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Analysis and Design of Formtraveller for Colorado River Bridge, Hoover Dam Bypass Project, U.S.A.

Abstract

Norwegian specialist, NRS AS, has been appointed by Obayashi/PSM JV to undertake the design and supply of four Formtravellers (Bridgebuilder, BB) for the construction of the reinforced concrete (RC) arch rib of the Colorado River bridge. The scope of work includes the design, steel fabrication, and supply of ancillary equipment for the BB. 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 BB 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 BB due to adverse weather anticipated while working over big Fjord, special considerations to ensure efficient installation and launching of BB, and a purpose-built internal formwork system for the curved and the longitudinal slope of 48°. The project is currently under construction with the expected complete date in May 2008.

Keywords: Formtraveller, Bridgebuilder, Reinforced concrete arch rib, Curved-concrete gravity dam, Arch bridge

Figure 1 Rear view of the Hoover Dam, photo taken in September 2005.

Figure 2 3D view of the Colorado River bridge.

1. Introduction

In 1931, during the height of the Depression, eight thousands American workers came to the Black Canyon on the Arizona-Nevada border to tame the Colorado River. They began construction on what would be the largest dam of its time "the Hoover Dam". Amazingly, they completed the dam in 1936 which was ahead of schedule and under budget. The construction cost was 165 million US dollars. The main purpose of building the dam was for hydroelectric power. The Lake Mead's reservoir has capacity of 1.24 trillion cubic feet (35 billion m^3). It generates more than four billion kilowatt-hours a year that's enough to serve 1.3 million people. The Hoover Dam is a curved-concrete gravity dam. At its base, the dam is as thick (210 m) as two footballs fields measured end to end and its height is about 222 m. It is so thick and heavy, it doesn't even need to be curved. It is heavy enough to resist the weight and thrust of the water pushing behind it, but designers thought people would feel safer with a curved design. Figure 1 shows site seeing point behind the dam.

The Colorado River bridge connects Nevada and Arizona states over the Colorado River. The idea is to bypass the Hoover dam, see Figure 2. The bridge is designed as an arch bridge with span configuration 106'+4 @ 120'+9@121.11'+120' +100', total span length of 1896' (≈578 m). The bridge structure composes of cast-in-place RC deck on top of steel box-girder. The steel box-girder is then embedded in post-tensioned RC cap in which supported by concrete pier. There are six piers over Nevada side and three piers over Arizona side which are supported by the foundation on the river's embankment. However, eight piers over the Colorado River are supported by RC arch rib. The arch span length equals 323 m

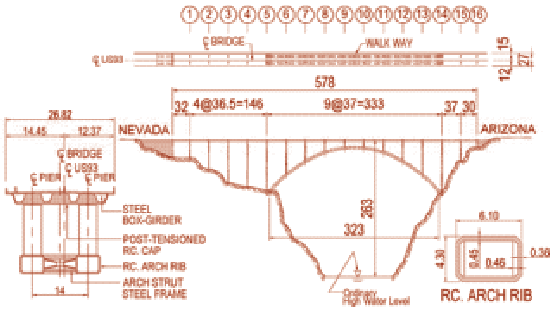

Figure 3 Bridge structural drawings.

consisting of 52 (2@26) segments and one closure stitch at center of the arch. The maximum longitudinal slope is 47.78° and minimum 1.47°. The box segment has the constant width of 6.10 m and constant height of 4.30 m. Segment length varies from 6.65 to 7.93 m, see Figure 3 for bridge structural drawings.

2. Design Criteria

Bridgebuilder, NRS type III-A12-80-0, approximately load capacity is 180 metric tons i.e. 168 tons concrete + 12 tons wooden shuttering, was specially designed for RC arch rib based on the following design criteria.

2.1 Design code

The structural calculations were performed according to the following design rules and specifications:

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

2.1.2 Wooden formwork: NS 3470 (6).

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

2.2 Load

The assumed loads and densities are as following:

2.2.1 Densities of concrete 26.4 kN/m^3, steel 78.5 kN/m^3, wood 8.0 kN/m^3.

2.2.2 Load from shuttering: vertical shuttering 0.6 kN/m^2, horizontal shuttering 1.0 kN/m^2.

2.2.3 Working platforms: front-, rear bottom-, front upper-, front lower-, rear upper-, and rear lower- working platforms are designed for a uniform load of 2.5 kN/m^2; lower bottom-, front beam-, and front bottom- working platforms are designed for a uniform load of 1.0 kN/m^2.

2.2.4 Wind: allowable wind speed for concreting ≤ 22 m/s, for launching ≤ 12 m/s. No operations are allowed when wind speed exceeds 22 m/s. and the BB should be secured in the position on the rails. The formwork must be separately secured to the bridge.

2.3 Deflection

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

2.4 Material data

2.4.1 Steel quality: Since the BB will be fabricated in China and shipped to U.S.A. after complete fabrication, therefore, material properties are based

Table 1 Steel properties.

Steel Grade	Plate thickness t, mm				
	t≤16 mm f_y/f_u, MPa.	16 mm<t≤25 mm f_y/f_u, MPa.	25 mm<t≤36 mm f_y/f_u, MPa.	36 mm<t≤50 mm f_y/f_u, MPa.	50 mm<t≤100 mm 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:	7850 kg/m^3

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.

2.4.2 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 properties.

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)	34CrNiMo6	980/1180	880/1080	780/980	690/880	590/780
	40 Cr	785/980				

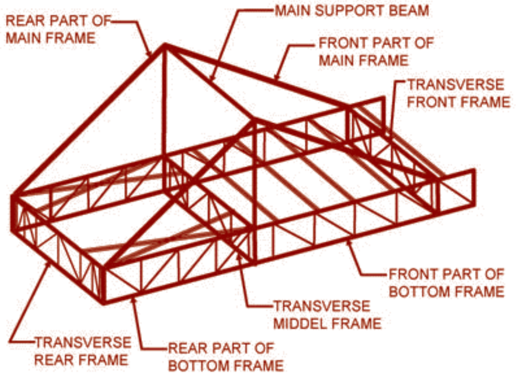

Figure 4 Computerized 3D modeling of the BB.

Table 3 Loads per frame.

	Type	Load factor	Weight (t)	No. of supports	Point Loads (kN)														
					P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}
32	Timber & Plywood of Ext form	1.20	2.6	10		3.0	3.0	3.0	3.0	3.0									
33	Timber & Plywood of Int form	1.20	3.0	4	8.8														
34	Timber, cover of Top Slab	1.20	2.8	4	8.2														
35	Timber, cover of Bot. Slab	1.20	1.9	10		2.2	2.2	2.2	2.2	2.2									
36	Shuttering	1.20	3.6	11	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9				
37	Concrete (Web)	1.20		10		96	194	194	194	48									
38	Concrete (Top slab)	1.20	192.0	4	64														
39	Concrete (Bottom slab)	1.20		10		67	67	67	67	33									
40	LL Side work pt on bottom	1.60		18		3.3	3.3	3.3	3.3	3.3		3.3	3.3	3.3	3.3				
41	LL Side work pt on ext.	1.60		18		3.3	3.3	3.3	3.3	3.3		3.3	3.3	3.3	3.3				
42	LL Upper work pt	1.60		2	22.0														
43	LL Bottom pt, rear	1.60		4														8.4	8.4
44	LL Bottom pt, front	1.60		4													21.0	21.0	
45	LL Front work pt	1.60		4			4.8	4.8											
46	LL Internal work pt	1.60		4			4.8	4.8											
	Total load summary (Pi)		314.1		202.7	254.0	327.2	331.1	308.8	133.3	61.1	13.1	13.1	13.1	67.3	66.8	35.7	54.4	31.1
	Total Vertical load (Pvi)	COS 41 =		0.75	153.0	191.7	246.9	249.9	233.1	100.6	46.1	9.9	9.9	9.9	50.8	50.4	26.9	41.1	23.5
	Total BB weight w/ conc 50%, Hori load (Phi)	SIN 41 =		0.66	112.0	113.4	129.2	131.7	117.1	60.8	40.1	8.6	8.6	8.6	44.2	43.8	23.4	35.7	20.4

2.4.3 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: ∅ 15 mm, 900/1100 MPa and ∅ 20 mm, 900/1100 MPa.

2.5 Material factors (γ_m)

Ultimate Limit State (ULS):

– All parts: γ_m = 1.15

Service Limit State (SLS):

– All parts: γ_m = 1.00

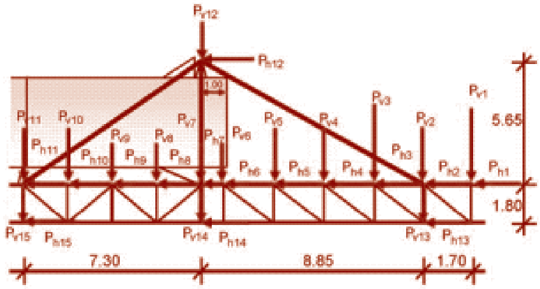

Figure 5 Loads on the BB per frame.

2.6 Load factors (γ_f)

Ultimate Limit State:

Dead load: γ_f = 1.20,

Concrete load: γ_f = 1.20,

Live load: γ_f = 1.60

Service Limit State:

All loads: γ_f = 1.00

3. Structural Analysis

Three dimensional (3D) finite element model of the BB was constructed based on the nominal geometric and material properties listed in Table 1. Every effort was made to first conceptualize and then to analytically simulate the 3D geometry as well as the boundary and inter-element of the BB.

PC-based STAAD-PRO(10) was selected as the software for structural analyses. This program also included modules for code checking according to the relevant design rules. The beam elements were used to model all the frames preserving the local 3D geometric attributes while ensuring inter-element compatibility, as shown in Figure 4.

Figure 6 Main frame system.

4. Description of Main Parts

4.1 General main frame system

The main frame system is consisted of Main support beam, Upper main frame, Bottom frame and 3 Transverse frames as per shown in Figure 6.

The main support beam is the part that supports directly from the Main jack and lift the whole BB through the Upper main frame. The part that attached directly to the Main support beam is Front bogie, Launching system, Main jack, Guider and Main frame.

Main frame comes in 3 pairs, front, middle and rear. It suspended through the pin bolt from the Main support beam to Bottom frame. Bottom frame comes in a pair each consisted of 2 modules that pin together for transporting purpose. Bottom frame is tied and braced together by transverse frame at 3 locations where Main frame pins in, see Figure 6 for details.

4.2 Bottom slab

The Bottom slab is built up with 5 transverse beams bolted to the Bottom main frame. There are longitudinal spread channels running on top of the transverse beam and 8 mm steel plates are used for the form surface.

4.3 Main support beam

Main support beam is the built-up box beam with the box height of 1.0 m, width 0.6 m, and the length 7.84 m. Plates thickness varies between 16 and 30 mm.

4.4 Main jack

Main jack is the two hydraulic jacks which supported directly over the web of the finished arch structure. It is designed to support the whole BB during concreting by transferring the loads from the Main support beam to the front end of segment at centre of each webs.

4.5 Rear jack

Rear jack is the two hydraulic jacks which supported directly under the finished arch structure. It is designed to support the rear part of BB during concreting by transferring the loads from the Rear transverse frame to the rear end of segment at centre of each webs.

4.6 Bottom frame

The Bottom frame consists of two longitudinal parallel space frames. The space frames are plates and profiles built-up box sections. The Bottom frame is divided into two sections i.e. Front bottom frame and Rear bottom frame for the transporting purpose. There are working access platforms running along the entire length and between the Bottom frame.

4.7 Main launching system

The Main launching system consists of two hydraulic cylinders positioned over the launching rails and connected to the front bogie and a gliding lock device. The gliding lock device is then gliding on the launching rail.

The Main launching system is designed to pull and push the BB longitudinally. Under pushing operation the gliding lock device is locked with pin bolt to the rail, then the Launching system push the BB longitudinally in step of 875 mm. When the jack is pushed to full stroke, the lock pin bolt on the front bogie is inserted to prevent the BB rolling backward under re-stroking of the jacks.

4.8 Main launching rail

The Main launching rail is the built-up box beam with the box height of 235 mm, width 200 mm, and the length 12,980 mm. Plates thickness varies between 6 and 30 mm.

The main rails are equipped with the locked items on both front and rear. These items are designed for locking the rails to top of concrete segment preventing the rails sliding backward during launching. These locking items must be removed under the relocation of the rails.

4.9 Rear bogie

Rear bogie is the two rolling bearing which supported directly underneath the finished arch structure. It is designed to support the rear part of BB during launching by transferring the overturning load from the Rear transverse frame to the rear of concrete segment. The Rear bogie is equipped with adjustable mechanical screw jacks such that it is possible to launch the BB through different arch angles.

4.10 Transverse front frame, Transverse middle frame, Transverse rear frame

Three transverse frames connect the two longitudinal Bottom main frames together at the inner side of each Main frame using pin bolts. Transverse front frame also supports the front working platforms. Transverse middle frame is equipped with bracing and the Anti-sliding jack.

Transverse rear fame is equipped with the Rear jack and the Rear bogie. Also, a bracing is bolted to the inner side of the frame.

4.11 Wind bracing

Wind bracing is designed to stiffening the rear and Middle transverse frames.

4.12 Front support system

Front support system is designed to support the Front Beam which supporting the Internal formwork support beam during concreting.

4.13 External formwork

The External formwork is designed for concrete load pressure of 2000 psf. Also, it is designed to cover different segment

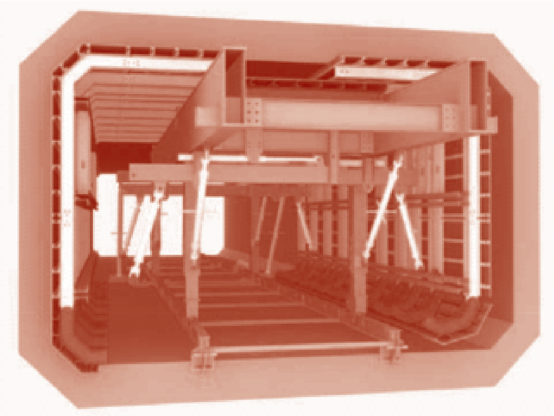

Figure 7 Internal formwork system.

lengths ranging from smallest 6645 mm to largest 7931 mm.

In launching position, external web form at both sides are designed to slide out with a gap maximum of 200 mm. The chamfers at the top and bottom slab are generally done by wooden formwork.

The External formwork is built up of steel frames with wooden columns. The purpose of this kind of assembly is to reduce the steel weight. The 21 mm plywood is used for the form surface, see Figure 7 for details.

4.14 Internal formwork

The Internal formwork is designed to cover different segment lengths with blister in various locations. The striping of the Internal formwork is done by the hydraulic system attached to the internal support beam system. The minimum width of the Internal formwork in launching position is 3832 mm for pier segment and 4270 mm for typical segment. The form panels are divided into 9 panels with hinge or bolt connection due to the striping system or transporting purpose. The Internal formwork is built up of steel frames with wooden columns for steel weight reduction. The 21 mm plywood is used for the form surface.

4.15 Internal formwork support beam system, Rail system and Launching system

The Internal formwork support beam system is designed to carry concrete load from top and bottom slab. Launching of Internal formwork support beam can be done by using roller and rail. Hydraulic jack is used to launch the Internal formwork support beam forward. The Internal formwork support beam is built up of steel box beam with adjustable legs.

4.16 Front bogie

The Front bogie is made up of plates with various thickness ranging from 6 to 30 mm together with the express rollers and connecting lugs. The two Front bogies carry the whole BB under launching situation. Each Front bogie is equipped with two express rollers 60 tons capacity which rolling on the top of main rails. The connecting lug is attached to the Front bogie for the longitudinal launching jack. The Front bogie is equipped with strand break for safety under launching. Pin bolt is used for locking under re-stroking of the longitudinal launching jack.

4.17 Working platforms

Areas on the BB that need access for working operation are equipped with working platforms i.e. Front upper-and lower-working platforms, Rear upper-and lower-working platforms, Front and Rear bottom working platforms, Front beam working platforms etc. Platforms are designed to take different angles by an adjustable step or screws jacks

4.18 Front beam

The Front beam is the built-up box beam with the box height of 490 mm, width 300 mm, and the length 6613 mm. Plate thickness varies between 10 and 25 mm. Front beam is used to support the Internal formwork support beam at the front during concreting. The beam is designed with transversely adjusting possibilities and for adjusting the height of the formwork.

4.19 Guider

The Guider is used to support the Main support beam for the diagonal force due to the varying angle of the arch. It supports the beam during concreting and during operation of lowering or lifting the whole BB by using main jacks. The Guider is designed with adjustable possibilities carried out by mechanical screw jack. The Guider is locked to the concrete at the front of the segment by three dywidags, in addition, there is a pin which taking the sliding force due to the varying angles of the arch.

4.20 Strand braking system

The purpose for this Strand brake is to add an additional launching brake in case of hydraulic jack fails under launching with the consequence of uncontrolled backward rolling of the BB.

This braking system is only for extra safety purpose and is not meant to replace the operation of pin bolt lock system on the Front bogie while re-stroking of the hydraulic jack under launching operation.

It is therefore extremely important to always clean the strands equipment before launching to avoid backward slide under launching.

4.21 Anti-Sliding Jack System

The Anti-Sliding Jack is used to support the diagonal component self weight of the whole Bottom frame and External formwork during Formtraveller adjusting operation.

Meanwhile, during concreting, it is designed to take 5% of the diagonal concrete load due to the varying angles of the arch.

The Anti-Sliding Jack supports bottom of the Formtraveller during concreting and during the operation of lowering or lifting the whole Formtraveller by using Main jacks.

The Anti-Sliding Jack is designed with adjustable possibilities carried out by mechanical screwed bolt with lock nut pushing with a hydraulic jack.

The Anti-Sliding Jack is locked through the bottom slab concrete on the segment by a pin bolt system. The pin bolt takes the diagonal sliding force due to the varying angles of the arch.

4.22 Bracing member

Bracing member is used to hold the distance between the two arch ribs under concreting of pier segments.

5. Assembly and erection

5.1 General

This section covers relevant issues for the assembly and erection of the BB. The BB consists of a large number of components, which need to be put together in a predefined order and in accordance with specific requirements. This section describes the necessary steps for assembling the structure.

Safe handling of large steel structures like this BB often requires detailed analysis of stresses and deflections during various stages of the erection works. Some times special handling equipment must be built and special temporary stiffening and bracing has to be provided during construction. Checklists are required to be completed for every segment to prevent any critical items being overlooked.

Estimated assembly schedule is five working days per Bottom frame with platforms and four days for Bottom slab and front platform. Three working days for External formwork, four days for the rest of platforms. It's assumed around 15 - 25 working days for the complete assembly of the BB.

5.2 Step-by-step assembly and 2nd segment casting

Below are step-by-step assembly of the BB including erection and concreting of 2nd segment of RC arch rib.

1. Rear bottom frame, Rear and Middle frames.
2. Installation of bottom platform, Rear bogie, Rear jack, Anti-sliding jack, and Wind bracing.
3. Installation of Front bottom frame, Front frame, Front working platform.
4. Installation of Bottom slab in 2nd segment casting position, Front working platform.
5. Installation of External formwork.
6. Installation of cable stays and rotate of BB.
7. Installation of rebar cage and front support.
8. Installation of Internal launching beam.
9. Installation of Internal supporting system and Internal formwork.
10. Installation of Front beam.
11. Installation of Bottom slab lock gliding formwork, and Top slab lock from.
12. Now, part of BB is ready for 2nd segment casting, see Figure 8.

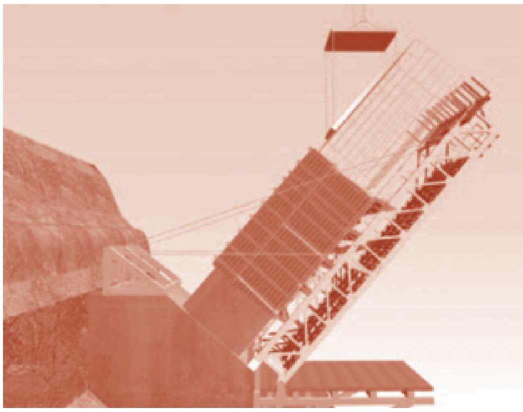

Figure 8 Installation of rebar cage.

5.3 Arch rib pouring rate and sequence

Concrete pouring pressure can be found as below:

$$P = C_w C_c \left(150 + \frac{43{,}400}{T} + 2{,}800\frac{R}{T}\right) \quad (1)$$

where P is the pour pressure (lbs/ft^2), C_w is the unit weight coefficient, C_c is the chemistry coefficient, R is the pouring rate (ft/hr), T is the temperature (°F). The chemistry coefficient depends on cement type or blend as given in Table 4.

The unit weight coefficient of normal weight concrete (140 to 150 lbs/ft^3) is taken as 1.0. To facilitate casting of the segment, the maximum pouring rate for various temperatures have been calculated and given in Table 5.

Table 4 Chemistry coefficient.

Cement Type or Blend	Chemistry Coefficient (C_c)
Types I and III without retarders	1.0
Types I and III with a retarder	1.2
Other types or blends containing less than 70% slag or 40% fly ash without retarders	1.2
Other types or blends containing less than 70% slag or 40% fly ash with a retarder	1.4
Blends containing more than 70% slag or 40% fly ash	1.4

Table 5 The maximum pouring rate of the segment.

Temp (°F)	Maximum, pouring rate (R) in ft/hr for a given C_c		
	1.0	1.2	1.4
72	32.07	23.50	17.38
74	33.39	24.58	18.29
76	34.71	25.67	19.20
78	36.04	26.75	20.12
80	37.36	27.83	21.03
82	38.68	28.92	21.94
84	40.00	30.00	22.86
86	41.32	31.08	23.77
88	42.64	32.17	24.68
90	43.96	33.25	25.60
92	45.29	34.33	26.51
94	46.61	35.42	27.42
96	47.93	36.50	28.34
98	49.25	37.58	29.25
100	50.57	38.67	30.16

In order to keep the concrete pressure below 2000 lbs/ft^2 and spread out uniformly during casting the segment, the pouring sequence is established as listed below and illustrated in Figure 9.

Step 1. Pouring from lower slab (concrete flow from lower slab to web).

Step 2. Pouring from web (concrete flow from web to lower slab and upper slab).

Step 3. Pouring from upper slab (concrete flow from upper slab to web and lower slab)

Step 4. Pouring from lower slab (concrete flow from lower slab to web and upper slab).

Step 5. Pouring from web (concrete flow from web to upper slab)

Step 6. Pouring from upper slab (concrete flow from upper slab to web)

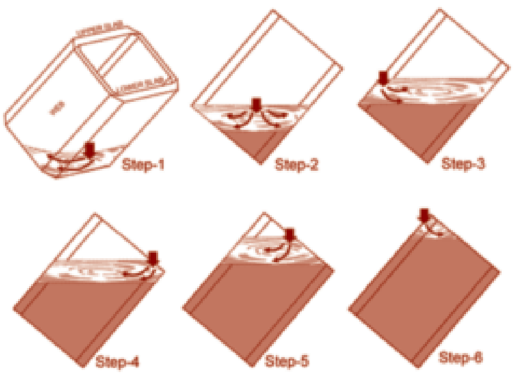

Figure 9 Pouring sequence.

5.4 Third segment casting preparation

After 2nd segment of RC rib has been cast, the rest of BB components can be installed and ready for the third segment concreting. Below are step-by-step of BB installation, see Figure 10.

1. Installation of second temporary support.
2. Removal of temporary cable stays.
3. Removal of Front beam and Front support.
4. Pulling Bottom slab and External formwork to final position.
5. Installation of Front support beam at final position.
6. Installation of Main rails.
7. Installation of Guider.
8. Installation of Main jacks.
9. Installation of Main support beam.
10. Installation of Launching system.
11. Installation of Main Frame.
12. Installation of all remaining plat-forms.
13. The segment is now ready for concreting.

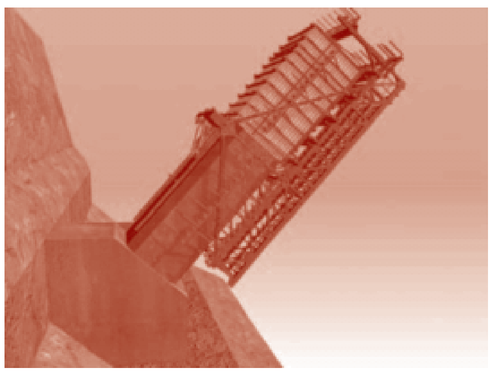

Figure 10 BB in 3rd segment casting position.

Figure 11 Foreland bridge piers construction.

6. Bridge Construction

6.1 Foreland bridge piers

The two abutments of the foreland bridges, and the nine piers, are constructed in reinforced concrete. All the piers are founded on bedrock. Their heights range from 14.5-90 m. The architects insisted on a consistent form tie and joint pattern throughout. It was possible to achieve this by using climbing formwork as can be seen on Figure 11.

6.2 RC arch rib

At present time, four BBs are installed and ready to cast the second segment of an RC arch rib as can be see on Figure 12.

Figure 12 RC arch rib construction.

7. Conclusion

The construction of the RC arch rib for the Colorado River bridge is a challenging task involving development of construction techniques and construction equipments.

The NRS Bridgebuilder is used for the construction of the RC arch rib. The optimised design of the main structural components and the use of recoverable high strength bars in all stays and hangers reduce the total steel weight to a minimum. The system is easily adjusted during operation to variations in segment length and road alignment. Formwork beams are designed for a maximum deflection of 1/400 of their length so the vertical deflection of the Bridgebuilder is less than 25 mm at maximum load. It takes as fast as 2 weeks to assemble on BB. During its operation, the system rolls forward on rails, making the reset time short.

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