

Development of the combination of vertical and horizontal swing techniques for the Dongping Bridge in Foshan (China)

Tingmin Mou, Jian Liang, Bikun Fan and Bangzhu Xie

Highway Network Planning, Survey and Design Research Institute, Sichuan Department of Transportation, Sichuan, China

ABSTRACTS: Dongping Bridge located in Foshan, Guangdong, China, is a cooperative-system bridge with steel box arch and continuous beam. Its main construction techniques, vertical rotation and the horizontal rotation construction methods, are introduced in the paper. A new technique for closing the main arch span is adopted. The main-span arch rib jointed horizontally with the low bracket is lifted up in position by the lifting tower. The balanced system consisting of the main arch, the sub arch, the boundary arch as well as the upper and lower rotation plate circles is used for the horizontal rotation construction.

1 INTRODUCTION

The Dongping Bridge, located in the south of Chancheng District of Foshan City in Guangdong Province, China, is an important bridge for the new Foshan City. The bridge crosses over the Dongping River. In order to coordinate the landscape with the traffic capacity, the arch-girder cooperation system is applied in Dongping Bridge. The general layout of the bridge is shown in Fig.1.

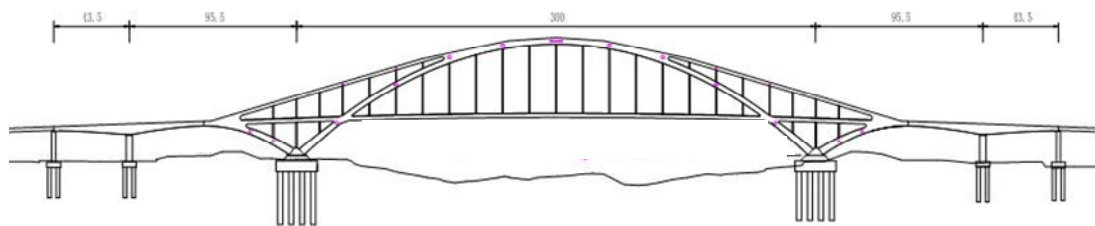


Figure 1 : General layout of the Dongping Bridge

The design load for this bridge is specified as Class I (trucks over 20tons and a trailer of 120 tons) according to the Chinese specifications. The local element is checked by City-A load codes. The bridge is totally 1322.2m long and 48.6m wide (2×15m clean wide traffic lanes and two walkways of 6m width each). The main span consists of the subarch and main arch with a span of 300m. The sub-arch rib is a combined straight and circular line type. Its height is 2m and the width 1.2m. A catenary shape and an arch axis coefficient of 1.1 were chosen for the main arch rib having a clean rise-to-span ratio of 1/4.55. The depth of the section of the arch rib is from 3.0m to 4.5m. The width of the section is 1.2m. The main rib and the sub-rib are joined near the crown to form a box section with a height of 4.0m to 7.2m. All the arch ribs are of the box-type cross sections.

The side span semi-arch located in each river bank is of parabola curve shape with a 53.2m span and a rise-to-span ratio of 1/6. The arch rib is a box-type cross section, 3.0~4.5m high and 1.2m wide. The concrete grade is C40 (Chinese code) inside the box. The PBL shear connector was adopted to make the steel box and the inner concrete work together. The vertical prop on the arch is an H-shape steel column, which has a width of 1.2m and a depth of 0.8m.

Fourteen permanent bracings are set to balance the horizontal force among every three hangers or vertical props. Concrete was poured in both the permanent bracings and the end floor beams of the side arch.

2 ROTATION CONSTRUCTION SYSTEM

There are many construction methods including the erection by vertical lifting large segments, the erection by the cableway and the rotation closure etc. Since it is busy between the two banks of the bridge, and the methods of erection by the cableway and vertical lifting rotation with large segments disturb the normal transportation inevitably, the vertical lifting rotation technique was applied to the Dongping Bridge with the following horizontal rotation without the buckles. This construction method could meet the design fundamentals such as little disturbance, a short construction period and the low cost of construction measures.

In the recent years, the horizontal swing system for large-span arches consists of a hoisting tower above the arch seat, a cable saddle assembled on the tower, a fastening cable and an anchored cable. The main arch ring becomes a self-balanced structure system by stretching the backstays at the end of the flying-bird-type span and then swinging to be closure. In Dongping Bridge, the main arch ring is comprised of main arch and sub-arches. The latter works as a “stayed cable” between the main arch rib and the side arch rib. Therefore the three arches as a self-balanced system perform the swing unit without any temporary structures such as a hoisting tower and a stayed cable. The detail of a horizontal swing unit of the half structure is shown in Fig.2.

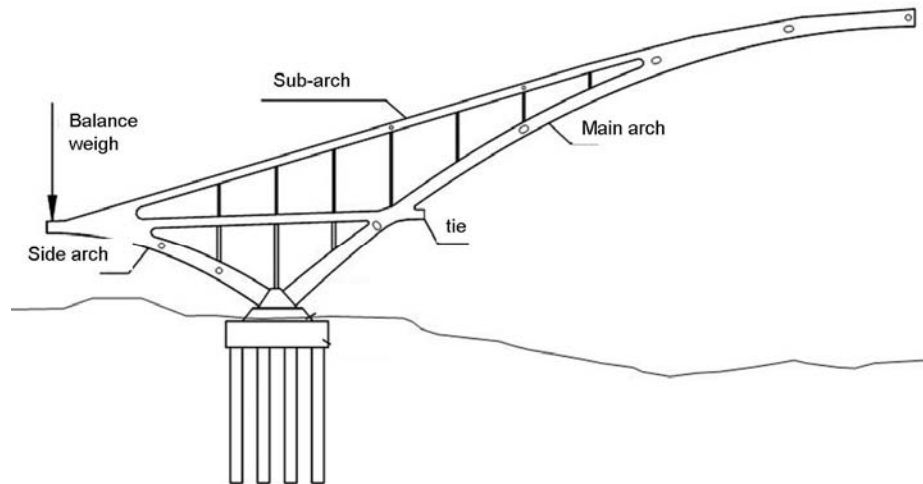


Figure 2 : Horizontal swing unit of the half structure

The local geological condition is quite poor with the thick soft soil covering and abundant ground water. If the embedded scaffolding method for the bridge was utilized, it would need a large number of brackets, cost considerable construction time and take a high risk for erection. Therefore, the method by using which the main arch was assembled in the short scaffolding and then erected in position by vertical lifting rotation technique was adopted. Compared with other flying-bird-type arch bridges, this method has the advantage of less material dissipation, fewer stayed cables and backstays, as well as a fewer lifting cables. And it also benefits from the small lifting force, as shown in Fig. 3.

3 CONSTRUCTION OF SWING STRUCTURE

3.1 Construction of vertical swing structure

3.1.1 Composition of vertical swing structure

The vertical lifting system consists of the lifting tower, the positive electrode method, free bearing of the vertical swing, lifting the stayed cables and the balanced cables of the tower.

When lifting the rib, the largest slope angle of the hanger cable was 15.3 degree and the vertical rotating angle of the arch rib was about 25 degree. The initial lifting angle and that in position were 17 and 0 degrees respectively. The largest lifting force of each hanger cable was 100t.

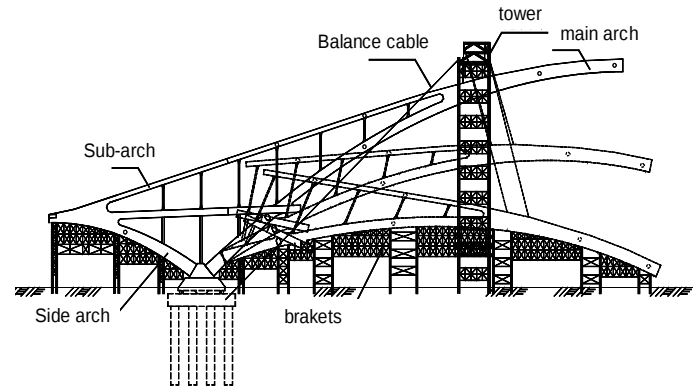


Figure 3 : Vertical swing system procedure for the Dongping Bridge

3.1.2 Lifting Tower and Balanced Cable

The lifting tower adopted a separate means where a lifting tower was used for each arch rib and had six $800 \times 14\text{mm}$ steel tubes to form the columns. In addition, at the position of 78 meters over the ground, truss was used among the three steel tubes set at each side of the tower for the sake of integrity, with a interval of 8m, as shown in Fig.4.

A tension platform for the synchronous centre-hole jack was set up on the tower head. Two hanging points were arranged on each side of the rib web. Three jacks were used to cooperate with one hanging point. The strand was made of fastening cables.

The balanced cables were set up on the top of the tower. They could adjust the horizontal component force and control the displacement of the tower head during the lifting of the arch rib. The cables' jacking end was located about 5m from the top of the lifting tower. The tension force of the balanced cables was adjusted to balance the horizontal component force when the lifting cable was in the process of swing. The horizontal displacement of the lifting tower was limited not greater than 3.8cm. For the side arch, the anchorage end of the balanced cable was on the pile cap of the main pier. The angle between the balanced cable and the horizontal plane was 41.4575 degree. The balanced cable of the mid-arch was anchored by the lug mounted on the sub-arch. The corresponding angle was 19.6028 degree. Because of the difference of the horizontal component force created by the balanced cable of the side and middle arches, the reinforced top beams with the space steel-truss structure were applied to distribute the horizontal component force of the lifting cable efficiently.

3.1.3 Hanging points of arch ribs

Under the lifting tower crane, there were two hanging points set on each side of the rib web. The hoisting rings of the hanging point and the rib web were welded together by the finger shape steel plate. There was a dowel shaft, through which the lug was linked with the strand anchorage, the plywood and the connector. The detail is shown in Fig.5 and 6.

3.1.4 Vertical swing hinge

About 1.2m space near the arch springing was used to set up the vertical swing hinge. The dowel shaft with a diameter of 250mm was designed in the center of the hinge. The axial force of the arch ring was transmitted by the externally bonded welding steel plates on the web of the arch rib during the vertical swing. Fig.7 and 8 show the constructions.

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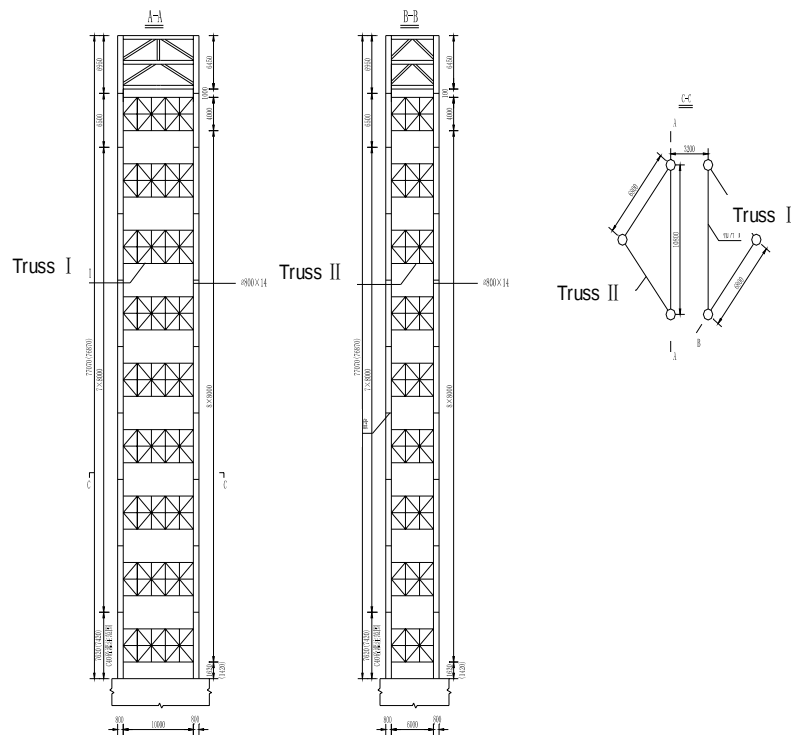


Figure 4 : The composition of the vertical rotating and lifting tower

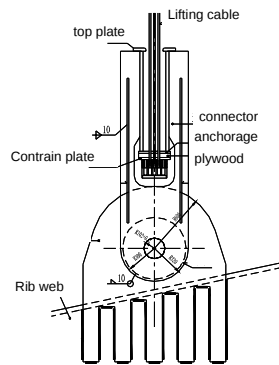


Figure 5 : construction of hanging point



Figure 6 : The hanging point

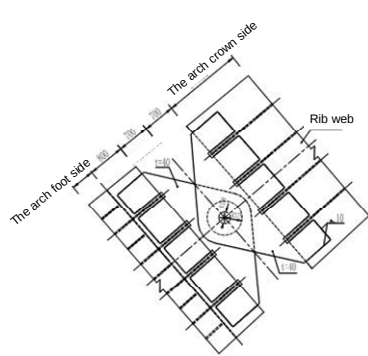


Figure 7 : Construction of vertical swing hinge



Figure 8 : The vertical swing hinge

3.2 Construction of horizontal swing structure

3.2.1 Composition of horizontal swing structure

Due to the characteristics of the landform conditions and the structures, after investigation, the closure construction of the main arch of the bridge was completed by the technique with low brackets, vertical rotation and then plane rotation. The horizontal swing angles of the Chancheng and Shunde sides are 104.6 and 180.0 degrees, respectively. The total swing weight was about 148000 kN for each side. The vertical swing system of the main arch ring comprises the side arch, main arch, upper rotary table, lower rotary table, counter weight and other members.

3.2.2 Upper rotary table

The upper rotary table consisted of the up-center-down streams arch seat, the girder jointed arch seat, the central rotation axis and the arm braces. The arch seat was a solid structure to support the arch ring and to swing the arm brace.

The cross-girder comprised of the top and bottom slabs and the web members. The top and bottom slab was made of an RC slab with 100cm thickness. The web member was a steel tube with the diameter of 457mm. Its wall was 10mm thick.

Ten arm bracings were installed in the every upper rotary table. It was divided into two categories. There were two reinforcing bracings located at both ends. Each bracing was made of three 800x14 RC columns. Three general bracings were set in the middle. Each of them was made of two 800x14 RC columns. The detail of the bracings is shown in Fig.9.

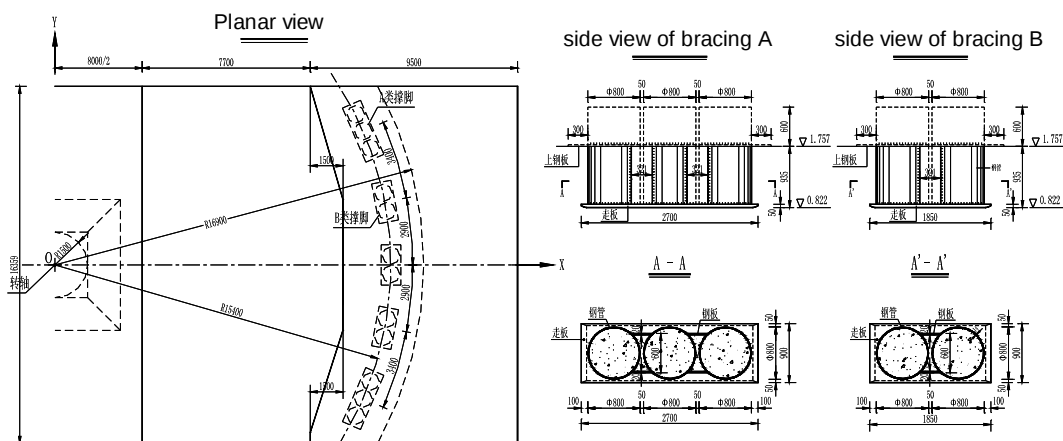


Figure 9 : The arm brace on the upper rotary table

The upper side of the arm bracings was embedded inside the upper rotary table. And the lower end was supported on the ring road of the lower rotary table. A running board was set around the ring road. The thickness of the running board was 50mm.

3.2.3 Adjusting reaction force for arm brace

The cross girder bore a negative moment as the center of an arch seat was off from the center of the arm bracing. The ring road was not flat, therefore the prestressed tendons were arranged in the top and bottom slab to join the cross girder. The tendons were used to adjust the swing weight between the arm brace and the central rotation axis, as shown in Fig.10.

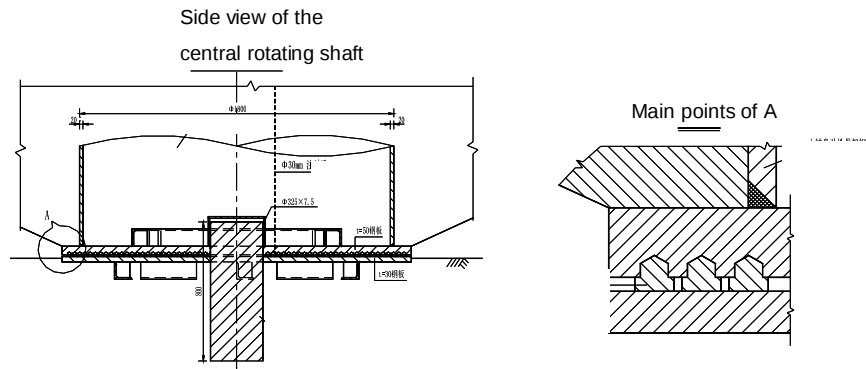


Figure 12 : The structure of the lower central rotating shaft

3.2.4.3 Dragging system of horizontal swing

The dragging system of the horizontal swing included the traveling rope of the cable crane, the pulling jack (automatic continuous tension jack), the aiding push jack and the corresponding reaction platforms. Since the horizontal swing angle was very large, the steering pulley block was added to the lower rotary table to connect the upper rotary table with only one swing to the designed position. The position of the jack was not changed as the swing.

The dynamic friction was overcome by the tension of the traction cable via the jacks. The differentials between the dynamic and static frictional coefficient was taken by the aiding push jack, as illustrated in Fig.13.

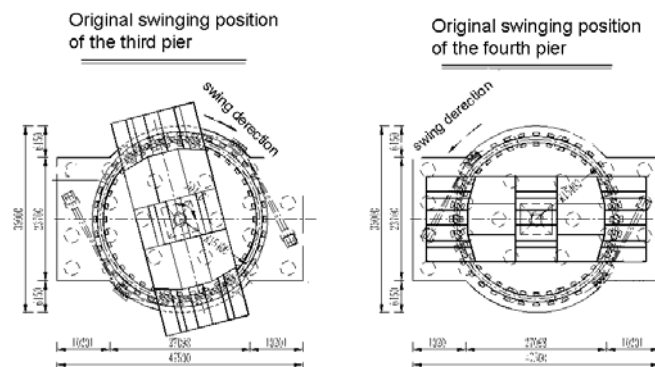


Figure 13 : The horizontal swing dragging system

According to some test results of the swing bridges in China, the value of the dynamic frictional coefficient was 3%~4%. The traction force, produced by the three beams each having 19 strands, was about 200 tons. The value of the static frictional coefficient was 6%~8%. The corresponding traction force was about 640 tons. The differentials between the dynamic and static frictional coefficient was taken by aiding push jack, which was jacked on the arm brace directly.

4 CALCULATION OF SWING CONSTRUCTION

4.1 Calculation results of the vertical swing

4.1.1 Stress results of the main arch

For the vertical swing, the maximum stress of the main arch was 107MPa. And it is found that the designed members met the requirements of the design codes.

4.1.2 Stress and displacement calculation of the hoisting tower

The overall stability critical stress of the steel tube pile was $0.897 \times [\sigma] = 179.4\text{MPa} > \sigma$

max=140MPa. And the maximum horizontal displacement of the tower was $\delta_{\max}=19.6\text{cm} \leq [\delta] = H/400 = 19.7\text{cm}$

4.1.3 Stability analysis

The stability safety factor of the main arch for the vertical swing is listed in Table 1.

Table 1 : Stability safety factor of the main arch

Work condition	linear stability safety factor				nonlinear
	first-order	second-order	third-order	instability mode(first-order)	stability
vertical position	8.8	8.84	15.7	transverse	

4.1.3.4 Dynamic behavior analysis

The structural dynamic behavior of the main arch for the vertical swing is listed in Table 2.

Table 2 : Structural dynamic behavior of the main arch

order	Vertically positioning period	
	Natural frequency	Vibration mode
1	0.1105	transverse swing of rib
2	0.4327	transverse bend of hoisting tower
3	0.5179	vertical bend of rib
4	0.5259	transverse twisting of rib
5	1.0016	longitudinal buckling of rib hoisting tower
6	1.0540	antisymmetrical transverse twisting of rib
7	1.2713	longitudinal twisting of hoisting tower
8	1.2925	longitudinal buckling of rib
9	1.3270	transverse bend of rib
10	1.5444	transverse bend of rib

4.1.3.5 Stability calculation against wind

The critical wind-speed calculation of the vertical swing construction showed that the proof wind-speed causing flutter vibrations was 49.3m/s, which was less than the critical wind-speed 122.6m/s. Thus the gradation of stability against wind is II.

In the stage of the vertical swing construction, all the linear stability safety factors were less than 4.0 and met the requirements by the codes. The dynamic calculation also showed that the wind-resistance stability of the vertical swing system was adequate for the safe structural construction, although the transverse wind-resistance of the arch rib and cable tower behaved so weak.

4.2 CALCULATION RESULTS OF THE HORIZONTAL SWING

4.2.1 In-plane static force

The structural calculation showed that the nominal stress of the primary members were less than 100MPa, meeting the strength requirements by the codes.

4.2.2 Stability analysis of the maximum cantilever stage

Table 3 shows the stability safety factor of the maximum cantilever stage (before the closure of the horizontal swing). The results demonstrate that in the maximum cantilever stage, the first-order stability safety factor was larger than 4.0, satisfying the requirements of the relevant codes.

Table 3 : Stability safety factor of the maximum cantilever stage

Work condition	linear stability safety factor			
	first order	second order	third order	instability mode(first-order)
the maximum cantilever	7.8	8.0	9.8	transverse

4.2.3 Dynamic behavior analysis of the maximum cantilever stage

The structural dynamic behaviors in the maximum cantilever stage are given by Table 4.

Table 4 : Structural dynamic behaviors of the maximum cantilever stage

order	Natural frequency	Vibration mode
1	0.2269	first-order transverse bend
2	0.39096	first-order longitudinal buckling
3	0.53798	first-order twisting
4	0.69765	Transverse torsional-flexural
5	0.76295	second-order transverse bend
6	0.87931	second-order vertical bend
7	1.2764	second-order twisting
8	1.3856	third-order transverse bend
9	1.4418	reverse vertical bending of the three ribs
10	1.5645	sub-arch transverse bend

In the maximum cantilever stage, the critical wind-speed calculation showed that the proof wind-speed causing flutter vibrations of the main arch was 49.3m/s. It was less than the critical wind-speed of 141.6m/s. And it also showed that the gradation of stability against wind is II.

4.2.4 Structural stability of the horizontal swing

The stability safety factor K was controlled to be greater than 1.5. The eccentric value (e) of the weight of the rotation part was 0.1 to 0.2, which came from the eccentricity off the center of the shaft. The calculation assumptions are listed as follows:

- (1) Wind pressure: $F_w=800\text{Pa}$;
 - (2) The unit weight of reinforced concrete and plain concrete were 25 and 23 kN/m³, respectively;
 - (3) The welding weight is counted by 1.0% of the weight of the steel structure.
- Through calculation, we have:
- (1) the longitudinal stability safety factor of 1.8 (considering the wind force);
 - (2) the transverse stability safety factor is 2.1(considering the wind force);
 - (3) the eccentric value of rotation system $e=3.4\text{cm}$.

4.2.5 Traction forces

According to the calculation, the weight of the shaft and ring road leg was distributed as 37% to the shaft and 63% to the ring road, respectively.

- (1) Traction force of the shaft frictional resistance : $T_1 = (R \times N \times \mu) / D$
where the traction force diameter $D=33.8\text{m}$; the weight transferred to the shaft $148000\text{kN} \times 37\%=54760\text{kN}$; and the frictional coefficient $\mu_{\text{static}}=0.07$, $\mu_{\text{dynamic}}=0.02$;
- (2) Traction force due to the drag between the arm brace and ring road:
Rotation weight: $N=148000\text{kN} \times 31.5\%$, eccentric value: $e=30.8\text{m}$; and the traction force due to the drag between the arm brace and ring road is $T_2=2974\text{kN}$;
- (3) Total traction force: $T=2 \times T_1 + T_2=3201\text{kN}$.

5 MAIN CONSTRUCTION PROCEDURES

5.1 Construction procedures of the vertical swing method

The construction sequence is shown as follows:

Erecting and assembling the horizontal scaffolding for the main arch according to the requirement of the designed vertical angle and the initial designed elevation respectively; then placing the scaffolding on the steel pipe pile foundations.

Lifting the arch rib segments by the crane ship, rotating them in position and then assembling the arch rib.

At the same time of erecting the scaffolding of the main arch and installing the lifting tower, filling the side-span arch rib and end cross girder with concrete, erecting side-span vertical props, sub-arch and tied box, installing and pouring part of deck slab.

Installing the lifting tower, erecting the cross beam and the platform to the tower head, stretching the balanced cable of the lifting tower, installing and lifting the jack.

Stretching the hanger cables by the hydraulic synchronization jack and then swinging the cable

After the vertical swing in place basically, taking the joint near $L/8$ of the span as a control point to adjust the arch axis shape for the accurate closure of the sub-arch and tied box

Rotating the sub-arch and tied box to their place vertically, readjusting the arch ring elevation with the fastening cable to the design value accurately, consolidating the vertical swing hinge and closure interface, removing parts of the scaffoldings set on the side-span end, distributing the counterweight(about 650 metric tons) according to the design requirements. Then, relaxing the tensioning force of the fastening cable step by step to form the horizontal swing system finally for swing.

5.2 Construction procedures of the horizontal swing method

Fabricating the rotation system for the upper and lower rotary tables and so on.

Assembling the main rib and side rib in a low position

Swinging vertically the main arch and the counter weight located at the side span.

Checking the rotation system and testing the rotation.

Consolidating the arch support with the main rib and side rib

Arranging the horizontal traction system and swinging the arch

Compelling the closure in the mid-span after adjusting the absolute elevation.

Assembling the closure segment in mid-span.

6 NEW TECHNICAL DEVELOPMENT OF THE SWING METHOD

Based on the mature swing technology and the innovation practice on the combination of the vertical and horizontal swing method, a new construction technique has been developed in this paper, as described as follows.

6.1 Advance on the vertical swing method

(1) Hydraulic synchronization lifting technique is applied as vertical swing power. It provides a technical protection to accurately and uniformly lift the cable tension synchronously

and then successfully finish the vertical swing;

(2) Adjust the linear shape of the arch rib by the hoisting power. In this new method, elevate the arch rib to a certain height previously, and then set a pivot on $1/8L$ the span of arch rib in both sides symmetrically, finally relax the lifting cable force to conform the shape to the designed one;

(3) The lattice columns with a triangle plane layout are used as a lifting tower. The application can not only ensure the stiffness and stability of the hoist tower, but also reduce the quantities;

(4) The arch rib webs and the ears of the hoist tower are connected by the finger joint. The rotation hinge pins are placed on the ears to meet the displacement produced by the rotation;

(5) The horizontal component force of the lifting cable is overcome because of the self-balance system composed of the balanced tail cable of the lifting tower, lower rotary table (pile cap) and side arch rib. This procedure reduces the construction cost;

(6) The vertical swing weight is 3,000 metric tons. It is one of the largest construction weight in China;

(7) The temporary material for the vertical swing is listed as: 63 tons of strand, 2144 tons of steels and 1489 m³ of concrete. The direct cost is 6,600,8009 chinese yuan (including the recyclable steels).

6.2 *Advances on the horizontal swing method*

(1) The RC composite structure is used among the bases of the top three arch ribs. Then, the transverse steel strands are prestressed in order to reduce the consumption of construction materials and, at the same time, to improve the total rigidity of the bridge;

(2) The ring road support system with a larger diameter is applied as a rotary table for the rotation system, which greatly improves the rotation stability;

(3) The hydraulic synchronous tension technology is used as the rotation power, which provides technical assurance on synchronism and homogeneity for both the left and right sides;

(4) Take advantage of the structure subtly by using the self-balance system composed of main arch, sub-arch and side arch. It not only saves the material cost, the procedures of the installation, and the removal of the fastening cable and fastening tower, but also simplifies the construction of the anchorage and fastening point;

(5) The horizontal swing weight is 14,800 tones. According to the statistics it is the largest weight for the counterweight horizontal swing at home and abroad recently;

(6) The construction cost is low. The temporary material for the horizontal swing was counted as 52 tons of strands, 488 tons of steels and 2063 m³ concrete. The direct cost was estimated as 3,606,000 chinese yuan;

(7) The combination of the vertical and horizontal swing method is applied for the main arch construction. The practice of innovational construction process for this bridge shows that the new technique has many advantages which include high degree of safety, obviously technical and economic benefits and greatly application value.