Design and static analysis of the Taizhou Yangtze River Bridge, China

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The Taizhou Yangtze River Bridge in China is a triple-pylon suspension bridge with double main spans of 1080 m; it is the world's first triple-pylon suspension bridge with double main spans larger than 1000 m. This paper presents the general design feature and innovation, global static analysis and construction of the main channel bridge, including the introduction of the general behaviour of a triple-pylon suspension bridge, the foundation and block of anchorages, foundation and shaft of pylons, steel box girder, main cable, cable band, main cable saddle, splay saddle, as well as the friction factor experiment between the main cable and main saddle.

Notation

F_{Ed1}	maximum cable force on either side of the middle pylon
F_{Ed2}	minimum cable force on either side of the middle pylon
K	slipping resistance factor of the main cable strands
α_s	angle in radians of the cable passing over the main saddle
μ	frictional factor between main cable and saddle trough

1. Introduction

The Taizhou Yangtze River Bridge, located 66 km away from the upstream Runyang Yangtze River Bridge and 57 km away from the downstream Jiangyin River Bridge, links the cities of Taizhou, Zhengjiang and Changzhou in China. The total width of the Yangtze River at the bridge site is about 2100 m. The profile of the river bed at the bridge site is W-shaped. The deep channel is more inclined towards one bank with the maximum water depth varying from 17 m to 30 m. Both banks of the river are typical middle and lower Yangtze River alluvial plains with soft soil and thick cover layer. The bedrock is located more than 190 m beneath ground level.

There are many port engineering and ship anchorages around the bridge location. To reduce the impact of bridge construction on the environment, keep flood discharge to a minimum, maintain the sustainable development and facilitate navigation, the bridge adopted a triple-pylon suspension with double main spans and a main cable span arrangement of 390 + 1080 + 1080 + 390 m. The steel box girder is suspended in the double main spans. The solution reduces the obstacle to the water current and ensures the original width of the main channel. The conventional double-pylon suspension bridge has a main span twice that of the triple-pylon bridge. Compared with this, the triple-pylon suspension bridge halves the horizontal force of the main cable, so the amount of anchorage and main cable is reduced significantly. The bridge includes the northern approach bridge, Jiajiang Bridge, main channel bridge and southern approach bridge. In this paper, only the main channel bridge is described – the key part of the project.

2. Design criteria

The key design criteria adopted for the bridge include

- carriage lanes: six lanes in the short-term and eight lanes in the long-term
- bridge width: 33.0 m (excluding cable anchorage zone width)
- design speed: 100 km/h

- live load standard: Chinese highway load class I
- navigation clearance: the width and height of the navigational channel should not be less than 760 m and 50 m, respectively
- design wind speed: the average maximum wind speed within 10 min is 31.83 m/s with 100-year return period and 10 m above the mean sea level
- according to the site earthquake safety assessment report, which was completed by the seismic department of the Jiangsu Province, the ground surface horizontal acceleration is 0.159g and with a return period of 100 years and an exceedance probability of 10%, and 0.207g with a return period of 100 years and an exceedance probability of 4%, respectively
- the ship collision force of the main pylon is 116 MN and 58 MN in the transverse and longitudinal direction, respectively.

3. Design standards

In accordance with the requirement of the client, the preliminary and detailed design of the permanent works were carried out following Chinese Specifications for Highway Steel Bridges (hereafter in short CSHSB). However, the steel orthotropic deck design of the highway bridge was not covered, so BS EN 1993-2 (CEN, 2005) and German national annex (DIN, 2003) were adopted in the bridge design for the supplement.

4. Design of the main bridge

4.1 General design of main bridge

Based on the construction conditions at the bridge site, both side pylons are set on the river bank, whereas the middle pylon is set in the middle of the river at a water depth about 18 m under ordinary water level. Both anchorages are designed on the bank. The main bridge is located on the straight line in plan. The main bridge is a steel box girder suspension bridge

with double main spans of 1080 m (Figure 1); the main cable arrangement is 390 + 1080 + 1080 + 390 m.

The ratio of cable sag to span is a key parameter of the general design of a large-span suspension bridge, which affects the structural rigidity, material quantities and the control point of main cable. It is determined by the balance of the global rigidity, dead load and construction cost. The ratio of cable sag to span was studied from 1/7 to 1/13. The static analysis result determines that, under live load, the slip resistance safety factor between the main cable and the main saddle increases with increasing of sag-to-span ratio, but the extent is very limited. In addition, the deflection of the main girder increases very rapidly with the increasing sag-to-span ratio. With the increasing ratio of sag-to-span, the critical flutter wind velocity increases, but the extent is very limited. Allowing for the static and dynamic structural behaviour and the quantities of construction materials, the sag-to-span ratio finally adopts 1/9, which ensures the vertical global stiffness and the slippery resistance factor between the main cable and saddle.

The global articulation is shown in Figure 2. Vertical bearings are installed at the bottom cross-beam of the side pylon; traverse wind bearings are installed on the inner side of all pylon shafts; longitudinal viscous dampers are installed on the side pylons; longitudinal cables are provided at the middle pylon cross-beam, which restrain the longitudinal displacement of main girder under traffic loading and earthquake loading. The approach bridge adopts a pre-stressed continuous box girder with a main span of 70 m, which is not included in the paper.

4.2 Pylon and foundation

4.2.1 Middle pylon and foundation

Compared with the conventional double pylon suspension bridge, the triple-ylon suspension shows some different structural behaviours.

Figure 1. The general arrangement of the main bridge (unit: m)

Figure 2. Global articulation of the bridge (unit: m)

- (a) When one of the main spans is loaded by a full live load, but another main span is empty, the middle pylon should provide the restraint to the main cable, so the horizontal component of main cable force will change significantly.
- (b) The main cable is anchored on the middle pylon; the longitudinal stiffness of the middle pylon is weaker than that of conventional double-pylon suspension bridge, in which the main cable is anchored on side anchorage, so the global vertical stiffness of the triple-pylon suspension bridge is weaker than the conventional double-pylon suspension bridge. In order to enhance the global vertical stiffness of the triple-pylon suspension bridge, the middle pylon often adopts a rigid or semi-rigid configuration, such as triangulation or inverted Y-type in the longitudinal direction. Therefore, the necessary longitudinal restraint of the pylon top is achieved by the large bending stiffness of triangulation or the inverted Y pylon structure. The solution can enhance the global vertical stiffness of the triple-pylon suspension bridge. The main disadvantage of applying triangular pylon structures is that this will induce a large longitudinal bending moment in the middle pylon shaft and foundation.

If the full rigid middle pylon is adopted, the scale of foundation will be very large because the bending moment under live load is very large. The horizontal difference of the main cable force of the middle pylon will be very large when one main span is fully loaded, and it will reduce the slippery resistance safety margin of the main cable on the saddle trough. Therefore a longitudinal semi-rigid steel pylon, with the inverted Y-type configuration in the longitudinal direction and transversely portal frame steel pylon, was designed for the middle pylon, as shown in Figure 3.

The semi-rigid middle pylon can ensure the global vertical stiffness of the bridge, and control the difference of the horizontal component of the main cable force, and ensure the slippery resistance between the main cable and middle saddle.

In the longitudinal direction, from the top to bottom, the middle pylon is divided into three sections: the upper linear shaft, the middle transition shaft and the bottom inclined pylon shaft. The middle transition segment is 25.775 m long. The pylon shafts are connected by two cross-beams. The cross-section of the upper pylon shaft is a single box with multiple cells and four corner chambers with a dimension of 0.6 m × 0.6 m to reduce the vortex vibration forces of wind. The cross-section of the middle pylon shaft is shown in Figure 4.

The middle pylon uses grade Q370qD and Q420qD steel, which is required to have yield strength of 370 MPa and 420 MPa, respectively. Both Q370qD and Q420qD are required to have Charpy impact energy of 41 J at a temperature of -20°C. The transverse dimension of the cross-section of the pylon shaft remains 5.0 m. The longitudinal dimension of the cross-section of the pylon shaft is variable.

The thickness of the flange and web of the pylon shaft varies from 50 mm to 60 mm and from 44 mm to 60 mm, respectively. All stiffeners of the pylon adopt bulb cross-section, with thickness 40 mm and 48 mm. The diaphragm spacing of the pylon shaft is 3 m or 2.5 m. The ordinary diaphragm is 20 mm thick.

The pylon shaft was divided into 13 segments, 10.775 m to 20.000 m long. The segment T0, which connected with the concrete cap of the caisson and embedded in concrete, was the

Figure 3. General layout of middle pylon (unit: mm): (a) front view; (b) side view; (c) segment length and weight

Figure 4. The cross-section of middle pylon shaft (unit: mm)

bored pile foundation were listed in Table 1. According to Table 1, the caisson foundation was accepted by the client. The pile foundation consists of 118 no. friction piles of diameter 2.8 m and of 106.0 m depth; the rectangle caisson with chamber had a plan dimension of 58.2 m $\times$ 44.1 m and a depth of 76.00 m.

According to the construction duration and the cost, the open suction caisson foundation was approved by the client. This was fitted with a cutting bottom edge facilitating sinking through sands by suction the sand in the honeycomb of large pipes. The open caisson used a rectangle cross-section with a plan dimension of 44 m and 60 m in the transverse and longitudinal direction, respectively. The total depth of the caisson was 76 m, including 32 m concrete caisson and 44 m steel-shelled concrete caisson. The sub-sealing concrete was 8 m deep, as shown in Figure 6. The total quantity of steel, concrete and reinforcement of the middle pylon caisson foundation was 4400 t, 94 934.0 m³ and 3666.4 t, respectively.

Alternatives of the caisson and bored pile foundation for the middle pylon were studied in the preliminary design stage. The material quantities and construction duration of caisson and

Both side pylons used a conventional reinforced concrete portal frame structure, and the foundation of the side pylons adopted a bored friction pile foundation. The pylon foundation at Taizhou side consisted of 46 no. piles with a diameter of

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Table 1. Bill of material quantities and construction duration of middle pylon foundation alternatives

duct and electrical central control panel and humidity control devices. The force of the main cable strand was transferred to the concrete block by post-tension tendons.

4.4 Steel box girder

The steel box girder was 39.1 m wide and 3.5 m deep, adopting a flat streamlined box with good aerodynamic configuration (Figure 7). The double crossfall was 2%. The double inner and outer inclined webs divided the steel box into three cells.

Allowing for the transportation capacity, the main girder was divided into 136 segments including 128 no. of standard segments and eight particular segments. The standard segment was 16.0 m long. The total weight of the standard segment was 215 t and maximum weight of the segment was 230 t. The top plate and bottom plate thickness of the standard segment was 16 mm and 10 mm, respectively.

In order to enhance the fatigue life of the steel orthotropic deck and improve the service performance of the deck pavement, the steel deck beneath the heavy carriageway in each direction was made of 16 mm thick plate and stiffened by 8 mm thick trapezoidal stiffener, whereas the rest of the steel deck plate was 14 mm thick and stiffened by 6 mm thick trapezoidal stiffener.

The bottom and top plate stiffener adopted a trapezoidal stiffener. The height and spacing of the top flange longitudinal stiffener were 280 mm and 600 mm, respectively. The structural

detail of the orthotropic deck including the dimensions of the top plate and longitudinal stiffener, minimum stiffness of longitudinal stiffeners, the connection of stiffener to deck plate and to the cross-beam, met all requirements of BS EN 1993-2 with the German national annex (Sedlacek *et al.*, 2004).

The height, spacing and thickness of the bottom flange longitudinal stiffener were 250 mm, 1000 mm and 6 mm respectively. The spacing of the cross beams was 3.2 m. Both inclined top and bottom webs were 10 mm thick with flat stiffeners. The maintenance walk was located on the cantilever.

The site splices of the steel box girder were welded. The total weight of the steel box girder was 33 681.9 t with unit weight of 414 kg/m². The grade Q345qD was adopted for the steel box girder, which was required to have a yield strength of 345 MPa. The grade Q370qD was adopted for the hanger connection with the steel box girder anchorage, which was required to have a yield strength of 370 MPa. Both Q345qD and Q370qD were required to have 41 J impact test energy at a temperature of -20°C.

The steel orthotropic deck system was analysed by the Peklian–Esslinger method (Wolchuk, 1963). The stresses of the deck system are presented in Table 2.

The hanger was connected with the box girder by a pin. The local stresses of anchorage zone were analysed by the finite-element model.

Figure 7. Typical cross-section of standard segment of steel box girder (unit: mm)

Item location	Steel deck plate		Bottom of stiffener		Middle span of cross beam	
	Support	Middle span	Support	Middle span	Top flange	Bottom flange
Stress: MPa	+4.3	−36.0	−34.2	+105.0	−46.9	+45.0
Note	Tension stress is +					

Table 2. Stresses of steel orthotropic deck

4.5 Main cable, hanger and cable band

The main bridge had two main cables, which used prefabricated parallel wire strand (PPWS). Each strand consisted of 91 no. of steel wire with a diameter of 5.20 mm and a minimum ultimate tensile strength of 1670 MPa. Each main cable had 169 steel strands. The length and weight of each strand was approximately 3100 m and 47 t, respectively. The main cables were protected with S-wire wrapping and a cable dehumidification protection system.

The S-wire consisted of ‘flat’, interlocking wire for the outer transverse wrapping of main cables. The S-wire wrapping had a S-shaped cross-section of 7 × 3.0 mm (Figure 8), and was wrapped around a cable in a spiral format. The interlocking mechanism of the S-wire minimised the gaps between successive loops of the wrapping wire. Therefore this method could minimise the amount of moisture penetrating into the cable after construction.

The cross-section area of the main cable was 0.3266 m². The main spacing ratio, based on both home and abroad long-span suspension bridges, was 18% at the cable band and 20% elsewhere; the associated diameter of the main cable was 712 mm and 721 mm, respectively.

All hangers were considered for the hanger replacement load case. The objective of hanger replacement is to satisfy the client

that any such future scenario could be undertaken under sustainable conditions involving limited traffic disruption and without the need for full closures. The total weight of the main cable, hanger was 15 929 t and 447.2 t, respectively.

The hanger used a prefabricated parallel wire strand, which included two types: (a) the particular hanger, located adjacent to the centre pylon with three prefabricated parallel wire strands and (b) the common hangers, located at the other locations, with double parallel wire strands. Each prefabricated parallel wire strand consisted of 87 no. of steel wires with a diameter of 5.20 mm. The minimum ultimate tensile strength of hanger steel wire was 1670 MPa.

The hanger connected with the steel box girder and cable band through fork plate and pin. The cable band consisted of upper and lower mating pairs, and the two halves were connected with high-strength waisted bolts to avoid the bolt breaking at the thread. The two halves were sealed with waterproof rubber strips. The cable band were made of ZG20SiMn cast steel, with wall thickness varying from 35 mm to 45 mm. The configuration of hanger and cable band are shown in Figure 9.

4.6 Main saddle and splay saddle

The main saddle and splay saddle were made of cast and welded steel structure. The head of the saddle was made of cast

Figure 8. Interlocking wrapping S-wire (unit: mm)

Figure 9. Configuration of hanger

steel owing to the complex configuration, and the body of saddle was made of welded steel plates. A stainless sliding plate was embedded on the pylon head, to provide sliding during the cable and steel box girder installation stages.

To facilitate the fabrication and installation of the main saddle, it was divided into two parts in the longitudinal direction, which were fabricated and installed separately. The site splice was connected by high-strength bolts, as shown in Figure 10. In order to increase the friction force between the main cable strands and saddle trough, vertical plates were provided to form channels in the saddle. After installation and adjustment of the main cable, the gaps between the plates were filled with zinc blocks, and then the side wall of the saddle trough was compressed against the cable through high-strength bolts. The weight of the middle pylon and side pylon saddle was about 94.8 t and 132.8 t, respectively.

The splay saddle used a hinge at the bottom so it could rotate around the hinge. The head trough was made of cast steel, and the saddle body was made of welded steel plates. The weight of the splay saddle was 102.7 t.

5. Global static analysis

5.1 Global static analysis

A three-dimensional non-linear finite-element model was adopted in the global static and dynamic analysis. The pylon and steel box girder were modelled as six-degree freedom beam

Figure 10. General configuration of main saddle on middle pylon
(unit: mm)

elements, and the main cable and hanger were modelled as three-degree freedom bar elements. The traffic live load adopted eight lanes of Chinese highway bridge design load. The design live load included a uniformly distributed load and a concentrate load. The magnitude of the uniformly distributed load and concentrate load was 39.06 kN/m and 1339 kN, respectively.

The bending moment of steel box girder under traffic load is shown in Figure 11. As shown in Figure 11, the maximum vertical deflection was 4.37 m. The ratio of maximum deflection to main span was 1/253.5, which indicated that the bridge was rigid. The limitation of the ratio of maximum deflection to main span in CSHSB was 1/250.

With the combination of dead load, traffic load and the lower temperature, the maximum main cable force was 210 909 kN, which was located at both sides of the middle pylon. CSHSB adopted an allowable stress method; the cable-related safety factor was 2.5 and 3.0 for the hanger. The factor for the main cable adopted in BS EN 1993-1-11 (CEN, 2006) was about 2.2, which took into consideration the live load and dead load with the combination factor of about 1.35 to 1.45. This was about 15% smaller than the Chinese code. The safety factor of main cable according to CSHSB is shown in Table 3.

5.2 Slip resistance stability of the main cable on the middle pylon saddle

The friction factor between the middle pylon cable saddle groove and the main cable is not described in the Chinese bridge design code and BS EN 1993-1-11 (CEN, 2006). In order to ensure the safety of the bridge, the friction factor was tested by Southwest Jiaotong University, China. The test included two groups, each group included three specimens.

One group was tested by 10 strands, and the other group was tested by a single strand. A photograph of 10 strands is shown in Figure 12.

The three specimens of the 10 strands test result are 0.521, 0.535 and 0.535, respectively. The three specimens of single strand test result are 0.302, 0.326 and 0.391, respectively. The friction factor tested by multiple strands was much bigger than those of the single strand because the top strands compress the bottom strands. The bridge was the first triple-pylon suspension bridge with a main span larger than 1000 m. The coefficient adopted in the design was 0.2. So the slipping resistance factor of the main cable strands on the middle pylon saddle was calculated by the Euler-Eytelwein formula (Gross *et al.*, 2009)

$$K = \frac{\mu \times \alpha_s}{\ln \left(\frac{F_{Ed1}}{F_{Ed2}} \right)} = \frac{0.20 \times 0.871}{\ln \left(\frac{202\,232.6}{190\,325.8} \right)} = 2.897$$

In which F_{Ed1} and F_{Ed2} are the design values of the maximum and minimum cable force on either side of the middle pylon; μ is the frictional factor between main cable and saddle trough; α_s is the angle in radians of the cable passing over the main saddle, $\alpha_s = 2 \times 25.1833^\circ = 0.879$ rad. The minimum slipping resistance factor K in CSHSB and BS EN 1993-1-11 was 2.0 and 1.65, respectively. As shown in the preceding formula, the minimum slipping resistance factor K met the requirement of CSHSB and BS EN 1993-1-11 (CEN, 2006).

6. Construction introduction of the main bridge

The side pylons were located on the bank, so the pile foundation was constructed with a rotated bored machine

Figure 11. The bending moment of steel girder under traffic load unit (kN m)

Location and item	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Axial force: kN	203 846	207 872	207 889	191 027	210 909	210 909	191 027	207 889	207 872	203 846
Safety factor	2.68	2.62	2.62	2.86	2.59	2.59	2.86	2.62	2.62	2.68
Location description

Table 3. Safety factor of main cable

directly with slurry. The steel shell caisson of the middle pylon foundation was fabricated in the workshop, transported to the site, and installed by a floating crane. The concrete was then cast in situ between the double wall of steel shells. A water-jet was used to wash the soil of the riverbed, so the caisson could penetrate in the sand by its self-weight (Figure 13). The depth of the caisson was extended segment by segment and then sunk down under the water step by step, until the caisson reached its design level. Then the bottom was sealed with concrete deposited underwater. Then the concrete filling was casted under water.

The concrete was supplied from both river banks. Two batch concrete plants were set up on both sides. The side pylon was constructed by a hydraulic self-climbing formwork in which a typical segment was 6 m long, and an ordinary cycle was achieved in 7 days.

The segments T0 to T7 and T8 to T28 of middle pylon were constructed by a floating crane and pylon crane, respectively. The longitudinal and transverse segments must be perpendicular to within an allowance of 1/10 000.

The main cable was constructed by a catwalk and traction system. The catwalk system consists upstream catwalk, downstream catwalk and several transverse path walk. The catwalk

was located beneath the associated main cable, and the cable strand traction system adopted a double-way system. The sag of each cable strand was adjusted between 0 and 3 am in the morning, because the temperature is very steady in this period.

The erection sequence of steel box girder was installed from the middle of the double middle span to the middle pylon and side pylons symmetrically. Two enclosure segments were set near the side pylons and middle pylon, respectively. Four main cable-supported cranes were used for the installation of the segments of the steel box girder, which can crawl along the middle span main cables. For each segment erection and site welding, the quickest cycle was achieved in 7 days. The Taizhou and Yangzhong side pylon main saddle was preset with a longitudinal deviation distance of 2.465 m and 2.410 m towards the bank, respectively. The splay saddle of Taizhou and Yangzhong side were also preset with an angle of 0.0591° and 0.0562° towards the bank, respectively.

The cable and deck construction was continuously monitored by the on-site technical team to ensure that the required final design vertical and horizontal profiles were achieved. The segment erection level was continuously adjusted to take into account the difference between theoretical analysis deflection and site measurements.

Figure 12. Slipping resistance test

Figure 13. Caisson sunk by suction of the sand and soft clay

Figure 14. Photograph of nearly completed main bridge

The construction of the bridge commenced on 26 December 2007. The construction duration of the middle pylon foundation and pylon shaft was 15 months and 14 months, respectively. The construction duration of main cable and steel box girder erection was 4 months and 8 months, respectively.

7. Conclusions

The bridge was opened to traffic on 25 November 2012. The nearly completed bridge is shown in Figure 14. The design and construction of the bridge were completed on time and on budget as a result of the excellent cooperation between the client, designer, contractors, sub-contractors and site supervision consultants.

The fast progress of the construction of the project benefited from a viable design concept and solutions, which changed very little during the construction. The considerable investment made by the contractor in additional ground investigation and scientific research and test enabled the development of a safe and efficient substructure and superstructure design.

The bridge has been well recognised by Jiangsu Province government and Ministry of Communication of China, who regard the construction of the first major triple-pylon large-span suspension bridge in the world as a symbol of bridge technology progress.

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