# Comparison and Selection of Arch-Rib Construction Schemes for Continuous Beam-arch Composite Bridge of High Speed Railway

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*Abstract: The paper summarizes the four different construction schemes based on engineering cases for the arch rib construction of continuous beam-arch composite bridges for high-speed railways. These methods include in-situ assembly, segmental lifting, incremental launching and longitudinal moving, and vertical rotation. The temporary structural designs, process methods, and technological equipment for each construction scheme are described in detail. The advantages and disadvantages of each scheme and its application scope under various conditions are analyzed, and opinions and suggestions for guiding the application of each scheme are proposed. The comparison and selection analyses show that the four arch rib construction schemes have certain applicability under different conditions such as bridge site status, bridge span, and construction environment. With the continuous increase of bridge span and progress of construction technological equipment, the arch rib construction technology is developing towards the overall erection direction. This leads to more obvious technical advantages of the segmental lifting method, incremental launching and longitudinal moving method, and vertical rotation method. Therefore, it is necessary to select the best construction scheme according to the construction status and technical conditions during application.*

Keywords: high-speed railway (HSR); continuous beam-arch composite bridge; arch rib; in-situ assembly; segmental lifting; incremental launching and longitudinal moving; vertical rotation

(This paper is selected from *China Railway*)

# 1 General Description

Among the bridges of high-speed railway in China, bridges with the spans of 100~300 m adopt in great number the structural form of concrete beam-arch composite bridge, among which the concrete continuous beam-concrete-filled steel tubular arch composite system bridge (abbreviated as continuous beam-arch composite bridge) is one of the kinds in the system. Such composite bridge of concrete-filled steel tubular arch and concrete beam possesses excellent static and dynamic performances and good economic performance and is widely applied in high speed railway bridge construction[1].

Construction of continuous beam-arch composite bridge usually adopts the construction method of erecting "beam before arch", which means that the concrete beam adopts the hanging basket cantilever pouring method for construction until the closure. Concrete-filled steel tubular arch rib can adopt multiple construction schemes such as in-situ assembly, segmental lifting for taking the place, incremental launching and longitudinal moving, and vertical rotation in according with the requirements for arch-rib design, topography and geomorphology of bridge site, and construction progress.

# 2 Construction Techniques

## 2.1 In-situ assembly

### 2.1.1 Brief engineering introduction

The continuous beam-arch composite bridge with the main span of 168 m is adopted to link Xuzhou City with the east-west high-speed railway in Lianyungang City crossing the Beijing-Hangzhou Grand Canal with the total length of 337.3 m and the standard width of 14.2 m. The arch-rib design is of the concrete-filled steel tubular structure with the rise-span ratio of 1/5, the sectional form is of the dumbbell-shaped structure with the height of 3 m and equal height arrangement along the way, the chord pipe specification is $\varphi$1 000×20 mm, and the center transverse distance of two-side arch ribs is 11.8 m. There are 9 space truss cross braces between the arch ribs. The whole bridge is provided with 16 sets of LZM (K) 7-I type double suspenders with the spacing of 9 m along the bridge direction.

### 2.1.2 Construction scheme

As the bridge site crosses over the Beijing-Hangzhou Grand Canal, the water transportation condition is good and favorable for large floating crane operation, for which the arch rib segments are divided into long segments by using the advantage of strong hoisting capacity of the floating crane, and then the arch rib segments are assembled in situ by using the bracket method. The single-side steel-tube arch rib is divided into five segments, which are processed and formed in the factory and then transported to the site by waterway. The arch rib is hoisted symmetrically from the arch foot at both ends to the arch crown by floating crane until the closure[2-3].

### 2.1.3 Support design

The temporary support is composed of 3 sets of steel-tube stand column and the connecting system among them, for which the design is the form of lattice mast with the steel-tube size of $\varphi$325×8 mm. Among them, the steel-tube stand columns of the *L*1 and *L*3 supports are with the longitudinal and transverse spacing of 3×2 m, and the steel-tube stand column of the *L*2 support is with the longitudinal and transverse spacing of 4×2 m. The $\varphi$219×6 mm steel tubes are used as the connecting system between the steel-tube stand columns, among which one unit of connecting system is arranged for every 2.5 m of the *L*1 and *L*3 from the tops of the supports downwards, and one unit of connecting system is arranged for every 3 m of the *L*2 from the top of the support downwards. At the top of the support, the three-piece 45a I-beam is used as the distribution beam, and at the top of the two sets of lattice masts in the left and right sides at the same position, the steel tube of $\varphi$219×6 mm is used to set the transverse connecting system.

The embedded parts shall be arranged near the arch foot of the beam face, and the continuous beam is anchored with 4 pieces of $\varphi$25 mm finish-rolled ribbed steel bar with prestress of 100 kN being applied. Lug is welded on the embedded parts as the anchor point, and $\varphi$24 mm steel wire rope is used as wind rope to connect the top of temporary support longitudinally. The steel wire ropes are in one-to-one correspondence with the steel tubes of stand column, and a total of two sets are provided in the transverse direction. The structure of assembled support is shown in Fig. 1.

### 2.1.4 Arch-rib hoisting

The arch rib and cross bracing adopt the hoisting scheme with coordination of the 500 t floating crane and the 80 t autocrane, for which the 500 t floating crane is used firstly for symmetrical installation of the arch-rib segments from the arch foot towards the direction of arch crown and synchronous use of the 80 t autocrane for installation of the cross bracing between the arch ribs. The 80 t autocrane is then used for the installation of the arch-rib closure segment. The 500 t floating crane is ultimately used for the installation of the arch-crown cross bracing. The site of arch-rib segmental hoisting is shown in Fig. 2.

## 2.2 Segmental lifting

### 2.2.1 Brief engineering introduction

The Xijiang River Super-long Bridge of Nansha Port Railway adopts the (110+230+110) m continuous rigid frame arch bridge to cross the Xiaolan Waterway with the total length of 451.7 m and the standard width of 13.2 m. The arch axis of the steel-tube arch rib for the main span is the parabola with the rise-span ratio of 1/5. The arch rib height is 4.25 m and the transverse spacing of arch ribs on both sides of the bridge along the bridge direction is 12 m, and a total of 9 truss cross braces are used between the arch ribs of both sides. The whole bridge is provided with 21 sets of twin suspenders in total with the

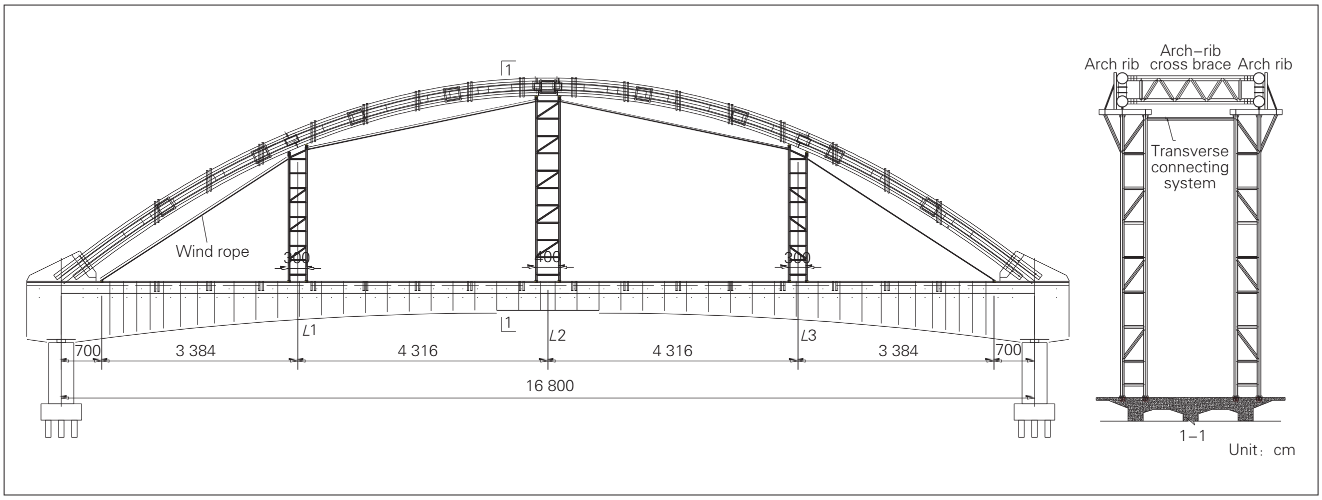


**Fig. 1** Structure of assembled support

standard spacing of 10 m for the suspenders along the bridge direction.

**2.2.2 Construction scheme**

As the main span of bridge is as long as 230 m and crosses the Nansha port with busy navigation of river course, no erection of support should be allowed in the river course and the time is short for the floating crane operation in construction. The scheme of combining the in-situ assembly of small segment with the large-stage integral lifting is adopted to rationally control the lifting weight and the height. The arch ribs are installed in three sections, for which the arch ribs of 32.4 m near the arch feet of the two ends are assembled in small segments by using the 130 t autocrane; and the arch ribs of 143.6 m near the mid-span are hoisted integrally in four sections to the horizontal-assembly support by using the 1 000 t floating crane and then be vertically lifted for 22 m onto the designed position for closure through the lifting tower support following the completion of welding. The site of arch rib lifting and closure is shown in Fig. 3.

**2.2.3 Support design**

(1) Horizontally-assembled support. The stand column of the horizontally-assembled support adopts the $\varphi$630×8 mm steel tube, the connecting system uses the $\varphi$219×6 mm and $\varphi$325×6 mm steel tubes, and the cross beam adopts the 2HN500×200 mm shaped steel with the adoption of welding and flange connection between the different members.

(2) Lifting tower support. The lifting tower support adopts the beam-column support, the stand column uses the $\varphi$1 000×12 mm steel tube, the connecting system adopts the $\varphi$630×8 mm and $\varphi$325×8 m steel tubes, and the load-bearing cross beam uses the 3HN900×300 mm shaped steel.

The large segment of the middle arch rib adopts the 4-point lifting with

**Fig. 2** Site of arch-rib segmental hoisting

**Fig. 3** Site of arch rib lifting and closure

each lifting point being provided with one set of 560 t jack. To maintain the alignment stability of arch rib at the time of lifting, the arch rib is provided with one piece of horizontal cable at each side with the maximum tension of 440 t. The layout of horizontal-assembly lifting scheme is shown in Fig. 4.

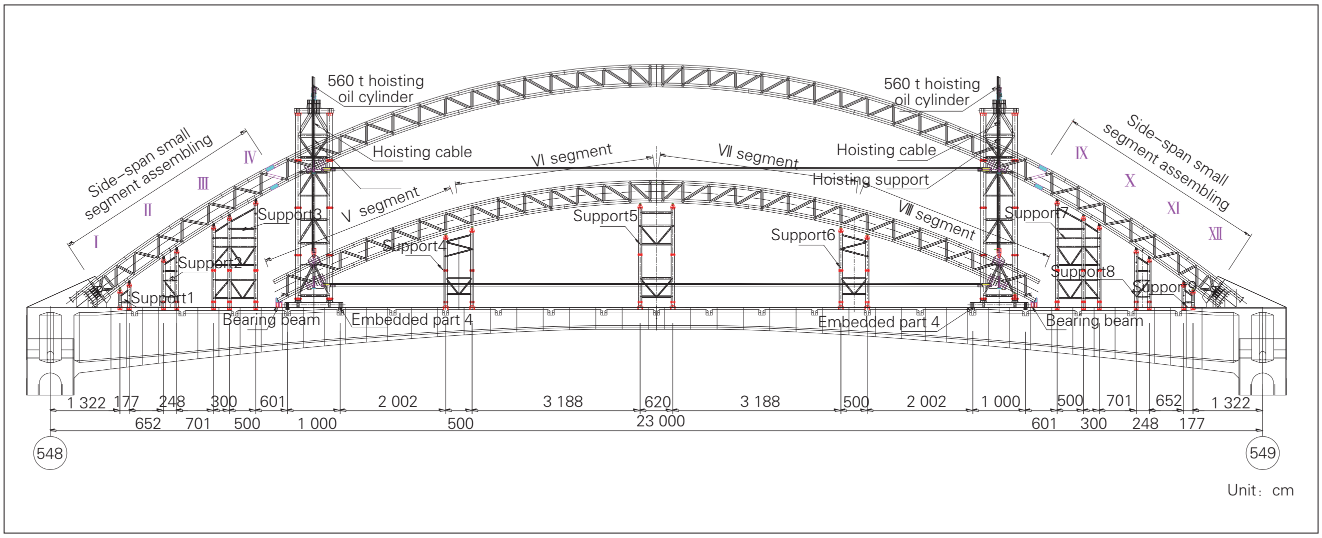


**Fig. 4** Layout of horizontal-assembly lifting scheme

### 2.2.4 Arch-rib lifting

The horizontal cable is pretensioned as per 10% of the rated tension before the arch-rib lifting. Then synchronous loading in steps is exerted to the lifting cable as per 10%, 20%, 50%, 60%, 80%, 90%, 95% and 100% respectively, and to the horizontal cable as per 20%, 30%, 45%, 60%, 70%, 85%, 90% and 100% respectively, for which deformations of arch rib and lifting tower support should be observed in the course of tension[4-6]. Following the complete separation of the arch-rib saddle of the lifting section from the load-bearing cross beam of the support, a pause and a standstill is kept for one hour. After the inspection of the lifting system without abnormality, the horizontal jack is kept with constant tension and the lifting jack is kept with the tension to move upward the lifting cable, enabling the arch rib to lift upward to the designed position with the lifting speed control being 3~4 m/h.

## 2.3 Incremental launching and longitudinal moving

### 2.3.1 Brief engineering introduction

The main bridge of the Qihe River Super-long Bridge crossing the Qihe River for the Huang'gang-Huangmei Railway adopts the (100+196+100) m continuous beam-arch bridge, for which the arch rib adopts the steel-tube concrete structure and the arch axis is a parabola with the rise-span ratio of 1/5. The arch rib is the uniform-height dumbbell-shaped section with the height of 3.2 m. The transverse spacing for the two units of arch rib is 12 m, the steel-tube diameter of arch rib is 1.2 m, and 10 truss cross braces are used for linkage between the arch ribs at both sides. The whole bridge is provided with 20 sets of PES (FD) 7-61 type suspenders with the standard spacing of 9 m along the bridge direction.

### 2.3.2 Construction scheme

As the main bridge of the Qihe River Super-long bridge crossing the river is the key node on the passage of girder erection for the Huang'gang-Huangmei Railway, the in-situ assembly of the conventional support method cannot meet the requirements for construction progress, for which construction method of ectopic assembly and longitudinal moving for taking the place is therefore adopted to solve the difficult problem.

The arch rib is divided into 16 segments including 1 arch foot segment and 15 longitudinal moving segments with the embedding section being arranged between the arch foot segment and the longitudinal moving segment. Among them, the arch foot segment at the large-mileage side is embedded in advance and construction of the arch foot segment at the small-mileage side will be carried out after the longitudinal moving of arch rib is in place. The construction of the longitudinal moving segment is conducted by adopting the method of support assembly + integral incremental launching, and the embedding section adopts the “fit-cut method” for closure at the preset temperature[7-8]. The site of incremental launching and longitudinal moving for the arch rib is shown in Fig. 5.

### 2.3.3 Support design

The arch-rib assembly support of the longitudinal moving section is set on the bridge deck of simply-supported box girder, for which a total of 14-row steel tubes is adopted to form the lattice mast with each 2-row steel tubes. The assembling space of about 22 m is preserved between the two sets to assemble the steel-tube arch, and each of the steel-tube arch-rib assembling segment is sustained on the two sets of support.

**Fig. 5** Actual scene of incremental launching and longitudinal moving

**2.3.4 Arch-rib horizontal assembly**

The incremental launching and longitudinal moving section is horizontally 185.5 m long with the height of 39.2 m, and the maximum segment axis is 16.9 m long with the single-limb mass of about 26.3 t. 15 units of the processed segments in the yard are brought onto the jig frame at the site and assembled and welded into 9 assembled segments, for which the maximum axis of the assembled segment is 31.7 m long with the mass of 47 t. Two sets of 160 t autocranes are then used to hoist them from the arch foot to the arch crown for completing the installation.

**2.3.5 Incremental launching and longitudinal moving**

(1) Technological equipment

Technological equipment for the construction of incremental launching and longitudinal moving mainly include the track, longitudinal moving trolley, temporary tie bar and incremental launching system.

The track is with the two sets of 4-piece P43 steel rails, and the distance between the centers of the two sets of tracks is 7.9 m. The longitudinal-moving trolley is arranged at the two ends of the steel-tube arch rib and consists of a steel box and a steel structure support, for which the model of longitudinal-moving trolley is shown in Fig. 6. The steel-box trolley is connected and fixed with the arch rib through the anchor ear, and the trolley is provided with four anchor ears and one temporary tie-bar anchorage point. The temporary horizontal tie bar adopts the steel-strand stay cable, the horizontal tie bar is fixed with a comb plate at an interval of 45 m, and the comb plates of the same section are connected with steel-wire rope. The incremental-launching system consists of an incremental-launching oil cylinder and a rail clamping device, and is arranged at the rear part of the longitudinal-moving trolley at the forward end with the provision of two 50 t hydraulic jacks in total[9].

(2) Construction steps

Step 1 is to remove the temporary support and observe the change of arch centering alignment.

Step 2 is to carry out incremental launching and longitudinal moving by adopting hydraulic continuous synchronous jack. The hydraulic cylinders are respectively connected to the rail clamping device and the wheel box in the advancing direction of the steel-tube arch, and the device for incremental launching is arranged on the front-end wheel box.

Step 3 is that operators of the pumping station shall cooperate with each other synchronously. Special personnel shall be arranged to observe the speed at the four arch feet during the incremental launching process. The speed at the four arch feet shall be dynamically adjusted during the incremental launching process to ensure synchronization. Based on this, the incremental launching and longitudinal moving along the track are repeatedly carried out to make it in place and connect it with the arch feet.

## 2.4 Vertical rotation

**2.4.1 Brief engineering introduction**

The main bridge of the Dong'guan waterway super-long bridge crossing the waterway for the Dong'guan-Huizhou Intercity Railway is the (100+180+100) m continuous beam-arch bridge with the width of 12.6 m and the rise-span ratio of 1/5. The arch rib is the uniform-height dumbbell-shaped

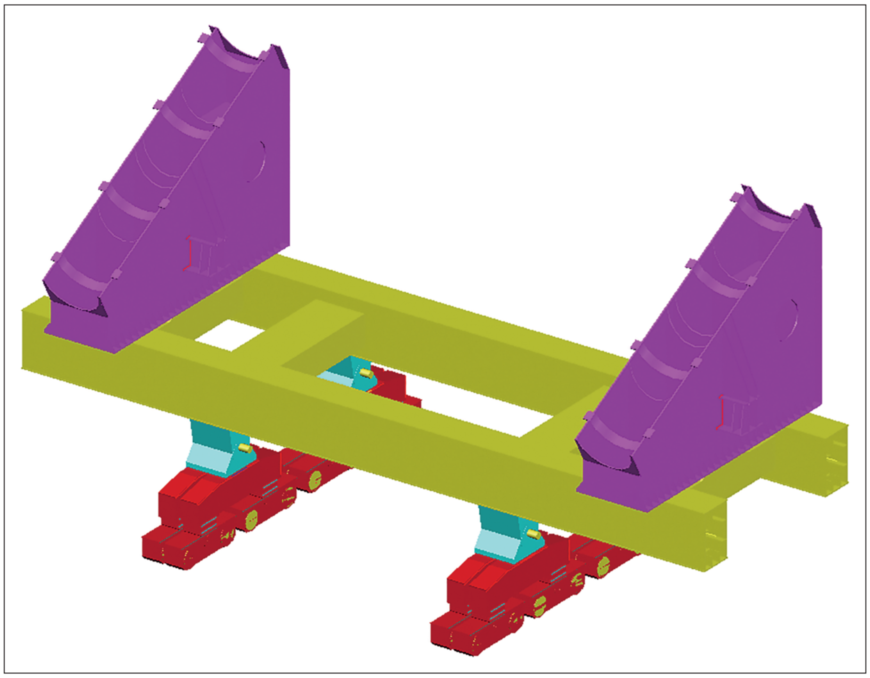

**Fig. 6** Model of longitudinal-moving trolley

section with the height of 3 m. The steel tube for the arch rib is $\varphi$1 000×20 mm, the batten steel plate is 6 mm thick, for which self-compacting concrete is filled in the steel tube and the batten plate. The spacing between the two units of arch rib is 11.2 m with a total of nine cross braces being provided. The whole bridge is provided with 17 sets of suspenders in total with the spacing of 9 m along the bridge direction.

### 2.4.2 Construction scheme

As the requirement of navigation for the Dong'guan waterway super-long bridge crossing the waterway is high, the floating crane cannot access to the waterway for operation, the arch-rib installation is therefore carried out by adopting the vertical rotation method so as to decrease the risks of operation at height and the influence of heavy-duty autocrane operation on the bridge to the bridge structure. Following the closure of the concrete main beam, a low support is erected on the bridge deck to assemble the two semi-arches of the left and right sides at a low position, and then make use of the vertical rotation for lifting the tower support to make the vertical rotation of the two semi-arches until the closure. The actual scene of vertical rotation closure is shown in Fig. 7.

**Fig. 7** Actual scene of vertical rotation closure

### 2.4.3 Equipment arrangement

(1) Lifting oil cylinder. The maximum tension of the lifting cables 1, 2 and 4 and the rear back cables 1, 2 and 4 for the vertical rotation of single-side arch rib is about 1 434 kN with the arrangement of 12 sets of 200 t oil cylinders, the maximum tension of the lifting cable 3 and the rear back cable 3 is about 1 638 kN with the arrangement of 4 sets of 350 t oil cylinder, and the maximum tension of the tower-pressing cable is about 281 kN with the arrangement of 2 sets of 100 t oil cylinder.

(2) Hydraulic pumping station. Three sets of hydraulic pumping stations are arranged for the single-side arch-rib vertical rotation. The way of intermittent operation is adopted with the rotation speed of 5~6 rad/h.

(3) Computer control system. One oil cylinder is selected from one group of cylinders for each lifting point to install the pressure sensor. One anchor sensor is respectively installed on the upper and lower anchor oil cylinders of each oil cylinder, and one oil cylinder intelligent sensor is installed on the main cylinder. One set of computer control cabinet is arranged on the ground, from which the proportional valve communication line, solenoid-controlled valve communication line, oil cylinder signal communication line and working power line are led out. The layout of vertical rotation scheme is shown in Fig. 8.

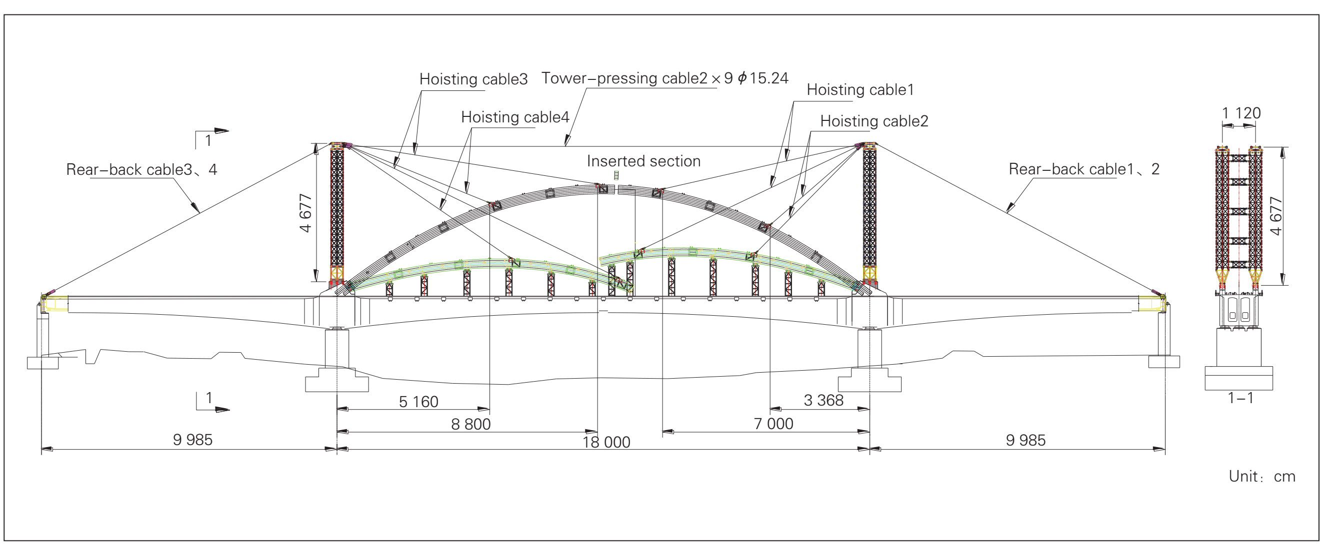


**Fig. 8** Layout of vertical rotation scheme

### 2.4.4 Arch-rib vertical rotation

(1) Trial rotation needs to be carried out before the formal vertical rotation and shall be subjected to stepped loading as per 40%, 60%, 70%, 80%, 90% and 100%. The connection between the rotation structure and the jig frame shall be released before the trial rotation.

(2) Pressures and heights of different points shall be recorded in the course of the formal vertical rotation. The formal vertical rotation shall be carried out according to the six-step procedures including operation, observation, survey, calibration, analysis and decision making, and kept well with the relevant records.

(3) The control system operation shall be in the automatic way at the time of formal vertical rotation.

(4) As the descending risk of the control system is high, the end position of vertical rotation shall be slightly lower than the theoretical elevation, which shall be accurately adjusted when it is in place[10-12].

## 3 Advantage and Disadvantage Analyses and Application Scope

The superstructure of continuous beam-arch composite bridge for high-speed railway usually adopts the construction method of erecting “beam before arch”, and the concrete main beam adopts the hanging basket cantilever pouring method for construction. The arch rib can adopt multiple construction methods such as in-situ assembly, segmental lifting, incremental launching and longitudinal moving, and vertical rotation in according with the bridge site status, arch-rib design, construction progress demands, hoisting equipment performance, arch-rib segment division as well as the transportation conditions, or adopts the method of combining incremental launching and longitudinal moving + segmental lifting. In case of non-availability for the conditions of erecting “beam before arch”, the construction method of erecting “arch before beam” can be adopted instead.

With the constant practice of weeding through the old to bring forth the new for the construction technologies of the continuous beam-arch composite bridge and the improvement of the construction equipment performance, the arch-rib construction begins the trend of development towards the orientation of integral erection. The segmental lifting, incremental launching and longitudinal moving, vertical rotation, and integral hoisting with large floating crane are the preferred schemes for integral erection of arch rib, which possess the advantages of simple techniques, easy control of alignment and quality, short construction period, low construction costs, and less influences to the bridge and the road underneath.

Comparison and analyses of the commonly-seen four main construction methods for arch rib are carried out in combination with the engineering cases, for which detailed analyses are conducted with respect to the advantages and disadvantages, application scope, and risks in safety and main points of quality control in the process of construction so as to offer references for the arch-rib construction of continuous beam-arch composite bridge of high-speed railway. Comparison and selection analyses of construction schemes are shown in Table 1.

## 4 Conclusions

The adoption of the construction method of erecting “beam before arch” for the continuous beam-arch composite bridge of high speed railway can make full use of the characteristics for the structural force of beam and arch to reduce the input for the temporary equipment of construction and decrease the engineering costs; and meanwhile also lessen the impact of construction on navigation and road traffic under the bridge to the maximum limit so as to secure the smooth implementation of engineering construction. Conclusions are reached as follows:

(1) To reduce the risks of working at height, decrease the quality control difficulties of welding at height, and lessen the influence of construction load on the internal force of concrete main bean, the applicability of in-situ assembly method will be gradually weakening and that of the construction methods such as segmental lifting, incremental launching and longitudinal moving, and vertical rotation will be more obvious with the increment of span for the continuous beam-arch composite bridge.

(2) To ensure safety for the construction, the arch rib of the long-span continuous beam-arch composite bridge can reduce the segmental lifting weight or decrease the length of incremental launching and longitudinal moving, for which the combined method of in-situ assembly + segmental lifting or in-situ assembly + incremental launching and longitudinal moving will be adopted.

(3) When the continuous beam-arch composite bridge is in the key nodes and with tight construction period, the incremental launching and longitudinal moving method or the combined method of incremental launching and longitudinal moving + segmental lifting will have very obvious advantages.

(4) With the constant improvements of the construction equipment performance and the technological equipment level for construction, it will be the development trend for the continuous beam-arch composite bridges with middle and small spans to adopt the integral erection method.

In a word, the selection of construction method for the arch rib of continuous beam-arch composite bridge can be made on the basis of superiority in the comprehensive conditions such as the engineering scale, operational environment, transport conditions, construction period, technical level and technological equipment.

(Translated by ZHENG Mingda)

**Table 1** Comparison and selection analyses of construction schemes

| Serial Nos. | Categories | Advantages | Disadvantages | Application scope | Recommended spans |
|---|---|---|---|---|---|
| 1 | In-situ assembly | Simple construction techniques, easy operation of construction and low requirements for construction equipment performance | With certain requirements for the construction site and environment and having certain impacts on road traffic or navigation of river course under the bridge;<br>With the influence of the bridge-deck width and restriction in model selection of hoisting equipment, the division of arch-rib segments is short and the construction load is liable to exceeding the limit; and with long construction periods, more operations at height and heavy workload of welding at height. | Construction loads of crane and support are within the permissible range against the bridge structure; with low demands for road traffic under the bridge and meeting the hoisting conditions; and with low demands for navigation of river course under the bridge and water depth and width of river meeting the conditions of floating crane operation. | Continuous beam-arch composite bridge with the main span being 100~150 m |
| 2 | Segmental lifting | High level of construction mechanization and technological equipment and less demand for mechanical equipment;<br>Reducing the height of construction operation, decreasing risks of safety for operations at height, and having less impact of construction on internal force of the concrete main beam | With high construction costs due to input of hoisting equipment for arch-rib segment; requiring the enhancement of the full-process observation for lifting tower and arch-rib alignment in the hoisting process with high risks in safety and more difficulties in control. | With high demands for road traffic under the bridge or for navigation of river course under the bridge; and construction method of combining in-situ assembly with segmental lifting can be adopted when the arch-bridge span is longer. | Length of arch-rib lifting being about 150 m |
| 3 | Incremental launching and longitudinal moving | Symmetrical implementation of arch-rib assembly and cantilever casting for concrete main beam can shorten the construction period prominently; and with high level of construction techniques to save the manpower costs. | With high construction costs due to input of equipment for incremental launching and longitudinal moving; exercising control over the running synchrony of four-legged longitudinal-moving trolley in the process of incremental launching and longitudinal moving, adopting temporary tie bar for force conversion, and with more difficulties for internal force control and high risks in safety. | With tight construction period and high demands for road traffic under the bridge or for navigation of river course under the bridge; and construction method of combining in-situ assembly with incremental launching and longitudinal moving can be adopted when the arch-bridge span is longer. | Length control of arch rib for incremental launching and longitudinal moving being about 150~200 m |
| 4 | Vertical rotation | Reducing the height of construction operation, decreasing risks of safety for operations at height, and having less impact of construction on internal force of the concrete main beam;<br>Reducing the demand for hoisting equipment and shortening the construction period;<br>and with high level of construction techniques to save the manpower costs. | With high construction costs due to requirement for input of vertical rotation equipment; requiring the enhancement of the full-process observation for rotation tower and arch-rib alignment in the vertical rotation process with high risks in safety and more difficulties in control. | When it is with high demands for road traffic under the bridge or for navigation of river course under the bridge, the long-span arch bridge is applicable due to the need of input with more construction costs to the rotation equipment. | Continuous beam-arch composite bridge with the main span being > 200 m |

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