girders are connected to the rear support ring which confers greater stability (to achieve Contractor's requirement for launching operation with wind velocities up to 70 km/h). The rear support ring is also equipped with 4 hydraulic jacks positioned between the rollers and the metallic structure, allowing

rear reaction control, and consequently the mitigation of imposed displacements effects throughout launching operations.
The expectations on cycle productivity of M60-I operation were exceeded. In fact, the M60-I was able to build several spans in less than 10 days, being 9 calendar days and 7 working days the fastest working cycle. The East viaduct construction was finished on Contractor schedule and without accidents.

3.5. OPS Impact

Besides the structural advantages and deformation control previously referred, the OPS had three major advantages in this particular project.

- When the deck top slab was concreted the "U" section previously constructed was already hardened. By controlling the MSS deformation to zero was possible to limit the stresses in the "U" section during the second concreting stage;
- The OPS deformation control incurs in great importance to avoid time loss due to pre-camber works. This was particularly relevant in the final spans of the Corgo river Bridge project due to their variable length;
- When the MSS disassembly project was being developed, it was noted that in the final span the front nose of the MSS would collide with the form traveler responsible for the construction the cable stayed bridge deck. It was necessary to disassemble the front nose during last launching and before the concreting last span. Due to the front nose absence there was a considerable increase on the positive bending moment of the main girders. By changing the OPS parameters it was possible to introduce an initial negative bending moment that guaranteed the structural safety of the MSS.

4. CASE STUDY 2 – BERD M30X2-S RODOANEL

4.1. Viaducts overview

The East viaducts of Rodoanel Mário Covas in São Paulo (Brazil) have a total length of 2669 m (the internal viaduct 1347 m and the external viaduct 1322 m). The East viaducts were built with two M30x2-S (one for internal viaduct and other for external viaduct) performing 92 spans with a maximum length of 30 m (please see Figure 11).

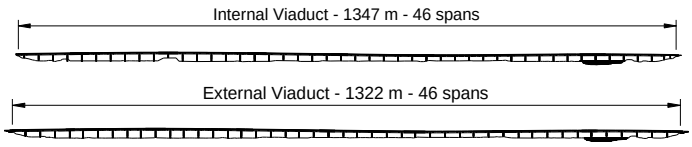

Figure 11 – Internal viaduct elevation (top) and external viaduct elevation (bottom)

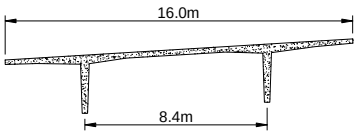

Figure 12 – Deck cross section

Figure 13 – M30x2-S on concrete pouring phase

The cross section comprises two parallel beam decks built simultaneously by two M30x2-S. The width of each deck is around 16m (please see Figure 12).

4.2. Project challenges

In order to develop the solution for the construction of the East Viaducts BERD faced important challenges:

- To fulfill Contractor's schedule the M30x2-S had to be prepared to build two 30 m spans (60 m) every 6 calendar days – 2 spans per week;

- Complex and very variable road axis (minimum plan radius = 745 m and minimum elevation radius = 6300 m), resulting on high kinematic requirements;
- Poor access for equipment operation by the ground (swamp);
- Bridge design was made simultaneously with M30x2-S (with mutual influence);
- Since the M30x2-S was built in Portugal and the operation was in Brazil, the time for design and manufacture had to be shortened and significantly overlapped, as much time was necessary to guarantee a successful transportation process.

4.3. Equipment description

The solution developed by BERD to build the East viaducts was an overhead double span movable scaffolding system (MSS) – M30x2-S. The main components of the M30x2-S are: (1) Main Girder; (2) Transversal Stuctures; (3) Pier Frame; (4) Bogies; (5) OPS Elements (please see Figure 14).

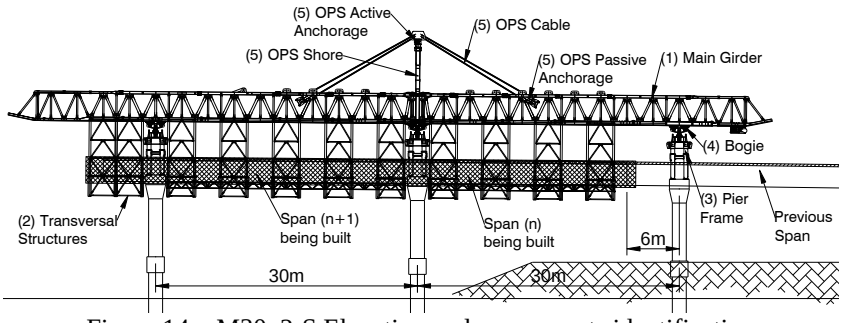

Figure 14 – M30x2-S Elevation and components identification

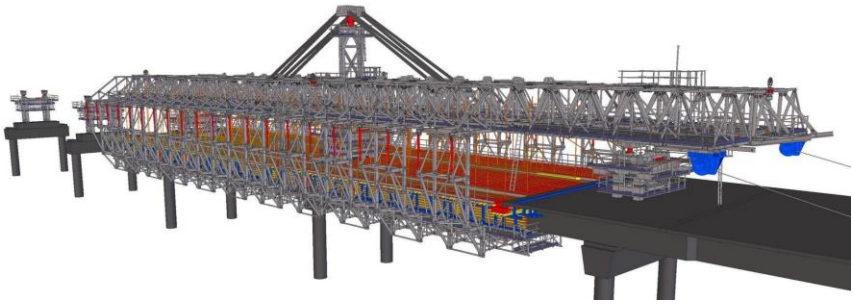

Figure 15 – M30x2-I 3D view

Like the M60-I, the M30x2-S has also the same 2 distinct phases: 1) Fixed Phase and 2) Launching Phase. The Fixed Phase includes all operations concerning span (n, n+1) construction and the Launching Phase comprises all operations in-between the M30x2-S fixed on spans (n , n+1) and fixed on spans (n+2 , n+3).
The M30x2-S supports are always performed by pier frames.

4.4. Working Cycle

The Contractor demand for 2 spans per week was very important to define all aspects of M30x2-S from design to operation.
Working cycle operations were studied to guarantee that all of them were possible to be made in the predefined schedule with safety.

Table 2 – M30x2-S working cycle

Tasks	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Deck Prestressing						
Preparation for Launching						
Launching						
MSS fixation and Transvesal structures Closure						
Formwork adjustments						
Position of deck web reinforcement steel						
Remaining works on prestress rebar						
Concreting						
Concrete Curing						
Deck Prestressing Preparation						
Admission and suspension of deck rebar on MSS						
Disassembly of MSS supports						
Assembly of MSS supports on following piers						

To make possible the preassembly of steel reinforcement, the M30x2-S is prepared to transport, suspend and assemble in place the rebar cages of deck webs. For that purpose the M30x2-S was equipped with 4 electric winches, movable all along the main girder length.

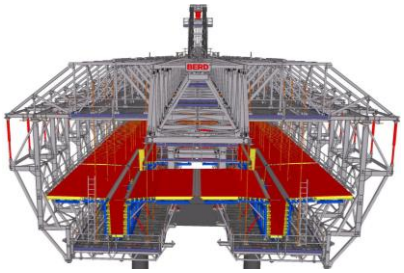

Figure 16 – Closed Transversal Structures closed 3D view

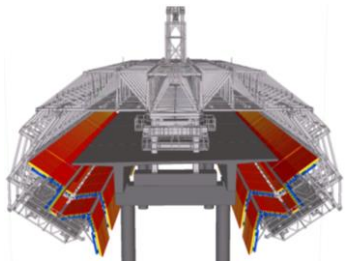

Figure 17 – Opened Transversal Structures closed 3D view

Before M30x2-S launching operations it is necessary to open transversal structures in order to avoid any collision with the bridge piers. All transversal structures are equipped with hydraulic cylinders in order to facilitate opening and closing operations (please see Figure 16 and Figure 17).
The East viaducts construction were finished on Contractor schedule (constantly 2 spans per week for each M30x2-S) and without any accidents.

4.5. OPS Impact

In this particular project the use of the OPS system results in a great advantage: it allows to adapt the initial position of the formwork in each span avoiding time loss with pre-camber works. This was particularly important because along these viaducts the deck was constantly changing (plan radius, transversal inclination and longitudinal inclination).

5. CASE STUDY 3 – BERD LG50-S LAGUNA

5.1. Bridge overview

The Anita Garibaldi bridge over "Canal das Laranjeiras" in Laguna (Brazil) is a cable stayed concrete bridge with a total length of 2830 m. It will be the first cable stayed bridge built in Brazil with plan curvature. The bridge is inserted on BR-101, the main road for load transportation between Brazil and other countries in South America. The existing road nowadays is visibly insufficient, especially during summer with the considerable traffic increase due to tourism. The LG50-S is responsible for the construction of the East Viaduct and also the West Viaduct, after a disassembly, transportation and re-assembly process. On both viaducts, LG50-S is building a total of 43 spans of 50m. (please see Figure 18).

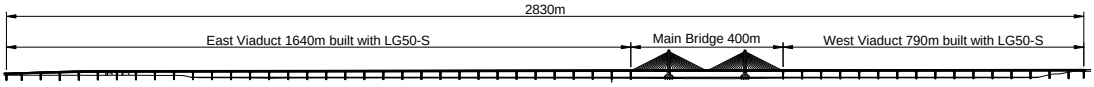

Figure 18 – Anita Garibaldi bridge elevation

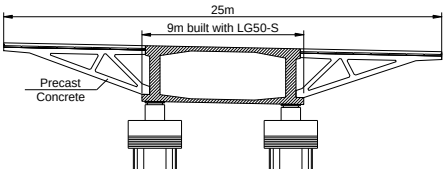

Figure 19 – Deck cross section

Figure 20 – LG50-S prepared for pre-loading

The deck cross section is a single box with 8.5 m width. The total width of the crossing platform – 25 m – is reached by continuous cantilever supported by precast concrete elements, precast slabs and finished with *in situ* compression slabs (please see Figure 19).

5.2. Project challenges

The construction of the Anita Garibaldi bridge access viaducts set some important challenges for the design of the LG50-S machine:

- To fulfill Contractor's schedule the LG50-S had to be prepared to build one 50m span every 5 calendar days;
- The Contractor required that LG50-S should be prepared to be assembled on East viaduct, disassembled and reassembled on West viaduct;
- The Contractor required that LG50-S had to be prepared work normally with wind velocity up to 60km/h and had to be supplied with extra bracings for winds up to 160 km/h to be assembled very fast (strong winds without any warn are usual in the region);
- The Contractor required that LG05-S had to be supplied with a lightning rod with connection to the ground (the region is one of the stormiest places on earth).

5.3. Equipment description

The solution developed by BERD to build the East and West Viaducts was an overhead movable launching gantry (LG) – LG50-S to move and assemble precast segments weighting 90 tons each. The main components of the LG50-S are: (1) Main Girder; (2) Overhead Crane; (3) Deck Frame; (4) Bogies; (5) Front Leg; (6) Rear Leg, (7) OPS Elements and (8) Launching Counterweight (please see Figure 21).

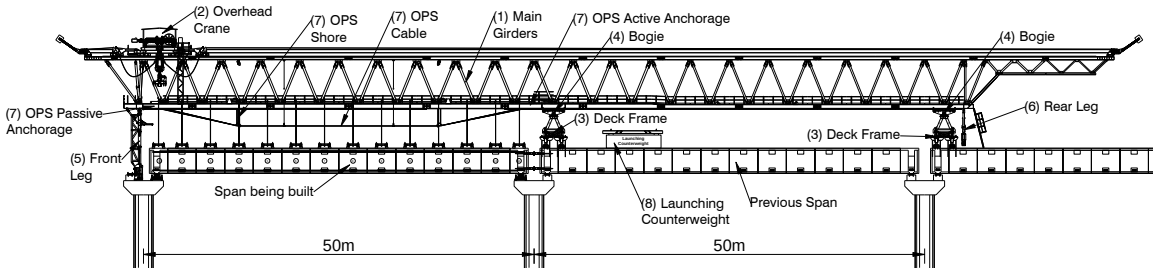

Figure 21 – LG50-S Elevation and components identification

Basically the LG50-S has 2 different phases: 1) Fixed Phase and 2) Launching Phase. The Fixed Phase includes all operations of span (n) deck construction and the Launching Phase comprises all operations in-between the LG50-S fixed on span (n) and span (n+1).
During Fixed Phase the LG50-S Front Support is performed directly on the piers and is done by the Front Leg. The LG Intermediate Support and Rear Support are performed on the deck by Deck Frames. During Launching Phase the LG Supports are on Deck Frames.

5.4. Working Cycle

Considering span by span construction, one of the most relevant variable for cycle time must be the number of segments that compose each span.
For this project, the interaction between the launching gantry and bridge project allowed the design of 14 segments deck.

Table 3 – LG50-S working cycle

Tasks	Day 1	Day 2	Day 3	Day 4
Launching Stage				
Segment Position				
Deck Prestressing				

Span construction begins with the girder pre-loading, which consists on suspending half of the bridge segments in the front area of the steel structure. Admission of new bridge segments is achieved either through the previously constructed bridge deck or from a lower level. While pre-suspension stage is undergoing the OPS is guaranteeing minimum tension in the OPS cables and therefore their passive behavior during the structure loading.
The span construction itself initiates with the positioning of the first two segments. This operation has to undergo a tight geometry control due to the importance of starting span construction within the defined tolerances for planimetric and altimetric alignment. Each positioned segment is glued to the previously erected segment and temporary prestress is applied in order to achieve a minimum contact pressure for epoxy glue cure. As the third bridge segment is raised to be positioned, the OPS is set to compensate any further girder deformation, up until the last non preloaded segment is positioned. This control results in minimum deviation in altimetric alignment which reduces dependency on deck geometry control system for position correction. It also allows the control of stress between the segments interfaces that may compromise epoxy glue collage in short term.

Figure 22 – LG50-S Girder Preloading (left) and Segment Positioning Operations (right)

After the last bridge segments are positioned the deck prestressing operations are initiated. Girder unloading due to deck deformation through prestressing is compensated in the OPS, by gradually reducing the OPS cables tension through deformation control. Once the weight of the deck is no longer supported by the girder, its altimetric and planimetric position correction is achieved through the vertical and transversal hydraulic jacks of the geometry control systems.

Figure 23 – LG50 Launching Gantry during Launching Operations – Longitudinal Movement.

When all prestressing operations are concluded, launching preparation operations initiate. The rear deck support is moved with the overhead crane to a frontal position near the pier support, which is disassembled next. After bracing disassembly, longitudinal movement is achieved through the overhead crane locomotion motors, while it is fixed to the rear support sustaining a counterweight.
The LG50-S Launching Gantry has a span construction cycle duration of 4 days as defined in Table 3. The relevance of Segment Positioning operations in cycle duration is clear as it takes approximately 40% of total cycle time.
In this project, the Contractor requirement for 5 days working cycle was surpassed, as the LG50-S managed to work on a 4 day cycle.
The construction is now near the end of East viaduct and the construction with LG50-S is ahead the schedule.

5.5. OPS Impact

Besides the structural advantages and deformation control explained before, the use of OPS leads to four major advantages:

- Direct impact on productivity due to the reduction of girder preload times (less segments pre-suspended);
- OPS continuous monitoring of the structure gains relevance in Launching Gantry Equipments due to the importance of deck geometry control during segment positioning, which becomes easier and more reliable;
- Furthermore, the OPS allows deformation control without significant increase in weight for structural stiffening purposes as well as a considerable cost reduction in geometry control system.
- The OPS use to control tension in the epoxy glued joints between segments makes possible the use of bigger segments (and consequently less segments per span) and less temporary prestress between segments, reducing significantly the working cycle time consumption.

6. CONCLUSION

As detailed in previous chapters for three significantly different bridge construction equipment – from underslung MSS to overhead launching gantry – the use of OPS proved to be very useful to achieve some similar goals like the use of less steel on bridge construction equipment and also the continuous information on deformation. Furthermore, the use of OPS showed as well some particular advantages on each equipment.
Also, the use of OPS allied to careful and detailed preparation of all tasks to be done on bridge site show great advantages on productivity – making possible working cycles that appear impossible and also advantages on safety – many times the accidents occur on tasks improvised on bridge site.

7. AKNOWLEDGEMENTS

The authors wish to thank all the BERD team who worked in these Projects, to LCW Consult and Enescil (bridge designers), ConstruGomes (equipment operator) and FCC, Soares da Costa, RRC, Contern, Camargo Corrêa, Aterpa M. Martins and Construbase (bridge builders).

8. REFERENCES

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