General design of Sutong Bridge

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Abstract: The main span of Sutong Bridge is a double-pylon, double-plane cable-stayed bridge with steel box girder, which has the world's longest central span of 1 088 m within cable-stayed bridges. To overcome problems caused by severe meteorological conditions, perplexing hydrological conditions, deep buried bedrock and higher navigation level, many new technics and methods were created. Keys including structural system, steel box girder, stayed cable, tower, pier, tower foundation, collision avoidance system, wind-resistance, seismic-resistance, structural nonlinear response and structural static stability were presented individually in this paper.
Key words: cable-stayed bridge; structural system; steel box girder; stayed cable; tower; tower foundation

1 Project outline

Sutong Yangtze River Highway Bridge (hereinafter referred to "Sutong Bridge") is located close to the estuary of the Yangtze River near Nantong in the southeast of Jiangsu Province. The bridge is about 82 km east of Jiangyin Yangtze River Highway Bridge and 108 km west of the river estuary. It is an important part to cross the Yangtze River for the national trunk highway.

Sutong Bridge project has a total length of 32.4 km, mainly consists of three parts: the 15.1 km north connection line, 8.2 km bridge across river, and the 9.2 km south connection line. Layout of bridge across river is [(12 × 30) + 3 × (11 × 50) + (50 + 9 × 75) + (10 × 75)] m prestressed concrete continuous bridge + (2 × 100 + 300 + 1 088 + 300 + 2 × 100) m steel box cable-stayed bridge + (5 × 75) m prestressed concrete continuous bridge + (140 + 268 + 140) m prestressed concrete continuous rigid frame bridge + 3 × (11 × 50) m prestressed concrete continuous bridge.

The main part of Sutong Bridge is a cable-stayed bridge of double pylons and double cable planes, with a main span of 1 088 m. This is the first cable-stayed bridge over 1 000 m in the world. The super-long span and stayed cables, super-high towers, as well as super-large foundations in deep water are all world records. The span configuration of the bridge is 100 + 100 + 300 + 1 088 + 300 + 100 + 100 = 2 088 m, as shown in Fig. 1[1-3].

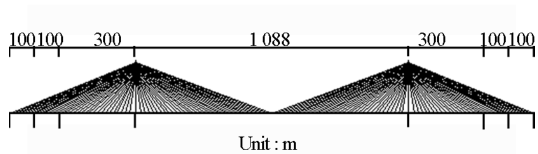

Fig. 1 General layout of main bridge

2 Technical standard

According to local condition and traffic prediction, following technical standards are adopted (only main items):

1) Highway standard: 6 traffic lanes in dual direction;

2) Design traffic speed: 100 km/h;

3) Design width: 34 m;

4) Design seismic intensity: level VI;

5) Reference wind speed: at 10 m height with 100 years return period is 38.9 m/s. For the construction period, the verification shall be based on a reference wind speed with 30 years return period being 35.4 m/s. The maximum wind speed where the wind load is combined with traffic load is 25 m/s[3].

3 Characters and difficulties

Sutong Bridge is located close to the estuary of the Yangtze River. According to construction condition, over 1 000 m cable-stayed bridge is adopted. Both local condition and design and construction technology have many characters and difficulties.

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3.1 Characters and difficulties of construction condition

Severe climate, complicated hydrology, deep-buried bedrock and high navigation level are the main characters and difficulties.

1) Severe climate: there are 179 days when wind speed is over level VI per year. On average, there are 120 rainy days and 31 foggy days per year. Reference wind speed is 38.9 m/s. Threatened by typhoon and monsoon.

2) Complicated hydrology: the river width is 6 km. There are two tides per day, and tidal range is 2 ~ 4 m. Wave height is 1 ~ 3 m. Depth of water at piers is 35 m. Flow velocity is over 2.0 m/s, with maximum velocity of 4.47 m/s.

3) Deep buried bedrock: bedrock is deeply buried under 300 m from mud line. Riverbed is prone to scour because of soft ground. Average scour depth is 25 m.

4) High navigation level: the navigation clear headway shall be no less than 62 m, and net width shall be no less than 891 m. Average passed vessels are more than 2 500, and maximum number is 6 000. Conflict between navigation and construction is severe.

3.2 Characters and difficulties of design and construction

Along with the expanding of span, some ignored factors in routine bridges will become prominent, control parameters will be complicated, and more researches should be conducted. Many technical problems should be solved while design and construction of superstructure, which mainly include structural system of over 1 000 m cable-stayed bridge, nonlinear influence and analysis of over 1 000 m cable-stayed bridge, wind and earthquake resistant design and construction measure, vibration-control of cables under construction and operation period, erection and monitoring of superstructure, design and construction of super-large scale deep water foundation, design and construction of super-high pylon.

1) Structural system of over 1 000 m cable-stayed bridge. Selection of proper structural system is the key of ensuring structural performance and safety to super long bridges. The main purposes of main-bridge structural system studies are to use additional devices to improve internal force and displacement response of structures under the action of ultimate wind, earthquake loads, etc.; to reduce the displacements and dynamic abrasions of expansion joints and supports, etc.; to increase the safety of the bridge under the action of ultimate static and dynamic loads.

2) Nonlinear influence and analysis of over 1 000 m cable-stayed bridge. Linear methods are adopted on medium and small bridges. Following the expanding of span, larger contrast is observed between results of linear calculation and nonlinear calculation. Study of nonlinear influence and analysis of over 1 000 m cable-stayed bridge will benefit design methods of super-long cable-stayed bridges and the safety of Sutong Bridge.

3) Wind and earthquake resistant design and construction measure. Sutong Bridge has large span, long cantilever girder under construction. Complicated 3D aerodynamic effect will occur. Aerodynamic stability is the key factor of safety. Seismic effect on deep and soft ground, seismic analysis of long and flexible structure and high-rise pile cap foundation, as well as proper earthquake resistant measure are the main considerations of design.

4) Vibration-control of cables under construction and operatiod period. Stay cables of Sutong Bridge have long length, small rigidity, low natural frequency and small damping. Under wind and rain as well as vortex-induced vibration of pylon and girder, rain/wind vibration, vortex-induced vibration and parametrical vibration are prone to occur. Vibration induced mechanism is not clear. Vibration countermeasures and vibration control standards should be studied.

5) Erection and monitoring of superstructure. Lifting height of girder section is more than 70 m. Weight of girder section is about 450 t. Length of maximum component of side span is 57.9 m, and weight is 1 300 t. This results in higher requirement of construction equipment. Long construction period, large amount of components, 540 m cantilever span under construction and small rigidity are easy to induce vibration. Typhoon will also cause problem under construction. High risk is one of the characters.

Because of nonlinear response of super long cable-stayed bridge under loads, structural deformation should be paid much attention to. Nonlinear methods should be adopted in detailed analysis and construction control. Characters of tall pylon, large span and long cable determine the small rigidity of bridge and hard measure work. Proper construction control methods should be adopted to ensure the stress and geometry control under girder erection.

6) Design and construction of super-large scale deep water foundation. Because of large scale of bridge, deep buried bedrock, huge vessel impact force, deep local scour, super-large scale deep water foundation is adopted. Keystones and difficulties are as follows: ultimate capacity of super-long pile in soft ground, measure to increase ultimate capacity, proper consideration on interaction of pile group foundation with soil mass, pile group effect, construction technics

and quality ensure measure of super-long bored concrete piles, and foundation scour protection.

7) Design and construction of super-high pylon. Design and construction characters and difficulties of 300.4 m super-high pylon are as follows: manufacture and assembling of steel anchor box, aerodynamic stability of super-high pylon under construction, erection technic and monitoring of super-high pylon[4].

4 Main innovation points

1) Sutong Bridge is the first cable-stayed bridge with the middle span over 1 000 m, of 1 088 m in fact, and it keeps the world record of span length. It is the landmark that denotes China from a large bridge country to an advanced bridge country.

2) Viscous damper system with lock-up is used. The system has the advantage of being able to limit the dynamic movement and load caused by turbulent wind, traffic braking, seismic load and dissipating energy, etc., but at the same time introducing little restriction to the slow movements caused by temperature, traffic and static wind. Under ultimate wind, it will provide a fixed connection between pylon and deck girder when the relative movement is out of the stroke length of the damper.

3) According to load character on different parts of steel box girder, different materials and different strength levels were adopted.

4) Parallel wires type of stay cables was selected, the strength of wires is 1 770 MPa, with design life of 50 years. It was domestic manufactured and reached international level.

5) Steel anchor box technology was selected as cable anchorage on pylon.

6) Pile group of 131 bored concrete piles with diameter of 280 cm/250 cm, length of 115 m were used for pylon foundation.

7) VTS and active anti-impact measure were adopted. Use pile cap as formwork to erect steel cofferdam, as well as variable thickness sealing concrete and pile group to establish holistic anti-collision system.

8) It was the first time in China to select geometry control method, which fit for long-span flexible bridge. Expanded construction control from erection site to manufacture factory and achieved whole-procedure control from manufacture to erection, in order to control the final geometry and internal force.

9) Numerical simulation technology was widely used, such as computational fluid design, structural 3D simulation analysis[4].

5 Study on bridge scheme

According to construction condition, feasible design bridge scheme was studied, such as cable stayed bridge, suspension bridge, cooperation system of cable-stayed and suspension bridge. At last double pylon cable stayed bridge over 1 000 m was selected. On preliminary design, five span or seven span continuous steel box girder cable stayed bridge, five span or seven span continuous composite girder cable stayed bridge, and seven span continuous hybrid girder cable stayed bridge were compared. From aspects of technology, economy and sight, proper scheme was proposed, as shown in Table 1[5].

Table 1 Bridge style selection of main bridge

Item	Control factor	Studied bridge scheme	Selected scheme
Main bridge	1. Navigation 2. Technology and economy 3. Hydrology and geology condition 4. Sight	1. (2 × 100 + 300 + 1 088 + 300 + 2 × 100) m seven span continuous steel box girder 2. (157 + 312 + 1 088 + 312 + 157) m five span continuous steel box girder 3. (2 × 100 + 300 + 1 088 + 300 + 2 × 100) m seven span continuous hybrid girder 4. (110 + 300 + 1 088 + 300 + 110) m five span continuous composite girder 5. (2 × 100 + 300 + 1 088 + 300 + 2 × 100) m seven span continuous composite girder	Seven span continuous steel box girder

6 Structural system

According to the characters of Sutong Bridge of large span, high wind velocity and severe seismic level, proper structural system was selected to solve following difficulties:

1) Reduce dynamic response of seismic action;

2) Lower internal force caused by temperature action;

3) Limit displacement of beam end caused by strong wind in order to reduce capacity requirement of expansion joint;

4) Limit deformation of pylon top and moment of pylon bottom. Ensure eccentric compression stability of pylon;

5) Limit deformation of girder vibration caused by vehicle braking force and turbulent wind, reduce the dynamic abrasions of expansion joints and supports to

expand their service life.

In order to select proper structural system, studies on damping limit restraint, hydraulic buffer limit restraint, elastic restraint, floating, fixed, as well as vertical support between deck and pier were conducted. According to the dynamic and static comparisons and analysis results, the pylon-girder connections in longitudinal direction adopt the composite device systems of rigid limit of nominal stroke capacity ±750 mm and dynamic damping to improve internal force and displacement response of structures under the action of ultimate wind, earthquake loads, etc.; to reduce the displacements and dynamic abrasions of expansion joints and supports, etc.; to increase the safety of the bridge under the action of ultimate static, dynamic loads. It is the first application of such equipment in the world, as shown in Fig. 2[5,6].

Fig. 2 Picture of the damper with lock-ups

7 Structural design

7.1 Steel box girder

The main girders are flat streamline steel box sections with good wind resistant characteristics. A girder section with wind nozzle has a total width of 41.0 m, and that without wind nozzle has a width of 35.4 m at the top slab, a width of (9.0 + 23 + 9.0) m at the bottom slab and a height of 4.0 m at its centerline.

According to load character on different parts of steel box girder, different materials and different strength levels are adopted[7].

7.2 Cables

In order to reduce the wind loads on cables, parallel steel wire cables are used for Sutong Bridge. The basic distance between the cables is 16 m on the girder, 12 m at side spans and 2 m on the pylon. The whole bridge has $4 \times 34 \times 2 = 272$ cables, with the longest being 577 m and the maximum size PES7-313. Dampers and aerodynamic provisions were adopted in combination for these cables according to their category for comprehensive vibration reduction. The amplitude of cable vibration is aimed to be controlled within 1/1 700 of the cable length. Based on the aerodynamic studies performed for Sutong Bridge, dampers and aerodynamic measures are planned to be installed to mitigate the vibration induced by wind/rain. At the same time provisions for installing cross ties are prepared in pylon and girder for possible future need[8].

7.3 Pylon

The pylons are inverted Y-shaped with the top at level 306.4 m. The total height of the pylon above pile cap is 300.4 m. A cross beam is placed under the girder. The height of pylon above bridge deck is 230.14 m.

Two major types of cable anchor in the pylon were studied: steel anchor box solution and prestressed concrete solution. Detailed comparison of the two solutions regarding force transferring mechanism, safety of force transferring, durability in operation stage, detailing and construction methods, etc. have been performed. According to the above factors, the steel anchor box solution was finally selected as the preferred solution. A full-scale mock-up test was performed to prove the constructability and effectiveness of the solution.

7.4 Large pile group foundation

The main pylons of the bridge are built on high pile cap pile-group foundation, with the cap sized 113.75 m × 48.1 m in a dumbbell shaped plane layout. There are 131 variable diameter bored concrete piles, and everyone is 120 m long and not set into the rock. As the foundation includes large and deep pile groups, we carried out special subject research on the interaction of pile group foundation with soil mass, load transfer and load bearing of the pile caps, foundation scour protection, pile bottom grouting technology and process, to provide grounds for evaluation of reasonable pile group layout, and overall foundation stability and safety. As shown in Fig. 3[9].

7.5 Vessel impact prevention measure

Sutong Bridge features a wide spread of water sur-

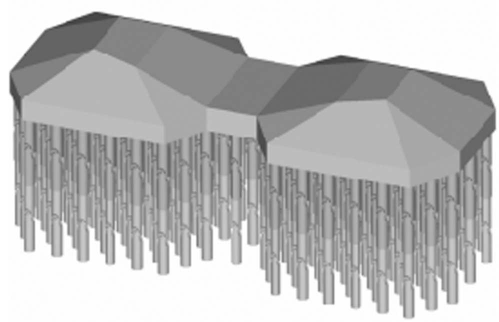

Fig. 3 Tower foundation

face, many bridge piers and dense traffic of vessels, hence high risk of collision with piers. The main design principles for collision prevention system of the bridge are: enhancing the anti-collision capability of the bridge structure as much as possible by adopting measures to optimize general layout and structure; providing reliable anti-collision facilities on the basis of maximizing the anti-collision capability of the structure itself; and reducing the risk of collision by setting up an active protection system. The researches were unfolded on four aspects: justification of navigation clearances and technical requirements; analysis of ship collision risks and determination of anti-collision strength criteria; justification of anti-collision facilities for the project; and studies on active prevention measures such as VTS in the bridge area.

8 Wind resistant design

For long span bridge, it is important to ensure the wind resistance and safety during its construction and after its completion. By fully digesting the successful experience in bridge construction at home and abroad, structural type selection and analysis were conducted in conjunction with CFD (computational fluid dynamics) numerical simulation, and finally chose a structural type and section mode that can suppress vibrations. Through the wind tunnel tests on the full bridge model, on the aeroelastic model of free-standing pylon, large scale high Reynolds number main girder section model, and rain/wind induced vibration on the cables and tension measurements, we studied the wind load parameters and the structural wind-resistance properties in the main construction stages and the operation stages, and the wind resistance stability and safety of the design[7].

9 Earthquake resistant design

According to dynamic seismic parameters under different probability level, response spectrum method and time domain method were adopted in earthquakeresistant design. Results showed that seismic responses of pylons, piers and foundations are critical design factors, but seismic response of superstructure is not critical design factor. Seismic suppress measure and partition measures were selected, which provided base data for future application[10].

10 Research of structural nonlinear response

Because of large span, Sutong Bridge has small rigidity, large deformation in construction and operation period, and obvious nonlinear response. Dimensional nonlinear program was adopted in design to consider p-Δ (pressure-deformation) effect of cables, large deformation effect and shear deformation. Calculation method of long span cable stayed bridge was achieved[11].

11 Geometry control method of superstructure

Because of small rigidity, long construction period, and obvious nonlinear response for main girder, conventional approaches will cause large errors. The unstressed dimensions of the precast or fabricated elements are stable factors. Therefore the principle of the geometry control is to strictly control the unstressed dimensions of the precast or fabricated elements, strictly control the geometry for each construction stage, ontime rectification of any construction errors, and to ensure that every fabricated or installed elements under control is achieved. Expanded construction control from erection site to manufacture factory and achieved whole-procedure control from manufacture to erection, in order to control the final geometry and internal force[12].

12 Conclusion

Sutong Bridge after completion is shown in Fig. 4.

Fig. 4 Picture of Sutong Bridge after completion

Total 21 research projects were conducted during design and construction of Sutong Bridge. Many productions were achieved. Several innovations were proposed on design scheme, design method and key technology. It achieved George-Richardson Medal of International Bridge Conference (IBC) in 2008 and proved to be the landmark that denotes China from a large bridge country to an advanced bridge country.

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