Multi-Span Large Bridges – Pacheco & Magalhães (Eds.)
© 2015 Taylor & Francis Group, London, ISBN 978-1-138-02757-2

High productivity in bridge construction – the OPS effect

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ABSTRACT: The growing dissemination of industrialized solutions has made productivity demand become a commonplace of bridge construction process nowadays. There is not a unique formula since different solutions have proved to be efficient. The choice for the most adequate solution is not linear and depends on several factors of quite different nature besides cost efficiency, such as bridge geometry, deck section, span length, span arrangement and bridge total length, environmental and climacteric conditions, site logistics, local construction and design traditions, constructor experience and preferences and overall project schedule.

In this paper, a general reflection regarding productivity is substantiated by a bridge construction process practical case. Throughout the text, particular reference is made to Organic Prestressing System (OPS), an actively controlled prestressing system. Besides increasing structural efficiency and safety, OPS confirmed a positive impact in productivity in its recent applications to bridge construction equipment.

Keywords: Bridge Construction, Productivity, Movable Scaffolding Systems (MSS), Organic Prestressing System (OPS)

1 INTRODUCTION

The demand for productivity in bridge construction may potentially derive from some very distinct causes:

- Impact of construction time in operation and construction yard costs;
- Interest of the concessionaire in opening the bridge to traffic as soon as possible in order to anticipate the capital return;
- Limited time for construction due to inadequate planning and control of bridge design and extended tender processes – leaving limited time for construction process preparation. This often results in narrow chance to make key adaptations in bridge design in due time.
- The impact of bridge construction on existent road network (traffic interference during construction and increased traffic flow after bridge opening);
- Political promises and marketing – pressure to integrate inauguration ceremonies with electoral events.

Regardless of the context and case by case restrictions, the approach for achieving high productivity in bridge construction should be based on the following general guidelines:

- Preparation of construction process from an early stage of bridge design. Simultaneous development of bridge design and construction process enables a more efficient design of both bridge and construction equipment, often leading to more productive and less expensive solutions;

– Adequate and timely planning of operation tasks, including preparatory works, assembly of construction equipment, current operation cycle and disassembly. In some cases, operation planning may justify changes or adaptations in construction equipment design;
– Bridge construction process analysis shall cover 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. Repetitive tasks such as steel reinforcement placement and formwork adjustments (using the example of cast in situ construction) may be largely simplified by an adequate design and by adding adequate auxiliary means to construction equipment;
– Reduction of in situ tasks to a minimum – for example, by prefabricating complete reinforcement cages;
– Use of specialized labor force in 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 and safety is impaired. Operation crew must receive an adequate training prior to beginning of site activities;
– The bridge construction process shall always include a specific risk analysis for all tasks to be done on site. All tasks shall be designed to have an acceptable risk level. Most commonly, a safe and intuitive task tends to be a more productive one;
– Coordination and efficient communication between bridge designer, construction process designer and operation crew;
– Monitoring and continuous improvement: during the construction of a bridge, the first cycles are often slower (especially in cases in which operation crew is not familiarized with construction technology or construction process). Lessons learned during first spans may lead to implementation of very effective improvement measures.

2 ORGANIC PRESTRESSING SYSTEM (OPS)

The present chapter, which appears to be disconnected from the previous, gives a brief and overall overview of Organic Prestressing System (OPS) to all readers not yet familiarized with this technology. This introductory chapter is important for a comprehensive reading of practical case described next.

OPS is an automatically adaptive prestressing system which has the ability to increase or decrease prestressing forces according to load variation. It was first developed using as an inspiration the behaviour of nature formed structures (biomimetics), more specifically the muscle behaviour. One can describe it as a prestressing system in which the tension applied to cables is automatically adjusted to the actuating loads, through a control system, in order to reduce the structural deformations and minimize tensions (Pacheco, P. 1999).

Using bridge construction equipment as an explanatory reference, the OPS main elements are 1) the actuator and 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).

The OPS control is ruled by an algorithm that adopts the girder mid span deflection as main control variable. Mid span deflection is monitored by pressure transducers (sensors) continuously transmitting signals to the control unit (PLC).

The control algorithm computes actuation decisions (hydraulic cylinders stroke variations) which consequently affects tension on prestressing cables. Actuation decision is based on mid span deflection changing tendency, filtering instantaneous deflection noise due to vibration.

To ensure an adequate reliability level, OPS is provided with distinctive and redundant sensors with measures that are permanently compared to guarantee that the algorithm decision is always based on accurate information.

If any inconsistency or incoherence is detected, there are several alarm combinations (buzzer and color light) warning the operator to check the data – always available on real time on intuitive touch screen interface (on girder control unit). Operator must then confirm if the data is correct and

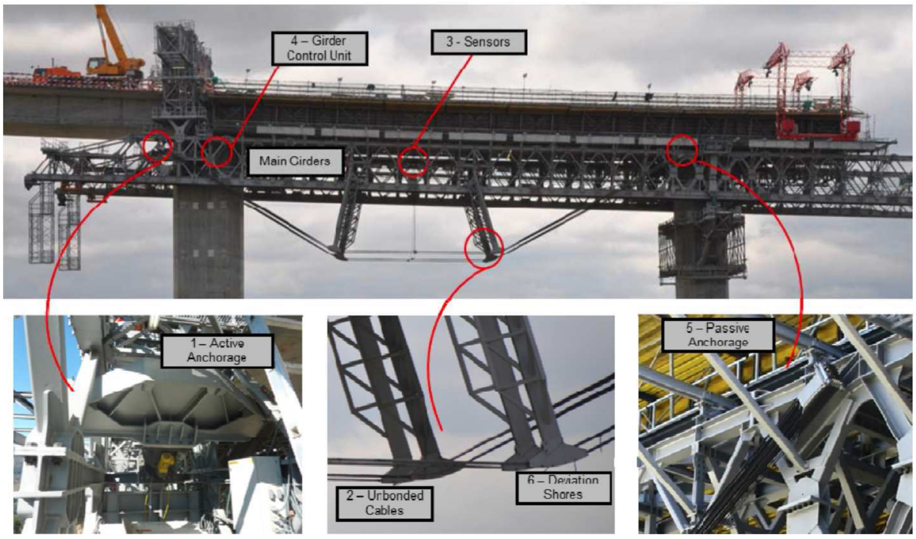

Figure 1. OPS main elements and layout.

Figure 2. M60-I on concrete pouring phase.

take immediate action so that regular operation may be re-established and potential risk situations prevented. Granting information to the operator about the bridge construction equipment behavior, the OPS increases the safety factor of the structure.

Application of OPS to bridge construction equipment 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 – BERD M60-I CORGO RIVER

3.1 *Bridge overview*

The bridge over Corgo river in Vila Real (north of Portugal) is a concrete bridge with a total length of 2796 m, including approach viaducts and the 552 m long cable stayed main bridge. By the time of conclusion, this was the 2nd highest cable stayed bridge in Europe. The East viaduct, with a total length of 1278 m comprising 22 spans with a maximum length of 60 m was built with M60-I (please see Figure 3).

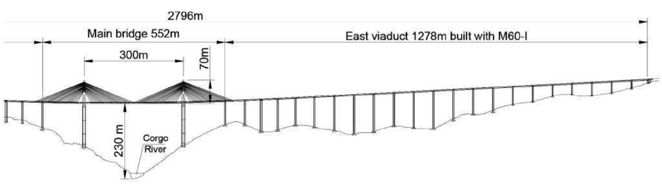

Figure 3. Bridge over Corgo river elevation.

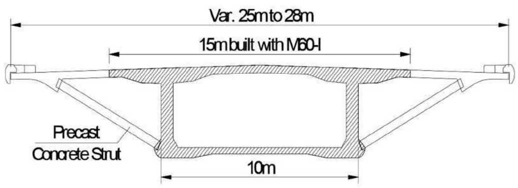

Figure 4. Deck cross section.

The deck cross section is a single box with a total width of the crossing platform changing from 25 m in approach viaducts to 28 m in cable stayed bridge. Even though the box is quite wide (10 m between external web external surfaces), the continuous cantilever is supported by precast concrete struts positioned every 3 m (please see Figure 4).

3.2 *Projects challenges*

The development of East viaduct construction solution presented some interesting challenges:

- M60-I design started being the bridge design almost finished. Construction works had already started and piers were actually partially constructed. To fulfill Contractor's schedule the M60-I had to be prepared to build one 60 m span every 10 calendar days (9 working days) and equipment assembly was scheduled 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;
- East viaduct comprises four distinctive types of piers with significant variation of width (4, 4.5, 5 and 6.5 m). Pier width variation means increased complexity for design of movable scaffolding system (MSS) supports (especially in underslung equipment) and for definition of interfaces between bridge piers and MSS (already with tight schedule in this specific case);
- The bridge is located over a deep valley and great part of construction was to be carried out in winter period. The Contractor required M60-I to be prepared for 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 (pier heights up to 113 m in East viaduct) and also because of the irregular topography it was not possible to have auxiliary equipment – mobile cranes – to assemble the machine supports. This means that the M60-I needed to be self-supporting and completely autonomous;
- Equipment assembly and disassembly in difficult conditions and with short preparation time. Topography was very difficult for assembly operation (there was only 18 m of free space behind the abutment) and also for disassembly operation (on last span the MSS was around 75 m from the ground);
- East viaduct was actually constructed in 3 different stages (first two by MSS – see Figure 3 – and a final stage comprising part of cantilever and the precast struts was built by auxiliary equipment). First stage included construction of bottom slab and webs. During construction of top slab in second stage, the "U" shaped deck section built in first stage was already rigid but still not prestressed. Interaction between M60-I main girders and "U" shaped deck section assumed an increased importance – main girders needed to be rigid enough so that the stresses in non prestressed 1st stage concrete were kept within allowable levels;
- The deck section built by M60-I was significantly heavy, with the deck weight varying from 338 kN/m in mid-span to 531 kN/m near the pier section.

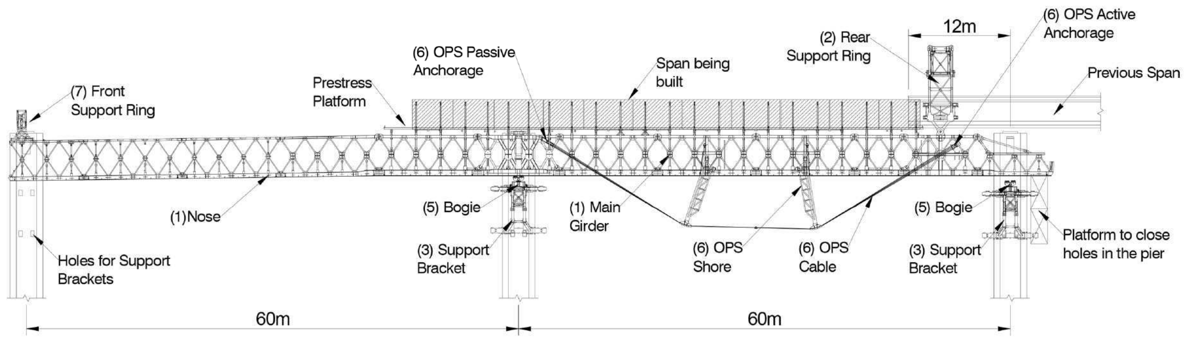

Figure 5. M60-I elevation and components identification.

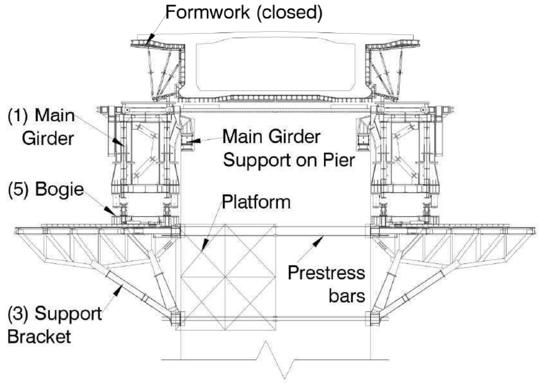

Figure 6. M60-I front support on fixed phase.

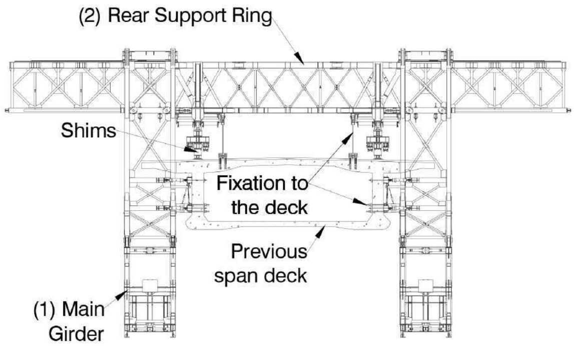

Figure 7. M60-I rear support on fixed phase.

3.3 *Equipment description*

The solution developed by BERD to build the East viaduct was an underslung 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).

Basically the M60-I operates in 2 distinctive phases with different structural configurations: 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).

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).

3.4 *Working cycle*

The Contractor demand for 10 days working cycle markedly affected the conception of M60-I, from design to operation.

Working cycle operations were designed to guarantee the predefined schedule while regarding all safety measures – period in which M60-I is unbraced and most affected by wind exposure (Phase 2) was reduced to minimum.

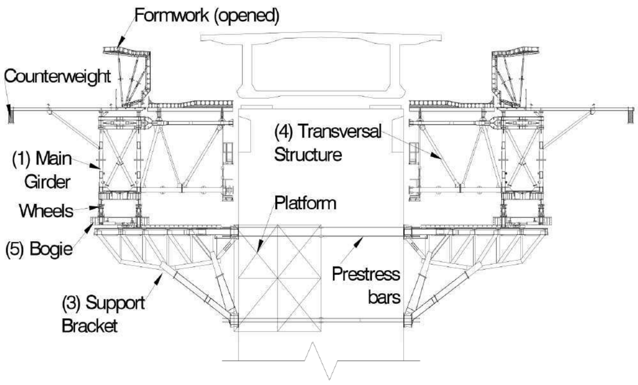

Figure 8. M60-I front support on launching phase.

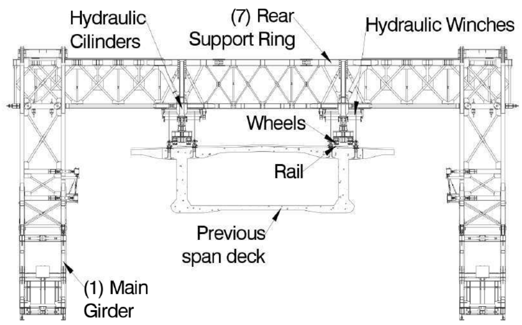

Figure 9. M60-I rear support on launching phase.

Table 1. Representation of 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.

As aforementioned, the construction of deck box section by M60-I was performed in two stages. The first stage comprises the construction of the bottom slab and the vertical webs ("U" shaped section) being that the top slab is poured in the second stage. 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 start 15 to 20 hours after finishing concrete pouring (starting on "U" section cables). Simplification of inner formwork was particularly advantageous in transition spans, in which the rearrangement of blisters relative position (different prestressing layout caused by span length variation) and deck width variation (transition from viaduct to cable stayed bridge section) required significant changes in internal formwork.

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

Supporting brackets relocation operation includes brackets disassembly, transversal sliding to achieve clearance from piers, transport to next pier and reassembly procedure. Relocation of 30 tonne weight supporting brackets was surely one the riskiest operations of M60-I operation cycle, strongly affected by climatic conditions – mainly the wind velocity. Being the M60-I directly supported on the pier and deck cantilever (front and rear support, respectively) throughout all Fixed Phase, two main advantages arise: (1) Avoiding concrete loads on brackets allows a significant

Figure 10. Auxiliary cranes placing rebar.

reduction of their weight and consequently the weight and complexity of all equipment and auxiliary structures used for its relocation – this is particularly significant in face of challenging East Viaduct −5% longitudinal slope; (2) Given that the Brackets are unloaded during almost the entire cycle it is always possible to choose a period with good climatic conditions to perform the relocation – this operation was never in the cycle critical path.

When the concrete of both stages reaches the resistance predefined by bridge designer, 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 lower the girders, by that unloading the formwork and then move the girders transversely. In this particular project the deck lower corner demanded previous stripping of lateral formwork panels before lowering the girders. After transversal movement of the formwork lateral panels the girders are lowered and moved outside towards launching position, guaranteeing compatibility with bridge pier position and geometry (please see Figure 8).

In this particular application, the M60-I longitudinal movement relied on gravity, since the deck longitudinal slope was −5,0% for almost the entire viaduct. The movement is controlled by 4 hydraulic winches on the rear support ring. During the launching operation the MSS girders are connected by the rear support ring which confers greater stability regarding lateral overturn (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 – this was particularly advantageous for last spans, in which longitudinal slope varied significantly. Longitudinal launching duration is around 1 hour, which is exceptionally fast for an underslung MSS.

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, clearly exceeding expectations around cycle productivity. The East viaduct construction was finished on Contractor schedule and, most important, without accidents.

3.5 *OPS impact*

Besides advantages previously referred, related with structural performance, deformation control and structural monitoring, three specific advantages may be pointed out, regarding OPS application to 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", it was possible to limit the stresses in the "U" section during the second concreting stage – there was no need for reinforcement due to construction process;

– 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 and longitudinal slope variation;
– During the bridge construction, while the MSS disassembly project was being developed, a collision between the MSS front nose and the form traveler used in the construction of the cable stayed bridge deck was detected. There was a need to disassemble the front nose during last launching and before concreting last span. The front nose removal meant a considerable increase of main girders' self-weight imposed positive bending moment (between MSS supporting sections). By changing the OPS parameters it was possible to introduce an initial negative bending moment that counteracted the effect of nose removal, therefore guaranteeing the structural safety of the MSS during last span concreting.

4 CONCLUSION

As introduced before, the demand for productivity is a common requirement of bridge construction process nowadays. The specific challenges of each project may justify the need to adopt special solutions, different concepts or even strengthen technical coordination between different entities engaged in the same project. Simultaneous and coordinated development of bridge design, construction process design and erection equipment design is strongly recommendable but not always possible which, per se, represents a major challenge.

Besides description of general design approach to achieve productivity goals, particular attention was given to the effect of OPS application in construction equipment. The design of lighter structures and continuous structural monitoring are advantages almost taken for granted. Furthermore, the use of OPS allied to careful, timely and detailed preparation of all tasks to be done on bridge site has shown great advantages on productivity – contributing to the achievement of working cycles that appeared to be unrealistic, plus reinforcing structural and operational safety – many times the accidents occur on tasks improvised on bridge site. Ultimately, safety is a synonym of productivity per se, since accidents are one of the most common causes for significant delays in bridge construction activity.

ACKNOWLEDGMENTS

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

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