TECHNICAL CHALLENGES OF LARGE MOVABLE SCAFFOLDING SYSTEMS

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ABSTRACT

The construction of bridges and viaducts with several spans of concrete, using movable scaffolding systems is an efficient and competitive method. This constructive solution is normally used for bridges and viaducts with spans up to 60m. The accumulated experience of the last years allowed the development of construction solutions, span by span, of bridges with spans between 70 and 90m. For this range of spans, the use of movable scaffolding systems can lead to surprising economic results, when the number of spans is significant and the cost of pillars and foundations is relatively high, as for example in bridges over the water. Additionally this equipment's allows achieving high productivity ratios and a very industrialized construction process.

Until very recently, bridges with spans between 70 and 90m were typically built by cantilever. The recent developments of span by span construction equipments brought a strong alternative. The contribution resulting from the introduction of the system of organic prestressing that allowed to lighten the weight and increase the load capacity of these equipments was very important and opened a new horizon concerning the applicability limit.

This article approaches the construction of bridges with spans between 70 and 90m. It also analyses the general aspects related to the conception and utilization of the construction equipments and the interaction between bridge and constructive equipment. In all article, examples of real applications of movable scaffolding systems to big spans are given and advanced constructive solutions are presented, referring also the span by span construction by precast segments using launching gantries. This paper is based in a paper published by Journal of Structural Engineering, IABSE.

Introduction

The construction of decks of bridges and viaducts with several spans with movable scaffolding systems (MSS) may be a very efficient and competitive constructive method. This solution is generally used for the 40-60 m span range. Over the last few years new experiences have been made and new solutions have been developed for the range 70-90 m (LMSS). In this range surprising economical results may be achieved if the number of spans is high and/or if the costs of piers and foundations are relatively high. With LMSS it is possible to achieve very high productivity ratios.

Moreover, the use of LMSS may represent very significant costs reductions if the accesses to the front line of site are difficult – for example, high piers or water access, because this may imply for significant costs of elevation equipments.

The span by span construction also ensures important advantages as the continuity of the deck and a significant optimization of materials consuming (in particular the prestressing steel consumption) because the construction stage may be almost neutral to the deck design.

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Until the last few years, bridges with 70-90 m span were typically constructed by precast solutions, with metallic solutions and by cantilever method [1].
Nowadays, with recent developments in span by span construction equipments, a new strong alternative arises.
However, this constructive method requires a complete and deep study of all the main technical challenges involved in its application, both for the bridge designers and for the bridge building equipment suppliers.
In international documentation [2,3,4] there is a significant lack of information about MSS or LMSS actions on bridges. Although in some countries there are very important contributions on this subject [5], it is clear that there is a lot of research and code standardization to be done.
In this paper, after the presentation of general aspects regarding the use and conception of a LMSS, main particular issues of these construction equipments are discussed, always with two clear objectives:

(1) to provide bridge designers information about presented construction method;

(2) to contribute for a discussion among MSS specialists considering that in this specific area there is an obvious lack of normative documentation.

Some of the presented issues are empiric and some result from different scientific works in progress (not published).
Along the text two examples of LMSS applications are presented allowing a more direct perception of the presented issues. In conclusions, recommendations are proposed, both for bridge designers and for MSS specialists. This paper is based in a paper published by Journal of Structural Engineering, IABSE.

General aspects regarding the use and conception of a LMSS

The construction of bridges and viaducts adopting span by span cast in situ construction with LMSS – is a strong possible solution in several span bridges and viaducts (especially in conditions described before).
If the particular aspects discussed in following issues of this paper are considered, the main particularity of span by span construction with LMSS in the bridge design remains on the fact that it is possible to achieve a deck conception and design mainly conditioned for the bridge service actions. In few words, the prestressing layout and quantities are very near the ones needed for the bridge service conditions.
Contrarily, both incremental launching, precast construction or cantilever method are strongly conditioned by constructive stage structural systems and loads. In these methods the prestressing layout and quantities are strongly conditioned by the construction method and in some cases the prestressing amount may increase about 50%.
The Rio Cabriel Bridge near Valencia, in Spain (Figure 1) and the Bridge across the Hostovsky Creek Valley, near Nitra in Slovakia (Figure 2 and Figure 3) are two examples of bridges where the use of LMSS is a rational choice. In both there are several spans, the piers are relatively high (about 45 m) and the cost of alternative methods would be quite high.
In Rio Cabriel Bridge, with a current span of 70 m, the probable alternative method would be the cantilever method.
With that method it would be possible to achieve a productivity of about 120 m/month (with 6 form travellers) against the normal productivity of 140 m/month achieved with the LMSS. Moreover, alternative method would imply for a very significant consuming of additional prestressing steel due to the implicit needs of the cantilever method.
In the Bridge across the Hostovsky Creek Valley, with a current span of 69 m, the probable alternative method would be the span by span construction with conventional MSS (42 m

span) implying the construction of provisional piers to reduce the deck constructive span. That solution would imply significant additional costs related with provisional piers construction and demolition.

Figure 1: River Cabriel Bridge

Figure 2: Bridge across the Hostovsky Creek Valley

Recent LMSS are very productive having plethora of operational tools and being prepared for safe night works (see Figure 3).

Figure 3: Bridge across the Hostovsky Creek Valley (night works)

LMSS span limits

One general question that may arise is: what are the span limits of LMSS?
The answer is as evolutive as the state of art. Presently, there are 2 main conditioning issues: the LMSS weight and the stability during launching operation considering wind action.
In current MSS (40m to 60m span) the equipment weight is not usually conditioning for the bridge design, what can be rigorously verified by specific calculation techniques [6]. But in larger spans (70m to 90m) that might not be the case, depending on the LMSS weight.
The LMSS weight is seriously influenced by the deck joints location. The most common location for joints in medium span range (40 m to 60 m) bridges is at L/5 (being L the current span). But the experience has been showing that for larger spans (70 m to 90 m) the most adequate location for joints is near from L/4. This solution enables to reduce flexural moments on the deck section over the penultimate pier with deck during construction and allows for a better deflection control. Both Rio Cabriel Bridge and the Bridge across the Hostovsky Creek Valley were constructed with joints located at L/4, with good results.
In Figure 4, two curves of LMSS limit travelling weights neutral for deck design are printed (deck width 12.0 m and 14.0 m respectively). These curves are based on a simplified study that equalizes the deck flexural moment over the last pier with deck for the maximum constructive loading scenario and for bridge service loading (the same pier with the complete deck).

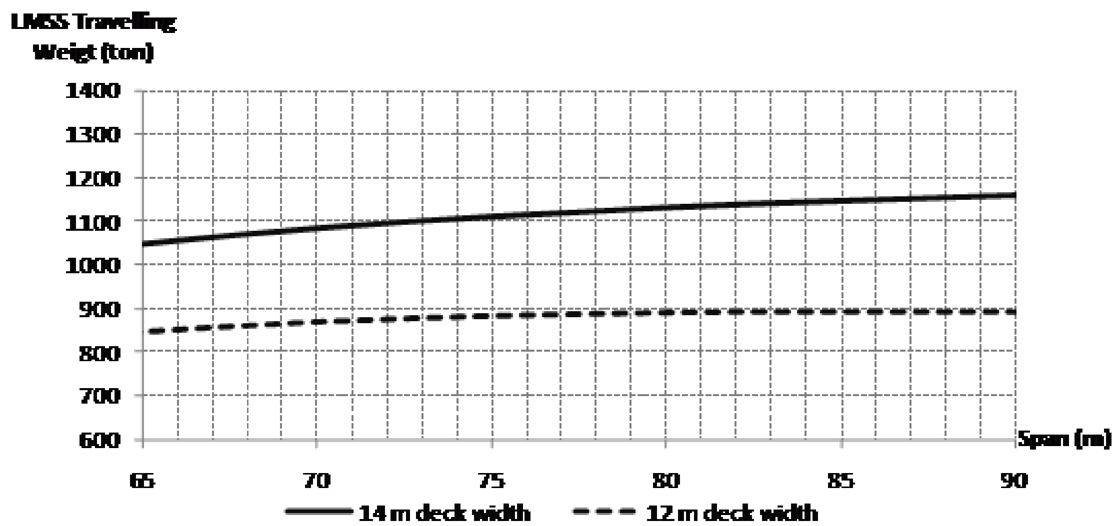

Figure 4: Indicative limits of LMSS travelling weights neutral for deck design

Thus, if LMSS design is optimized, its use can be neutral to the deck design, not implying additional material consumption due to constructive stage.
Both presented examples – LMSS of Rio Cabriel Bridge and the LMSS of Bridge across the Hostovsky Creek Valley – were not conditioning for deck design, with LMSS travelling weights near from 770 ton for spans about 70 m.
In what concerns to the stability of LMSS considering wind action during launching operation, although such operation is to be conditioned by actual winds measured during the operation, if natural frequencies are too low, there
is not an adequate domain of involved phenomena.

Considering a basis of 16 modelled MSS and LMSS approximated curves of natural frequencies for different spans were printed, for underslung (2 main girders) and for overhead equipments (see Figure 5).

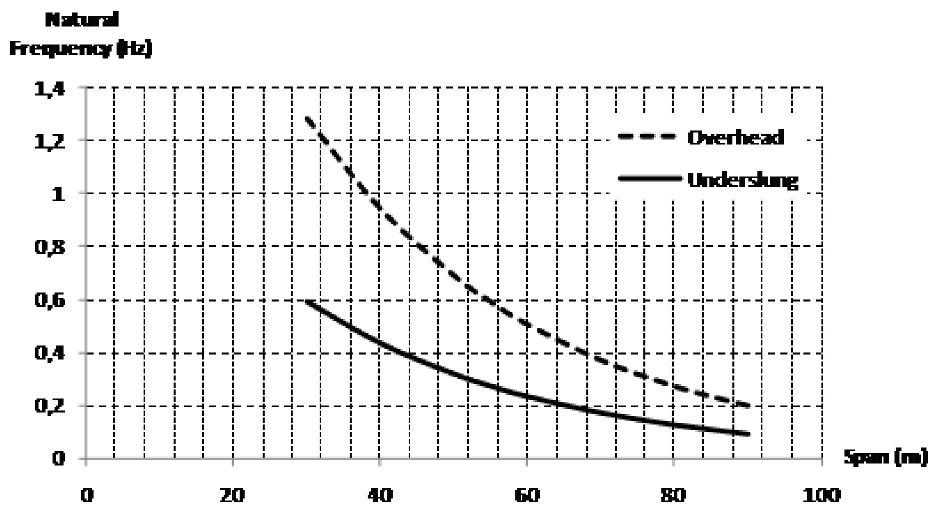

Figure 5: Natural frequencies on MSS (horizontal transversal mode) on maximum cantilever position during launching

Unless scientific research is made, the limit of the lower frequency is established by experience. There are several MSS worldwide with frequencies of about 0.2 Hz to 0.25 Hz (horizontal transversal mode).
Then, for equipments that reasonably accomplish the weight limits of Figure 4, actual limit of spans for LMSS is about 90 m (for overhead equipments).

Horizontal forces on piers due to LMSS

Horizontal forces on Piers due to LMSS mainly result from 6 following actions: (1) horizontal projections of LMSS weight (sliding supports with slope); (2) friction (during launching); (3) braking loads (during launching); (4) forces in locomotion reaction points; (5) wind actions (transversal and longitudinal) and (6) accidental LMSS induced forces (actions 5 and 6 are developed in subsequent points).
Usually, if there are no seismic relevant actions and if wind is not conditioning, piers may have horizontal forces Href of about 4% to 5% of the deck weight (related with the pot bearings friction). Of course, this must be studied by the bridge designer in a case by case basis, but to have conceptual references, this value gives a first approach of the importance of admissible LMSS induced horizontal forces (not to condition piers design by LMSS actions).
Horizontal projections of LMSS weight (sliding supports with slope) may be relevant for the piers design if the longitudinal slope is above 5% (that may represent about 0.5 Href).
Current sliding solutions in MSS are bogies with wheels (typical frictions of about 2%-5%) or bogies with low friction sliding materials (typical frictions of about 6%-10%). Thus considering the bridge design, in the LMSS conception is preferable to adopt wheels bogies. With this solution friction on launching would imply forces of about 0.5 Href.
The action due to LMSS braking operation (during launching) strongly depends on the locomotion mechanical solution but should be carefully analyzed by the LMSS designer/manufacturer and transmitted to the bridge designer.
Obviously, this action may be more severe than launching friction, if friction braking devices

are adopted. Moreover, if braking operation is too fast, relevant dynamic phenomenon is to be considered. Nevertheless, if the LMSS are moved with hydraulic locomotion solutions, braking operation may be “soft” and neutral for bridge piers.
In some MSS`s, and that may be applied to LMSS, the point of reaction of the locomotion system may be far from the more loaded bogie. That applies for example when locomotion is promoted by winches which are fixed on the MSS (the main body) and on a MSS support (the extremity of the cable) this last one fixed on a pier. This force value is usually of the same magnitude of the sum of the friction with the longitudinal slope horizontal projection (unless accidental actions are induced by the equipment).
The combination of these actions leads to several combination cases, from which a few cases are typically to be selected. In Figure 6, as a reference example, the 6 more severe cases for Rio Cabriel piers design are presented.
Although Rio Cabriel piers are considerably high (> 45 m) these actions were not conditioning for their design.

		Fz [kN]	Fy [KN]	Fx [kN]	Mx [kN.m]	My [kN.m]	Mz [kN.m]
Case 1	Concrete pouring / wind 60 km/h	14354	174	8	922	32	24
Case 2	Launching - wind 60 km/h	5493	230	330	6824	2541	224
Case 3	LMSS fixed – wind 170 km/h	5374	1398	4	7478	51	445
Case 4	Concrete cure- wind 170 km/h	14756	1398	5	7490	112	436
Case 5	Accidental Launching (position 1)	4392	0	828	3490	6380	1880
Case 6	Accidental Launching (position 2)	3458	0	787	2743	6071	1827

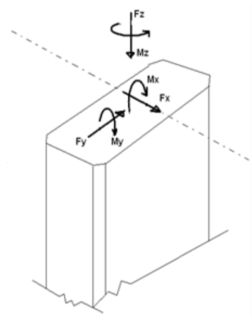

Figure 6: Service loads on the front pier in Rio Cabriel Bridge

Wind actions

Wind actions on MSS or LMSS are clearly different in launching operation stages and in equipment stationary stages, considering the duration of the stages/operations and adequate return period.
For current MSS there are sustainable recommendations of wind design and wind operation velocities [5] (see Table 1). For LMSS there is no normative documentation and there is not enough registered information to determine fixed values. Nevertheless, if piers are high, there is registered information (in projects where authors were involved) that confirms that mentioned values for MSS may not be not on the safe side. Thus, not dismissing a case by case analysis, the wind velocities design intervals for LMSS are to be enlarged as in Table 1.

	Launching Operation (average wind)	Launching Operation (peak)	Equipment Fixed (storms)
MSS [5]	40 Km/h	60 Km/h	140-170 km/h
LMSS´s	40-50 Km/h	60-70 Km/h	150-200 km/h

Table 1: MSS/LMSS wind design velocities

These ranges of wind velocities were proved to be adequate for the 2 presented examples, where natural frequencies were both near from 0.36 Hz.

LMSS with natural frequencies (horizontal transverse mode) in maximum cantilever position (launching operation) lower than 0.2 Hz, should be evaluated with proper tools (eventually wind tunnel tests).

Wind induced vibrations on piers with eventual MSS stabilization

Currently, bridge designers take into account the necessary dynamic assessments of the bridges, both in construction and in service stages, considering the bridge structure by itself. Nevertheless, there is one particular picture of the construction stage, which is not obvious for someone skilled on the art, because it is not identified in a single bridge calculation model and which becomes more relevant in high pier bridges where typically LMSS are to be used.

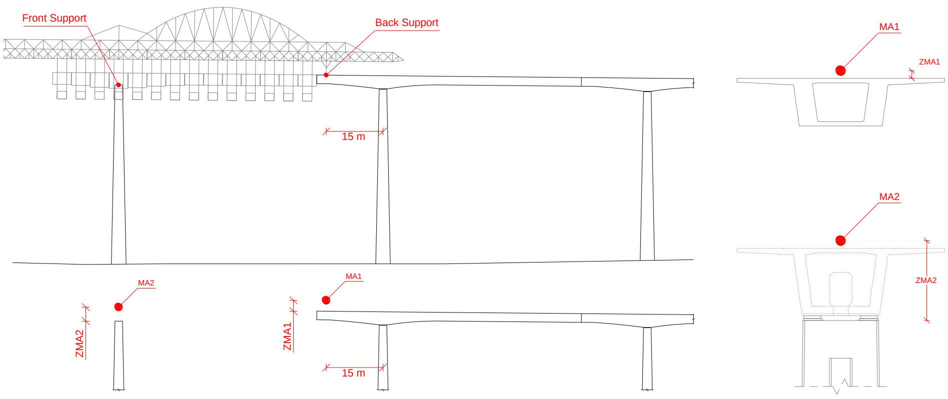

Figure 7: Location of LMSS plus liquid concrete mass in Rio Cabriel Bridge during concrete pouring operation

During the concrete pouring operation, there is significant increase of mass in the front pier, without immediate stiffness increase (because the concrete is still liquid). Indeed, the concrete filled on the MSS formwork significantly reduces the front pier natural frequencies, because there is an important mass on the top of the pier (see mass MA2 in Figure 7) when there is not a stiff deck to provide its bracing yet. The more relevant wind-induced vibrations forms for this matter are the vortex-induced bending oscillation and the transverse galloping [7].

In Rio Cabriel Bridge, the most relevant phenomenon was the vortex-induced bending oscillation leading to a critical wind velocity of 20.3 m/s, due to low natural frequency of the pier (0.34 Hz) [7].

Mentioned critical wind (very low) could not be accepted and additional measures were taken in cooperation between the bridge designer and the MSS designer (an interaction model was developed). The connections between the LMSS and the bridge were studied to provide an horizontal elastic support of the pier (33000 kN/m) which leaded to a critical wind velocity over the maximum concrete pouring operational wind velocity (25 m/s).

In LMSS applications this particular issue is to be studied by the bridge designer, in particular if piers are high.

Accidental LMSS induced actions on the Bridge

An analysis of a register of 47 accidents and incidents (in four continents) with bridge building equipments (PhD research of one of the authors) clearly induces that a great part of the accidental situations are much more relevant for the equipments design than for the bridge design. Nevertheless there are 2 accidental situations that should be considered in the bridge design:

1) imbrication of LMSS in sliding devices or wheels;
2) dynamic force on structural elements where winches are fixed, due to collapse of one winch;

The first typically results of geometric defects on the sliding surface of the steel structure of the LMSS main girder. If there is a vertical step in 2 modules connection, depending on the step magnitude, during launching operation the locomotion force is incremented when the step passes the sliding device or wheel, until locomotion unit power limit is reached. If the step is significant, that action may lead to significant horizontal displacements on the pier. This must be computed by the LMSS designer considering steel construction tolerances (or measured values) and geometric characterization of the sliding device or wheel and is to be transmitted to the bridge designer. This may be treated as a major "equivalent accidental friction coefficient".

The second is exclusively connected with LMSS with winch locomotion, typically characterized by having 2 winches, for redundancy. In this case, if one winch gets in collapse, the other assumes the force of the first. That may be a fast phenomenon which implies for dynamic amplification. So if the service force of each winch is F, the structural elements where winches are fixed should be designed for the accidental force (3.F), considering a conservative dynamic amplifying factor of 2.0 (unless more accurate calculation is done).

Thermal induced horizontal displacements on the LMSS supports

In the construction of the closing span of a bridge a LMSS is longitudinally typically supported on 2 supports with independent movements (D1 and D2). This may happen nearby an abutment, where the support displacements D1 are nearly null, or may happen in the middle of a bridge, where both displacements are to be evaluated. These displacements may produce important internal efforts in the LMSS structure, unless other measures are taken. In long bridges this should be evaluated by the bridge designer and transmitted to the LMSS designer.
In Figure 8 a picture of the closing position is given in the Bridge across the Hostovsky Creek Valley where the horizontal displacements on the LMSS are indicated. In this bridge special sliding devices on the LMSS were conceived for the "closing" span.

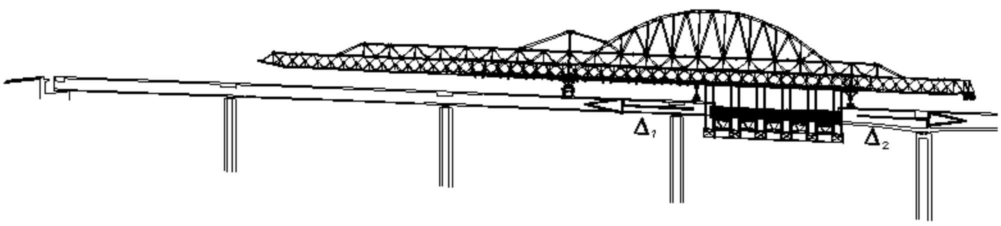

Figure 8: Picture of the closing position in the Bridge across the Hostovsky Creek Valley

Deflection control

The common practice in the specification of scaffoldings is to limit their maximum deformation to L/400 [8] (being L the deck span). In LMSS`s this limit should more restrictive because such deformation may imply for structural problems on the deck during deck prestressing application [8], and because operational difficulties may arise in the LMSS as problems regarding lowering the LMSS after deck prestressing and problems regarding the adjustment of the formwork.

Moreover, the geometric tolerances for bridge construction are absolute values [9] which represent very reduce relative values for LMSS`s span ranges (from L/3500 to L/4500).
According to the experience, for LMSS good results are achieved if the mid-span deflection limit is L/1000.
One very effective solution to achieve reduced deflection on MSS and LMSS is the application of organic prestressing (OPS) [10,11,12,13]. This solution also provides other relevant additional advantages [12,13].
In the presented examples, Rio Cabriel Bridge and the Bridge across the Hostovsky Creek Valley, with OPS strengthened overhead arches the maximum mid span deflections registered were clearly bellow L/2000 (see Figure 9)..

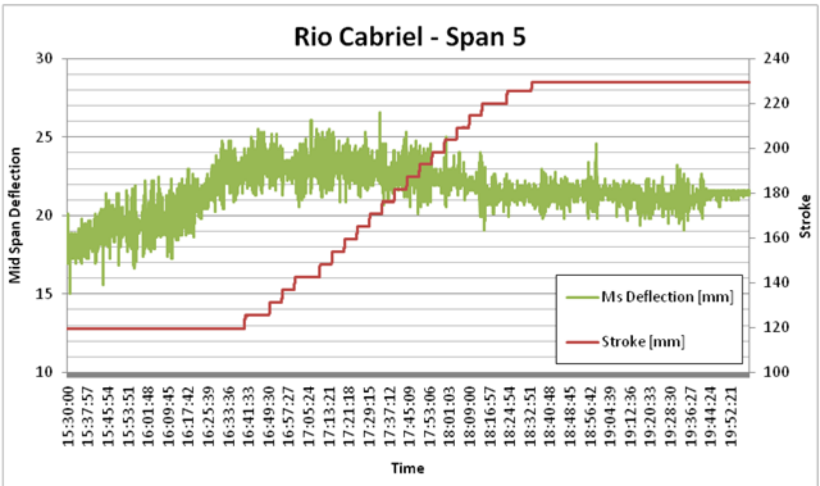

Figure 9: Measures of mid-span deflection and OPS actuators stroke during a concrete pouring operation in Rio Cabriel Bridge

Conclusions

Main conclusions are presented in tables 2 and 3.

	Bridge Design Recommendations
1	Maximum actual span with LMSS - 90 m
2	Location of joints – at L/4
3	Prestressing layout – classical span by span solution
4	Consideration of Horizontal loads at front piers: (1) horizontal projections of LMSS weigh; (2) LMSS sliding friction; (3) Braking loads; (4) forces in locomotion reaction points; (5) Wind actions on LMSS and (6) accidental LMSS induced forces.
5	Consideration of adequate combinations of Horizontal Forces and Vertical forces, according to LMSS functioning
6	Eventual consideration of wind induced vibrations on piers, eventual need of LMSS bracing
7	Consideration of accidental LMSS induced actions on the deck

Table 2: Bridge Design recommendations

	LMSS Design Recommendations
1	Minimum Natural Frequency (horizontal transversal mode) 0.2 to 0.25 Hz
2	LMSS travelling weight nearby 650 +4.5L (L is the span)
3	Bogies desirable friction – 2% to 5% (wheels)
4	Use of hydraulic "soft" braking system
5	Consideration of higher wind velocities for LMSS (table1)
5	Consideration of thermal induce displacements on LMSS (closing spans)
6	Maximum mid-span deflection of about L/1000

Table 3: LMSS Design recommendations

If these recommendations (or similar) are followed, the construction of 70 m to 90 m span long bridges adopting span by span construction with LMSS may be a very economic, safe and fast construction method, as happened with the success cases of Rio Cabriel Bridge and the Bridge across the Hostovsky Creek Valley.

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