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Analysis and Design of An Overhead Self-Launching Movable Scaffolding System for Arsta Railway Bridge, Sweden

Abstract

Norwegian specialist, NRS AS, has been appointed by the contractor of Swedish Traffic Authority, Pihl, to undertake the design and supply of a Movable Scaffolding System (MSS) for the construction of the Arsta railway bridge in Sweden.

The Transport department projects Citybanan constructs at the moment Sweden's fourth longest railway bridge in Arsta in southern Stockholm. The length of 1,400 meters railway bridge being built over the track area in Arsta. The bridge will begin north of Arstaberg station and end just south of Alvsjo goods station.

The railway bridge is a single viaduct, pre-stressed, solid box-girder bridge. Bridge span length varies from minimum 24.67m to maximum 34.22m with the average span weight of 20.0 t/m. The bridge has minimum horizontal radius of 800m and maximum longitudinal slope of 1.25%. There are two types of piers, i.e. single and portal pier, standing up around 10 meters above the ground with the pier head of 1.70m x 2.90m. The 1.4 kilometer long bridge is casted in the MSS – a mold that is moved forward bit by bit until casting process is completed. Tracks for the new railway bridge will be built in stages on the already casted bridge piers, straight above the current road and rail traffic. The 75-meter MSS is mounted on the piers that are in the area immediately south of Alvsjo freight rail yard.

The scope of NRS's work includes the design, steel fabrication, and supply of ancillary equipment for the MSS. NRS AS will also provide engineering know-how, technical support and advice on the construction of such bridge. NRS Consulting has been assigned by NRS AS to carry out the design of MSS for this bridge. This paper presents several design challenges due to site constraints and the bridge structures itself. These challenges include high impact loads on the MSS due to adverse wind load anticipated while working nearby the moving train, special considerations to ensure efficient installation and launching of the MSS. The project is currently under construction with the expected complete date in 2014.

Keywords : Movable scaffolding system, MSS, Pre-stressed concrete bridge, Railway bridge

1. Introduction

Bridge construction especially for a whole span cast in-situ concrete bridge, over deep valleys, water crossings with steep slopes, over highway or railway, or environmentally protected regions can offer many challenges. The Movable Scaffolding System (MSS) for bridge construction may offer advantages over conventional construction (Conventional Scaffolding), including creating minimal disturbance to surroundings, providing a more concentrated work area for superstructure assembly, and possibly increased worker safety given the improved erection environment.

Conventional Scaffolding or Formwork was formerly built in place, used once and wrecked. Because of high labor cost and material costs, the trend today is toward increasing prefabrication, assembly in large units, erection by mechanical means such as "movable forms" and continuing modify and reuse the forms for other projects.

Movable Scaffolding Systems are conceived to be used in the construction of cast in-situ concrete bridges and they are travelling steel structures supporting the formwork that gives shape to the bridge. The MSS is built to be backed off from the hardened concrete, moved to a new position, and precisely adjusted for concreting the next span.

The Movable Scaffolding System was developed in the mid 1970's. The system has since been further developed and has become a very popular system for constructing bridges worldwide. The ability to adapt the MSS to different cross sections allows the contractor to use the equipment for different projects elsewhere.

The MSS consists of a support structure spanning between two piers from which formwork is either supported or suspended. The inner formwork (core form) is collapsible and can run on a rail system to allow easy relocation to the next span. The system is designed so that the outer formwork can be opened sufficiently to allow it to pass around the bridge columns during the launching process. After launching, the formwork is closed again and after setting to the correct alignment, placement of reinforcement can start.

The MSS can be divided into two types, namely, (i) underlane (or underslung) and (ii) overlane (or overhead). The underlane type of MSS has two parallel girders which supports the formwork. The overlane type of MSS has one or two main girders from which the formwork is suspended. The choice of which type to be used depends on site conditions such as height restrictions, type of bridge deck (e.g. single cell, twin cells, double-T) and height of columns.

NRS is the first in the world to develop the Self-launching MSS (SL-MSS) in order to solve the problems related to the difficulties in handling pier support brackets over water as well as on high piers. This system is able to transfer forward and mount the pier support brackets without any need of an independent crane. The SL-MSS has been successfully used in the construction of several major bridge projects worldwide and is widely sought after due to its cost and operational efficiency.

However, the existing problems related to current MSS include requirement of long cycle time, inability to deliverable whole rebar cage simultaneously or all at once, requirement of several block-outs in the superstructure, requirement of hanging bars passing through the superstructure deck to support the formwork, requirement of other equipments necessary for relocation of the supports and, last but not least, the complexity of its operation as well as the labor intensive work.

Moreover, most of the movable scaffolding systems at present have limitations in their operation regarding the high costs of construction manpower and the cost of assembling, dissembling and re-assembling.

This invention provides the new MSS with the self-launching system used for cast-in-situ bridges which can offer many cost-saving advantages to the bridge construction project.

2. Bridge Configuration

This section includes requirements and information provided by the client (the contractor of Swedish Traffic Authority, Pihl) regarding the configuration of the bridge. The railway bridge is a single viaduct, pre-stressed, solid box-girder bridge. The bridge has various span length with the start span of 25.20 m and many intermediate spans length of 24.67, 25.09, 28.30, 29.25, 29.88, 31.00, 31.35, 31.50, 31.56, 34.22m with the end span of 29.25m as shown in figure 1 below.

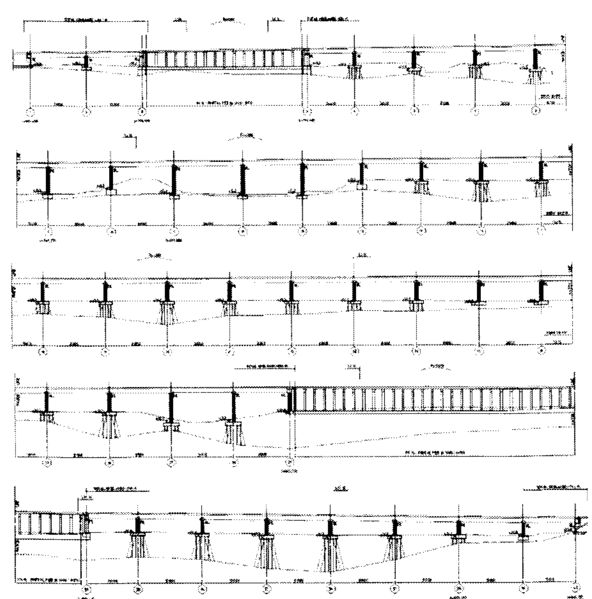

Figure 1 Bridge structural layout drawings.

The bridge is constructed as continuous span with the expansion joints at abutments. It has minimum horizontal radius of 800m and maximum longitudinal slope of 1.25%. The bridge superstructure is 9.0m wide and 2.20 m in depth with the span weight of 20.0 t/m. The bridge substructure has pier width of 2.70 m. and pier length of 1.70 m There are two types of piers, i.e. single and portal pier. In general, the single piers are for installing the rail system and portal pier areas (175m and 80m) are for the station areas.

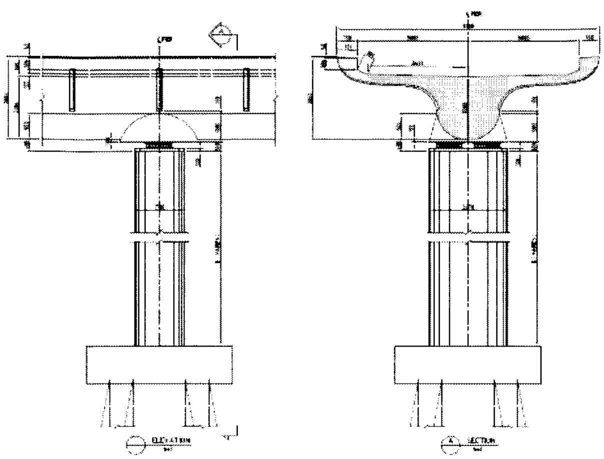

Figure 2 Bridge superstructure and piers.

3. Design Criteria

3.1 Design code

The structural calculation of the MSS was performed according to the following design rules and specifications:

3.1.1 Steel structure: Eurocode 3 (1), AISC (2), NS 3472E (3), AASHTO (4), and BS 5950 (5).

3.1.2 Wooden formwork: NS 3470 (6)

3.1.3 Lifting equipment: F.E.M. 1.001 (7) and DnV rules (8)

3.2 Load

The assumed loads and density are as following:

3.2.1 Density of: concrete 26.0 kN/m^3, steel 77 kN/m^3, wood 8.0 kN/m^3.

3.2.2 Working platforms: upper-working platform of top panel formwork are designed for a uniform load of 2.5 kN/m^2

3.2.3 Wind: allowable wind speed for reinforcement and concreting $\leq$ 22 m/s, for launching $\leq$ 12 m/s. No operation is allowed (MSS parked) when wind speed is 23-30 m/s. The MSS should be secured in the position when wind speed is 31-68 m/s.

3.3 Deflection

Maximum deflection of formwork during concreting is less than or equal to L/400, when L is span length of formwork.

3.4 Material data

3.4.1 Steel quality : since the MSS will be fabricated in China and shipped to Sweden after complete fabrication, therefore, material properties are based on Chinese standard. Steel grades are Q345 for main member and Q235 for secondary member. Steel strength is depending on the thickness as shown in Table 1 where f_y is the yield strength and f_u is the ultimate strength.

Table 1 Steel properties.

Steel Grade	Plate thickness, t (mm)				
	t ≤ 16	16< t≤ 25	25 < t ≤ 36	36 < t ≤ 50	50 < t ≤ 100
	f_y / f_u, Mpa.	f_y / f_u, MPa.	f_y / f_u, MPa.	f_y / f_u, MPa.	f_y / f_u, MPa.
Q345 (16Mn) (Profiles/plates)	345/510	325/490	315/470	295/470	275/470
Q235 (Profiles/plates)	235/340	225/340	225/340	215/340	205/340

Young's modulus of elasticity:	210,000 MPa.
Poisson's ratio:	0.3
Density:	7,850 kg/m^3

3.4.2 Fastening elements: the fastening elements are those for connecting each structural members together for example threaded bolts and pin bolts. The strength of these fastening elements are depending on size, code, and grade of the elements as shown in Table 2.

Table 2 Fastening elements

BOLTS		Diameter, t (mm)				
		0 –16	17-40	41-100	100-160	160 – 250
CODE:	GRADE:	f_y / f_u, MPa.			f_y / f_u, MPa.	f_y / f_u, MPa.
NS-180898-1&2 (Threaded Bolts)	8.8	640 / 800			-	-
NS-180898-1&2 (Threaded Bolts)	10.9	900 / 1000			-	-
EN 10083-1 (Pin Bolts)	34CrNi-Mo6	980/ 1180	880/ 1080	780/ 980	690/ 880	590/ 780
	40 Cr	785/980				

3.4.3 Wooden Formwork: design of wooden formwork is based on following:

Plywood: thickness 21 mm, Dokaplex formwork standard.

Wooden material: Norwegian, quality T18 or equivalent NDS.

Formwork ties: ø15 mm, 900/1100 MPa and ø20 mm, 900/1100 MPa.

3.4.4 Material factors (γ_m): Ultimate Limit State (ULS): All parts, γ_m = 1.15; Service Limit State (SLS): All parts, γ_m = 1.00

3.5 Design approach

The Load and Resistance Factor Design (LRFD) specification for Structural Steel Buildings governs the design, fabrication, and erection of steel-frame buildings. The strength and the failure condition are considered. Load factors are applied to the loads. Then, a selected member would have enough strength to resist the factored loads. In addition, the theoretical strength of the member is reduced by the application of a resistance factor. The criterion that must be satisfied in the selection of a member is

Factored load < Factored strength

$$\Sigma \gamma_i Q_i \leq \phi R_n \quad (1)$$

where Q_i is a load effect, γ_i is a load factor, R_n is the nominal resistance (or strength) of the component under consideration, and ϕ is a resistance factor.

4. Sturctural Analysis

Three dimensional (3D) finite element model of the MSS was constructed based on the nominal geometric and material properties listed in Table 1.

PC-based STAAD-PRO (9) was selected as the software for structural analysis. This program is also included modules for code checking according to the relevant design rules. Figure 3 shown 3D structural model of the MSS.

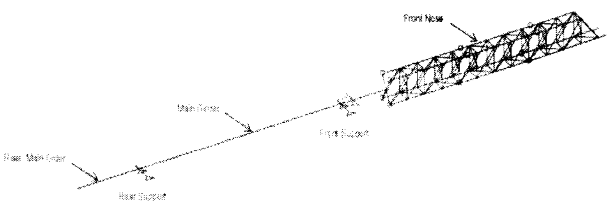

Figure 3 3D analytical model of the MSS.

After 3D analytical model is completed, loads would be applied on the MSS based on the actual weight of concreting bridge span, steel self-weight of MSS, external formworks, and live loads on working platforms. Wind load was also included in the analysis of the MSS for both concreting and launching positions. Figure 4 shows one example of analysis result when the MSS is in concreting position.

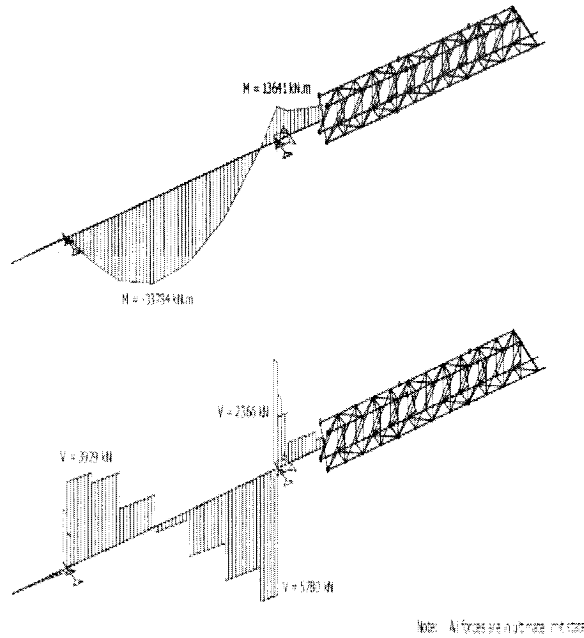

Figure 4 Analysis result shows bending moment and shear diagrams when MSS is in concreting position.

5. Design of MSS Main Parts

The self-launching movable scaffolding system (SL-MSS) according to this project comprises of:

5.1 Main Girder is the principle bearing component, which transfer the design loads to the supports. Concrete loads are transferred from the formwork into the hanger trusses, which are bolted to the Main Girder. During launching, the Main Girders are supported on the Launching Wagon bogie. During concreting, they are supported by the main jacks i.e. 2 at the rear support and 2 at the front support. At the front end, there are connections for joining the Nose to the Main Girder. The Main Girder is divided into four sections, length varies from 9.765-11.800m suitable for transport, connected together on site by bolted connections, as shown in figure 5 below.

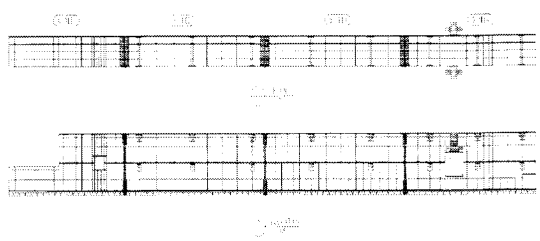

Figure 5 Main girder after lower and upper sections are assembled.

5.2 Rear Nose which provides a transfer of load to Rear support during casting and launching is equipped with the mono-rail for electrical lifting hoist used for rebar cage loading.

5.3 Hanger Trusses which provides a transfer of load from formwork to main girder during casting. There is the second folding function on the upper part of the hanger trusses which creates the wider opening and the higher position as shown in figure 7. This will allow the MSS to pass the portal pier area or other obstructions.

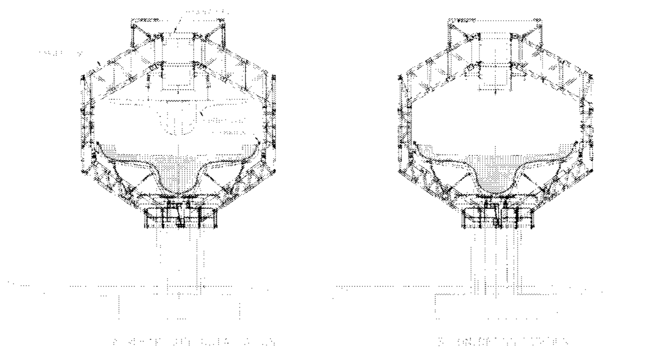

Figure 6 Hanger Trusses: rebar cage installation & concreting position.

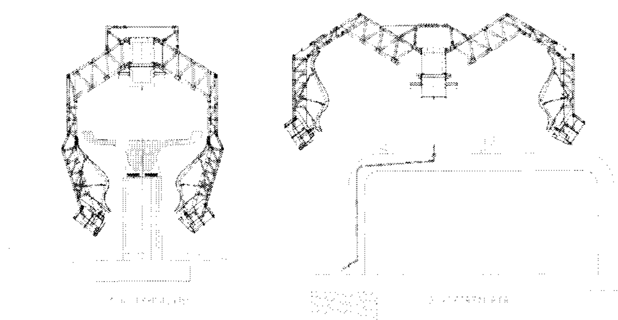

Figure 7 Launching position at typical pier & portal pier.

5.4 Rear Support which provides support to the MSS during rebar cage installation, casting, and launching. The rear support can be opened in the center for rebar cage to pass through as shown in figure 8 and unlike the other previous systems that require the additional rear support for casting, the Rear support of this invention is now designed to take the casting load. The foldable legs, parts of the Rear support, are folded up to support directly to the main girder during casting and launching. The rear support main jacks are activated and transferred load to existing bridge. During MSS launching, the rear support main jacks are deactivated and load is transferred pass through the express rollers to the existing bridge. There are rear support side shifting cylinders equipped at top of the rear support and the main girder. They are used for transverse adjusting of the main girder during launching pass through curve spans and for transverse adjusting of the rear support itself before casting. The Rear Support is fixed to the main girder. No other external equipment is required for its relocation.

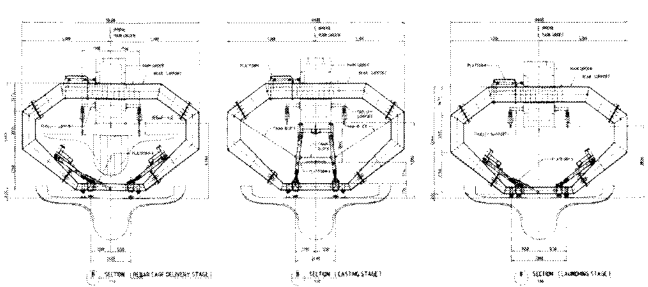

Figure 8 Rear support positions in rabar cage delivery stage, casting stage and launching stage.

5.5 Front Support which provides support to the MSS during rebar cage installation and casting. As shown in figure 9, the Front support is opened at the center for rebar cage to pass through. Once finish placing the rebar cage, tension bars are installed and engaged to the front support to confine the deflection of the front support during casting stage. Unlike the other previous systems that require the block-outs in bridge structure, there is no any part of the Front support pass through the bridge structure. Therefore, block-outs are not required. During casting, the front support main jacks are activated and transferred load from main girder to the front support. The Front support legs which are parts of the front support provide a transfer of load further to column footing. There are front support side shifting cylinders equipped at top of the front support and the main girder to allow the transverse adjusting of the main girder.

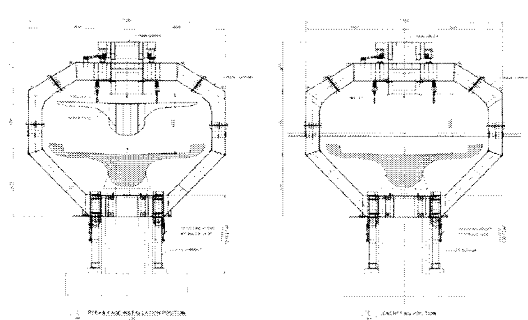

Figure 9 Front support in rebar cage installation position and concreting position.

As shown in figure 10, the locking arms at the lower part can be opened to pass the pier during launching. The Lower parts of the front support can be disconnected when launching pass the portal area. The front support is fixed to the main girder. No other external equipment is required for its relocation.

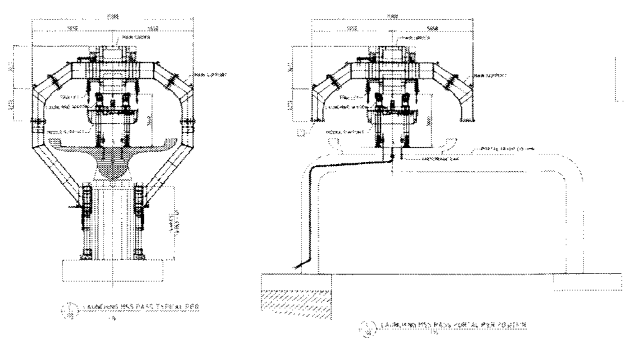

Figure 10 Front support in launching positions over typical pier and portal pier.

5.6 Front Launching Support provides support to the MSS during launching operation. The front launching support is set and secured on the pier top, as shown in figure 11, with the launching wagon at top which allows the front nose and the main girder to glide or move over to the new set position. The front launching support can be dissembled from pier and suspended to front nose in order to relocate to the next pier.

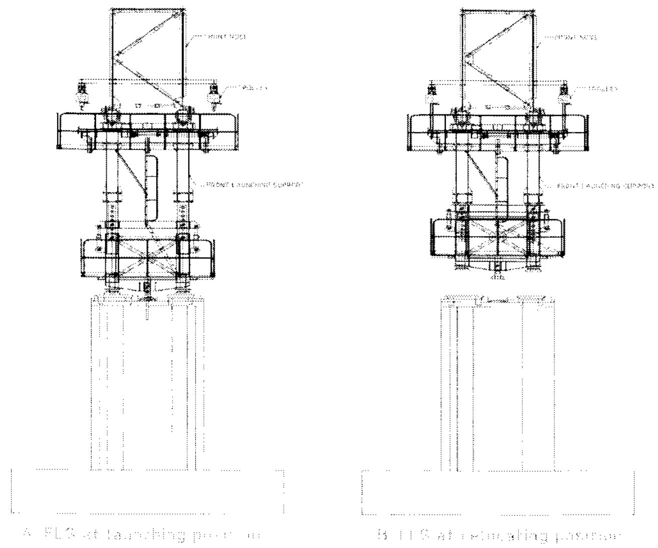

Figure 11 Front launching support in launching and relocating positions.

5.7 Middle Launching Support provides support to the MSS during launching operation. The middle launching support is suspended to the front nose during casting. The middle launching support is moved back and set on already cast concrete and activated to support the MSS during launching.

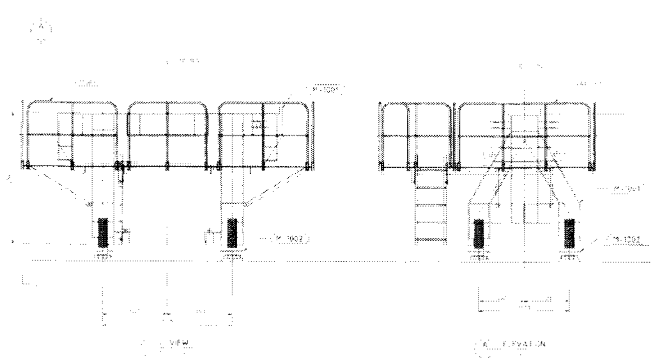

Figure 12 Middle launching support with working platform.

5.8 Trolley system provides relocation to the Middle lunching support and the Front launching support and also provides the rebar cage delivery. The trolley system is composed of the monorail set along the rear nose, main girder, and front nose and the electrical lifting hoist as shown in figure 13 below.

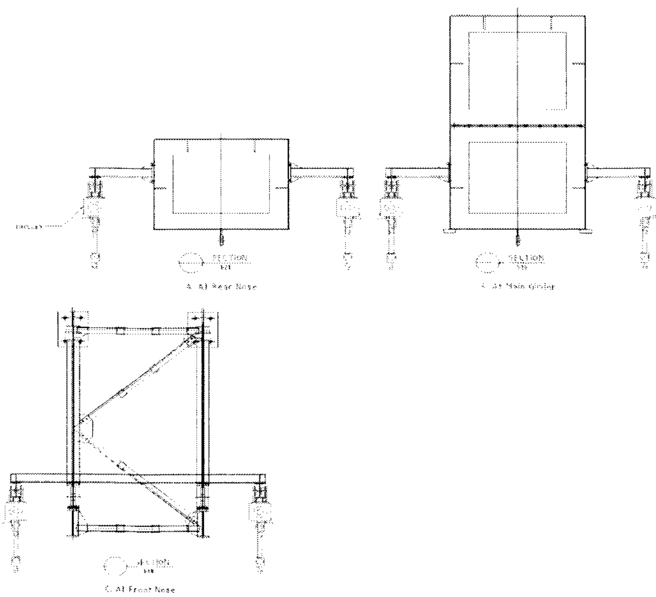

Figure 13 Trolley system at main girder, rear and front nose.

5.9 Formwork which is supported by formwork support frame according to this invention does not require hanging bars for its hanging. Therefore, there is no obstruction during the rebar cage installation and concreting as shown in figure 14 below.

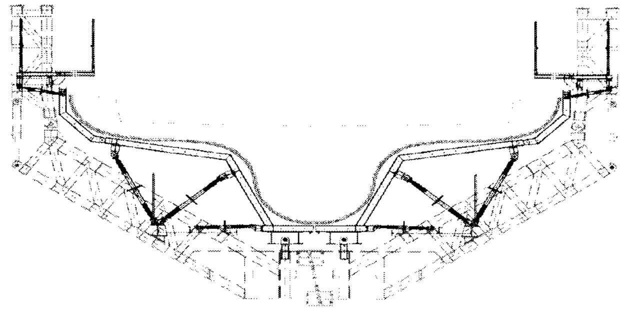

Figure 14 Cross section of the Formwork system.

6. Assembling and Erecting Sequence

In order to operate the MSS, the assembling and erecting sequence of the SL-MSS can be described as the following:

1. Install the temporary tower at the front pier of the span being cast.

2. Install and secure the middle launching support over the temporary concrete foundation behind the abutment.

3. Assembly the main girder on ground. Install the main girder on to the temporary tower and the middle launching support.

4. Install the front support and front support legs, and rear support to the main girder. Activate both supports to take load.

5. Remove the temporary tower and the middle launching support.

6. Install the hanger trusses to the main girder.

7. Install formwork support frame and formwork on hanger trusses.

8. Assembly the front nose on ground. Install the front nose to the main girder.

9. Install trolley system.

10. Install other miscellaneous parts i.e. hydraulics equipment, pumps, working platform to complete.

Now, the MSS is ready for bringing in the rebar cage for the first span of the bridge as shown in figure below.

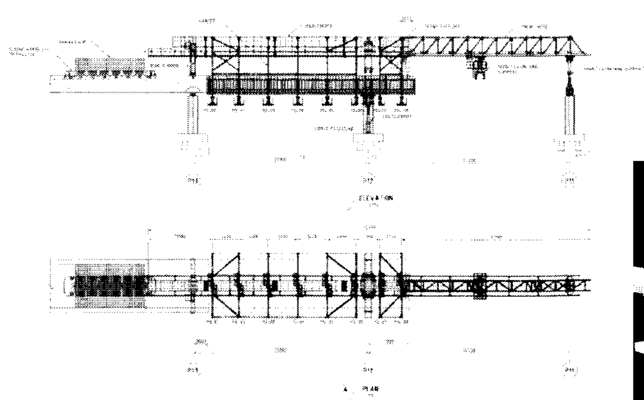

Figure 15 General views of the MSS: Elevation & Plan.

The MSS is a complex structure which requires a great number of operations to be performed in a safe manner. The safety check lists need to be implemented before starting each operctions.

Contractor-engineering office shall carefully plan each single operation based on the input given in the operation manual and on the relevant conditions for each single operation. The planning shall be performed in advance to reduce the risk of leaving out important issues. The planning shall include relevant obstructions for each span.

Verify that all involved personnel are aware of the operations to be performed and that they are informed about the risks and safety measures involved in the different steps of the operation. Check that the hydraulic system is working properly.

All personnel working on the formwork prior to securing with tension bars shall be supplied with safety harness attached to the Hanger Truss.

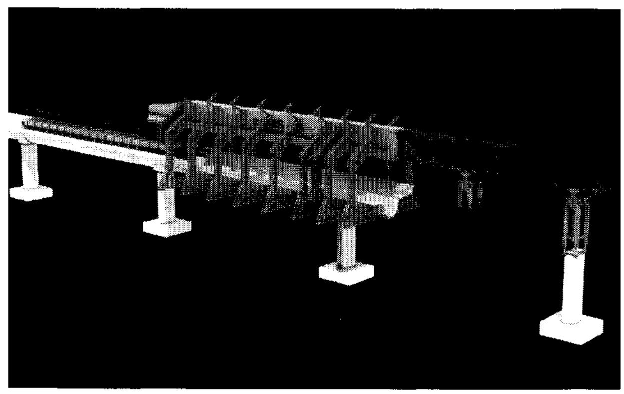

Figure 16 Three dimensional analytical model of the MSS.

After bringing in and installing the reinforcement and prestressing steel, now the MSS is ready for casting the first span of the bridge as shown in figure below.

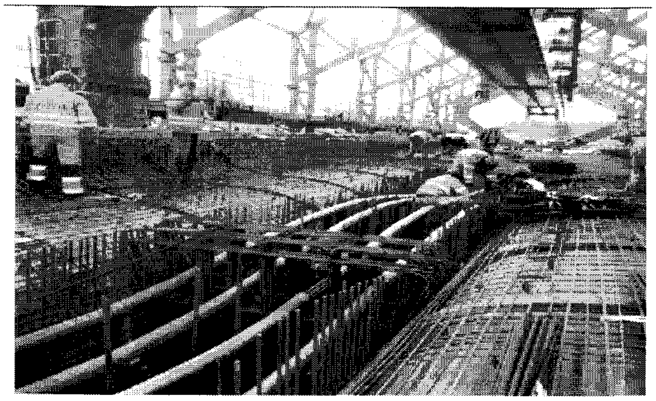

Figure 17 Reinforcement and prestressing steels installation.

The concreting work is a fast activity, where the workers move continuously along the formwork. The following main safety comments are noted. Workers on the top slab shall be especially careful when vibrating and moving along.

The concrete hoses will need to be located within the MSS structure. Attention shall be paid not to damage any of the MSS components.

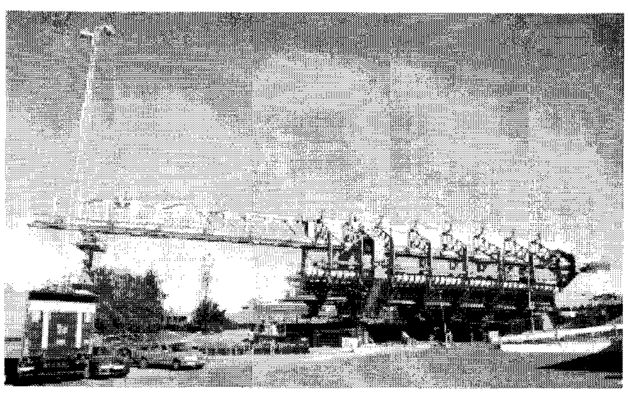

Figure 18 The MSS in concreting position for start span, photo taken at construction site in August 2012.

7. Concreting Sequence and Launching Procedures

7.1 Concreting sequence

Concreting starts above the front pier of the MSS and continues symmetric both in front and back of the pier, and then working back to the previous span. Based upon the past experience, the maximum allowable unbalance during concreting is 100kN (10 tons). This unbalance is defined as the difference of concrete between the right and left sides of the superstructure.

By starting the concrete at the front end of the MSS, the Main Girder will have virtually reached its maximum deflection by the time concreting reaches the previous span. Below is an example of concreting sequence of 34.22 m span in both vertical and horizontal directions. These sequence are based on NRS past experience; however, the actual construction sequence for each project must be decided by the bridge designer or the bridge construction site engineer.

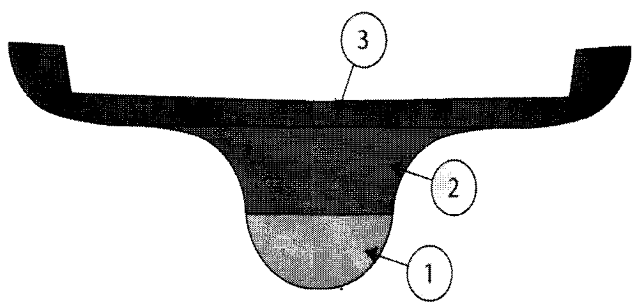

Figure 19 Concreting sequence in vertical direction.

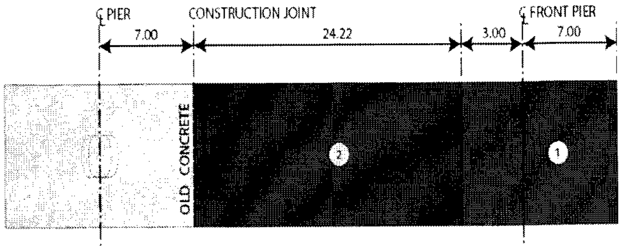

Figure 20 Concreting sequence in horizontal direction.

7.2 Launching procedure

The launching condition is the most extensive of all operations. It involves using almost all the facilities of the MSS. The launching method is for example affected by the obstructions below the formwork, obstructions on the sides of the formwork, already cast concreted sections, radius of spans and span lengths etc.

During launching, it is essential that all personnel are given specific responsibilities and understand the potential problems that could occur. The main problem when launching through a radius and adjacent to an existing structures will be the possibility of the launching rail getting jammed in the launching wagon or the hangers clashing with the existing structures or other obstructions.

In addition to the above, it is also necessary to observe any obstructions that may be present beside the bridge as the MSS is launched forward with the hanger trusses together with formwork opened outward.

The launching sequence of the SL-MSS comprises of the concreting and launching stages as the following:

<u>Stage 1</u>

1.1 MSS is set at the concreting position.

1.2 Front support and rear support are activated.

1.3 Middle launching support is suspended to the front nose.

1.4 Front launching support is ready set on top of the next pier.

1.5 Install rebar cage and cast the span.

<u>Stage 2</u>

2.1 Move back and install the middle launching support on the already cast deck.

2.2 Release the main jacks at front support and rear support respectively. Rear support is now on the express rollers.

2.3 MSS is supported by middle launching support and rear support.

2.4 Open the hanger trusses.

2.5 Prepare for launching forward to the next span.

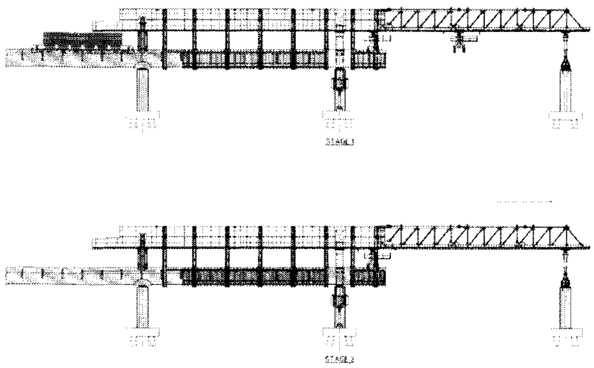

Figure 21 Launching sequence and kinematic, Stage 1 and 2.

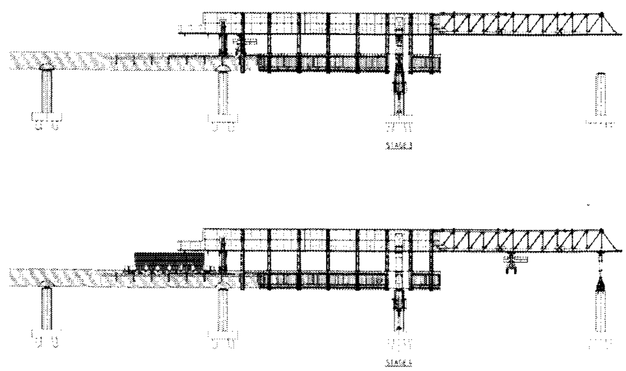

Figure 22 Launching sequence and kinematic, Stage 3 and 4.

Stage 3

3.1 Launch forward the MSS to the new span until the front support is in same line with the front launching support. During launching, the MSS is supported by front launching support, middle launching support and rear support

3.2 Activate the main jacks at front and rear supports to take load of the MSS. Middle launching support and front launching support are now free.

Stage 4

4.1 Relocate the front launching support to set on the next pier.

4.2 Relocate the middle launching support to suspend to the front nose.

4.3 Close up the hanger trusses. Prepare the MSS for the casting.

4.4 Repeat the stage 1-4 to complete the cycle for the next span.

8. Dismantling Procedure

The dismantling process of the SL-MSS can be described as the following:

Process of this operation is depended on the actual condition at site and varied from job to job. A careful planning and drawings should be done before actual dismantling begins. The general steps to dismantle the MSS after the last span has been completed are as follows:

8.1 Install temporary tower at rear of main girder to take load of MSS.

8.2 MSS is supported by temporary tower at the rear and the middle launching support at the front.

8.3 Dismantle the front nose and front launching support.

8.4 Fold down the bottom hangers & start dismantling the formworks and formwork support frame.

8.5 Dismantle the hanger trusses.

8.6 Dismantle the front support and front support leg.

8.7 Dismantle the rear support.

8.8 Bring down the main girder and dismantle each module.

8.9 Dismantle the middle launching support and the temporary tower.

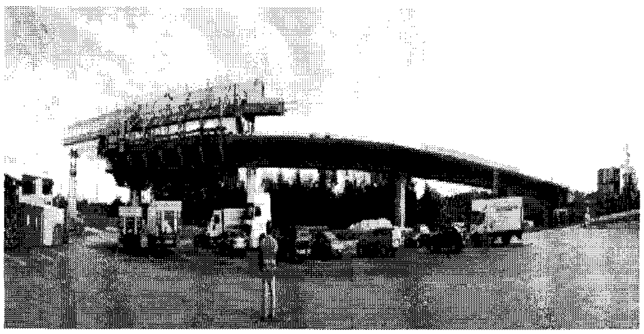

Figure 23 The MSS in concreting position for fourth span, photo taken at construction site in October 2012.

9. Conclusion

The advantages of the movable scaffolding system when compared to conventional scaffolding or launching gantries are as the following

- High efficiency in achieving rapid cycles
- Lightweight
- Easy to assemble
- Reduce manpower
- Can be adapted to different cross sections (allowing reuse elsewhere)
- High resistance to torsion
- Maximum deflection = L/400 of span
- Self launching option (no cranes required for pier bracket relocation)
- Limited interference to road users below during construction (if applicable)
- Pre-stress cost reduction (up to 30%) by reduction of deck pre-stressing amount (no cantilever moments) or reduction in number of anchorages & couplers in the pre-stressing of the deck and reduction in amount of pre-stressing operations in the deck
- Reduction in number of high risk operations (movements & launching)
- Easier geometry control (span by span construction)
- No requirement for scaffolding to support the structure
- Prefabricated rebar cage can be lifted and placed by MSS
- Less forces in piers
- No requirement for segmental casting yard and associated transport costs.

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