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Research on Design Optimization of Long-Span Hybrid Girder Cable-Stayed Bridge with Two Unequal-Height Towers

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Abstract. The cable-stayed bridges (CSBs) with high-low towers have obvious asymmetry in structural layout and mechanical behavior. The stiffness and vibration mode of CSBs with high-low towers are obviously different. In order to optimize the mechanical performance of CSBs with high-low towers, taking the Shunxing Bridge with the main span of 626 m as example, a design optimization study is carried out from the suitable structural system, the ratio of side span to main span, and the setting of auxiliary piers. The results show that temperature load is a key factor in determining the unconsolidated system of the CSB with high-low towers, and it is also related to the height of the lower pylon. A reasonable ratio of side span to main span can decrease the static and dynamic response of the CSB with high-low towers; The setting of auxiliary pier can increase the structural rigidity and greatly reduce the stress and vertical deformation of the main beam on the side span. The research results can provide reference for the design of long-span CSB with high-low pylons.

Keywords. cable-stayed bridge with high-low pylons; design optimization; structural system; ratio of side span to main span

1. Introduction

Cable-stayed bridge (CSB) with high-low pylons belongs to a special bridge type of CSB with double tower. Due to special geological, topographical conditions, river channel, aviation, and navigation requirements, or certain environmental, water conservancy and other conditions, it needs to adopt the CSB with high-low towers to meet demand. The mechanical characteristics of CSB with high-low towers have difference with those of CSBs with general double tower [1,2]. When the tower heights on both sides of the bridge differ greatly, the side of the high tower will bear the main load as a single-tower CSB, and the side of the low tower will be used as an auxiliary structure; When the tower height difference between the two sides of the bridge tower is small, the side of the high tower and the side of the low tower are both the main load-bearing structures, and the

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system is similar to the CSB with equal height double tower.

Due to the influence of high and low towers on the stress and deformation of the whole bridge structure is quite different, researchers have conducted a lot of research on CSBs with high-low towers. Taking Chongqing Shuitu Jialing River bridge as the background, Ma Zhendong et al.[3] studied the structural design of solid system CSB with high-low towers, and proposed the corresponding design principles. Fan Xiaobo[4] and Pei Bingzhi et al.[5] studied the influence of auxiliary piers on the stress of CSBs with two unequal-height pylons. Yang Yongqing et al. [6] studied the temperature effect of CSBs with unequal height towers; Lv Long [7] and Lei Chunxu et al. [8] studied the dynamic characteristics and vibration reduction measures of CSBs with high-low towers under earthquake; Wang Xiaojie et al.[9] studied the seismic response of a CSB with high-low tower under three lateral restraint systems. Wang Dong[10] established the finite element model of a high-low tower CSB of the Fuyang-Huaibei High-speed Railway, and analyzed the seismic response of structural internal force and displacement. Cui Miaomiao[11] studied the structural systems for long-span cable-stayed road/rail bridge with different-height towers. Zhang Xinxin and Xu Jun[12] analyzed the static, stability, earthquake resistance, wind resistance, and windmill bridge coupling effect of the Yinghe Bridge with high-low towers.

Shunxing Bridge, has large span (626 m), many control factors and difficult structural design, is a double-tower double-cable-plane hybrid girder CSB with high-low towers. Taking Shunxing Bridge as an example, this paper studies the optimal design of long-span CSB with two unequal-height pylons from three aspects, which includes the appropriate structural system, the ratio of side to mid-span and the number of auxiliary piers.

2. Project Overview

Shunxing Bridge is a controlling project of the Extension Line Project of Nanguo East Road, Shunde District, Foshan City. As the obstacle removal area on Daliang side is close to the law enforcement base and border inspection station, to reduce the impact on the law enforcement base and border inspection station, a line segment of about 130 m is allowed on the side span of Daliang side, and then a curve with a radius of about 200 m is used to avoid the obstacle removal area. Therefore, it is determined to adopt the scheme of hybrid beam CSB with high-low pylons. The height of low pylon and high pylon is 151 m and 204 m, respectively. The upper tower is the steel structure, and the lower tower is the steel-concrete composite structure.

Shunxing Bridge is a double-cable-plane hybrid girder CSB with semi floating system. The middle span adopts a steel box girder with a closed full box section, and the side span adopts a prestressed concrete beam with a single box and four chambers section. The steel concrete junction section at the Daliang side of the middle span is set at 11.5 m from the center of the cable tower to the middle span, and the steel concrete junction section at the Ronggui side is set at 12.5 m from the center of the cable tower to the middle span. The standard cable spacing of stay cables for mid span and side span is 15 m and 7.5 m, respectively. 160 stay cables are set for the whole bridge. As Daliang side is controlled by geographical location, horizontal alignment, and other factors, the side span length of Daliang side is determined as 132 m, which adopt 2×66 m span layout (see Figure 1).

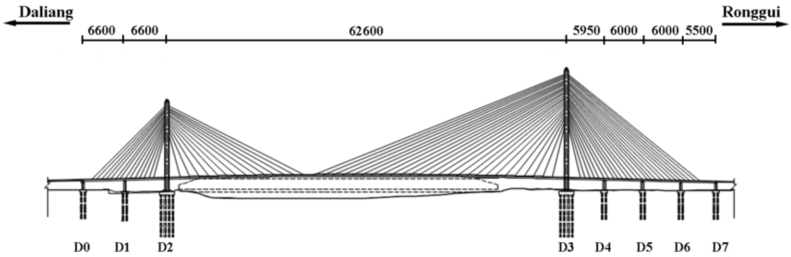


Figure 1. The diagram of the cabler-stayed bridge (Unit: cm).

The bridge structure is assumed to be in an elastic state, and the material parameter values of the model are shown in Table 1. The influence of Rayleigh damping is considered in dynamic analysis, and the damping ratio is 3% [13].

Table 1. The material parameters values of bridge components.

Bridge Components	material	Elastic modulus /kN.m	Possion's ratio
Steel main tower	Q345qD	2.06×10^8	0.3
Concrete main tower	C55	3.45×10^7	0.2
Steel beam	Q345qD	2.06×10^8	0.3
Concrete beam	C50	3.55×10^7	0.2
Stay cable	Strand1860	1.95×10^8	0.3

3. Structural Optimization Design

3.1. Structural System

The existing research shows that the connection mode between the tower and the beam of the CSB has a great influence on the static and dynamic performance of the CSB, and the stress of the bridge tower largely depends on the connection mode between the tower and the beam [14]. The common structural systems of CSBs include floating system, semi-floating system, tower beam consolidation system, and rigid structure system. The Chongqing Fuling Wujiang Second Bridge and Chongqing Shuangbei Jialing River Bridge are the typical consolidation system CSBs with high-low towers, while Jiangxi Poyang Lake Bridge and Jingyue Yangtze River Bridge are semi-floating system CSBs with unequal height towers. Taking Shunxing Bridge with a main span of 626 m as an example, this paper compares the stress of main beam with different materials (Table 2) under different load conditions of the semi-floating system and the tower beam consolidation system. Moreover, this paper also compares the internal force of the tower beam connection and the tower bottom for the low pylon and the high pylon (Table 3).

As illustrated in Table 2, under the action of vehicle live load, the stress difference of concrete main beams in the two systems is small, and the tensile stress of steel main beams in the unconsolidated system is slightly larger. Under the action of temperature load, the stress of both concrete main beam and steel main beam in the unconsolidated system is less than that in the consolidated system, which is about 50% of that in the consolidated system. It can be seen that the temperature load is the key factor to determine whether the CSBs with high-low towers adopt the consolidated or unconsolidated system. Under the action of short-term load combination, the tensile stress of the concrete main beam in the consolidated system is up to 3.74 MPa, while the main beam in the unconsolidated system is under full compression; At the same time, for the steel girder, the stress of the girder in the consolidated system is 1.25 times greater than that in the unconsolidated system.

Table 2. The comparison of stress for main beam.

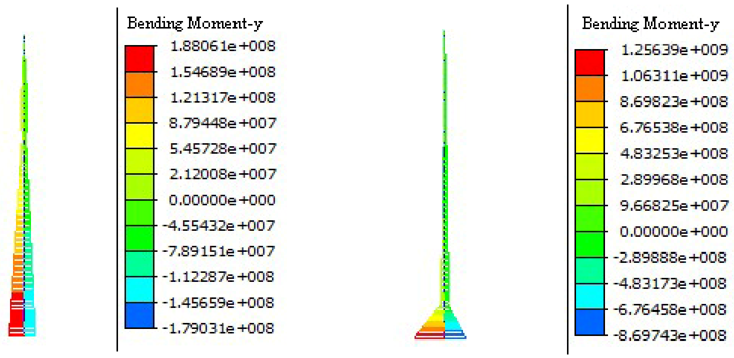
Loads	Unconsolidated system				Consolidated system			
	Concrete main beam (MPa)		Steel main beam (MPa)		Concrete main beam (MPa)		Steel/ main beam (MPa)	
	Max	Min	Max	Min	Max	Min	Max	Min
Live load	1.99	-2.52	33.90	-28.64	1.72	-2.70	13.64	-29.67
Temperature	3.32	-5.56	26.85	-49.31	7.36	-10.25	47.35	-90.45
Short-term combination of crack resistance	-1.23	-15.78	37.57	-120.40	3.74	-19.50	61.94	-156.23

Table 3. The comparison of stress for main tower.

Location		Unconsolidated system			Consolidated system		
		Axial force (kN)	Shear force (kN)	Bending moment (kN·m)	Axial force (kN)	Shear force (kN)	Bending moment (kN·m)
Low tower	Tower-beam connection	-188413	3002	302091	-186565	3927	496203
	Tower Bottom	-235312	3118	353224	-232173	60923	855535
High tower	Tower-beam connection	-327171	2925	358792	-325393	4246	539721
	Tower Bottom	-374657	3093	407784	-370722	61027	939027

As presented in Table 3, there is little difference between the axial forces at the tower-beam connection and the tower bottom in the two systems, while the shear force and bending moment of the consolidated system are far greater than those of the unconsolidated system. For the tower-beam connection, the shear force of the bridge tower in the unconsolidated system is 70% of that in the consolidated system, and the bending moment is 60% of that in the consolidated system. For the tower bottom, the shear force and bending moment of the unconsolidated system are also far less than those of the consolidated system. This difference is also caused by temperature load. Figure 2 shows the distribution of the internal force along the height of the bridge tower under the temperature load in the two systems. The bending moment at the tower bottom in the unconsolidated system is 15.0% of that in the consolidated system.

According to the distribution of main beam stress and tower internal force in the two systems, it can be seen that the temperature load is the key factor to determine the unconsolidated system for the CSB with high-low pylons of Shunxing Bridge, and the temperature load effect is related to the height of the lower pylon. The lower tower columns of Shunxing Bridge are all less than 20 m high (only 17.34 m high), and the semi-floating system is adopted due to insufficient flexibility.



(a) Unconsolidated system (b) Consolidated system

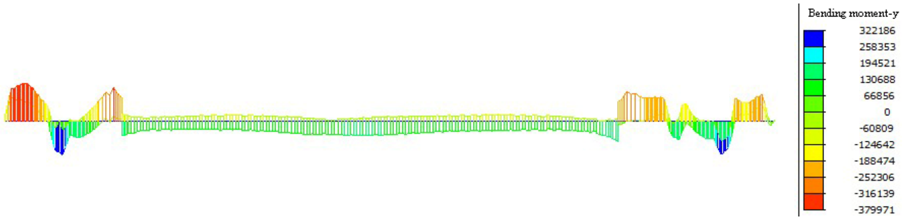
Figure 2. The distribution of bending moment for main tower (Unit: kN·m).

3.2. Ratio of Side Span to Main Span

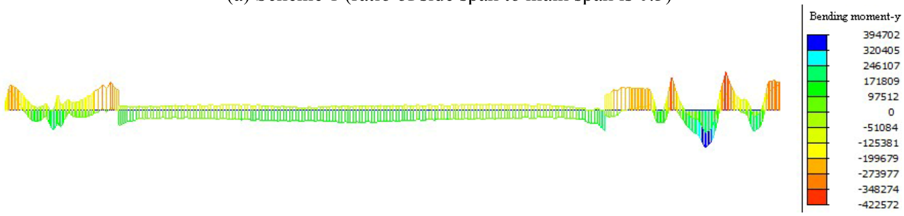
The ratio of side span to main span has an impact on the stress of the main beam, bridge tower, and auxiliary pier. Too small ratio of side span to main span may aggravate the negative reaction of the side bearing, while too large ratio of side span to main span may increase the stress of the side span and deteriorate the stress of the main span. According to the characteristics of Shunxing Bridge, three ratios of side to main span of 0.3, 0.277, and 0.25 are selected for Ronggui side (high tower side), and the bridge span layout at Ronggui side of Shunxing Bridge is comprehensively compared and selected from the aspects of stress and dynamic characteristics for the main beam.

3.2.1. Main Beam Stress. The bending moment distribution of the main beam for the three schemes under the action of automobile and temperature load is shown in Figure 3. It can be seen that the range of bending moment response value of main beam in Scheme 1, Scheme 2, and Scheme 3 is -257894 ~ 233847 kN·m, -422572 ~ 494702 kN·m, and -379971 ~ 322186 kN·m, respectively. The bending moment of the main beam in Scheme 1 is about 60% of that in Scheme 2, and is about 70% of that in Scheme 3. Table 4 shows the bearing reaction of three schemes with different ratio of side span to main span. It can be seen that, the negative reaction of the bearing appears only at one auxiliary pier at the high tower side (Ronggui side) in Scheme 1, which is 11933 kN; the negative reaction of the bearing appears at all the auxiliary pier at the high pylon side (Ronggui side) in Scheme 2, and the maximum force is 10525 kN; the negative reaction of the bearing appears at both the low pylon side (Daliang side) and the high tower side (Ronggui side) in Scheme 3, and the maximum force is 27946 kN. Based on the bending moment of the main beam and the reaction force of the bearing, it can be concluded that Scheme 1 is superior to Scheme 2 and Scheme 3.

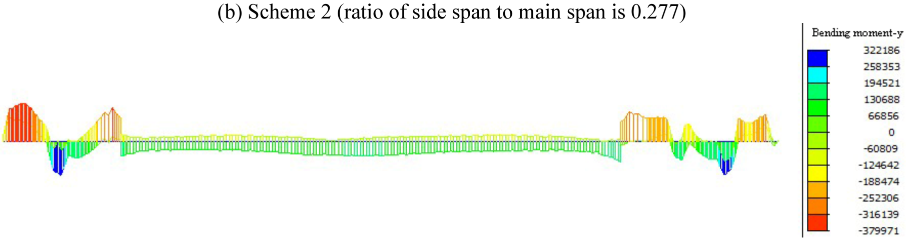
In conclusion, when the ratio of side span to main span is too small, under the action of live load and temperature effect, the bending moment of the main beam at the side of the low tower will be larger than that at the side of the high tower. It needs to set a large range and concentrated weight to prevent the beam from being pulled up. However, too much counterweight will cause many inconvenience to the design and construction.



(a) Scheme 1 (ratio of side span to main span is 0.3)



(b) Scheme 2 (ratio of side span to main span is 0.277)



(c) Scheme 3 (ratio of side span to main span is 0.25)

Figure 3. The distribution of bending moment for main beam (Unit: kN·m).

Table 4. Bearing reaction.

Scheme	Daliang side			Ronggui side		
	Transition pier 1	Auxiliary pier 1	Auxiliary pier 1	Auxiliary pier 2	Auxiliary pier 3	Auxiliary pier 4
1	6030	8829	2803	-11933	2273	15525
2	556	6271	-5951	-10525	--	-303
3	-6181	-13518	-24473	-27946	--	6979

3.2.2. Dynamic Characteristic. The dynamic characteristics of the structure affect its dynamic response. By modal analysis, the first five order dynamic characteristics of the three schemes are presented in Table 5. It can be seen that, the first order period of the three schemes is the longitudinal drift of the main bridge; The first order vibration period of Scheme 1, using a semi floating system for the bridge, is smaller than that of the other two schemes, which indicates that the full bridge stiffness of Scheme 1 is slightly larger than that of Scheme 2 and Scheme 3; The main beam can dissipate energy in the process of longitudinal drift, which is beneficial to reduce the seismic response of the bridge, however, excessive period will lead large displacement of beam end. The second order vibration mode of Scheme 1 is mainly the vertical vibration of the main bridge, while the second order vibration mode of Scheme 2 and Scheme 3 is mainly the lateral vibration of the high tower. Since the lower order vibration mode is easier to be excited due to the lateral stiffness of the main tower is relatively weak. In the seismic design, the main tower is generally used as a protective component, and no damage is allowed under a strong earthquake. It should be ensured that the main tower has sufficient strength and stiffness. Therefore, from the perspective of bridge dynamic characteristics, Scheme 2 and Scheme 3 are unfavorable to Scheme 1.

Table 5. The comparison of dynamic characteristic.

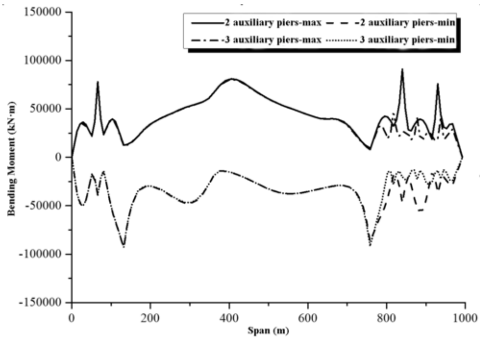
Mode number	Scheme 1		Scheme 2		Scheme 3	
	Period (s)	Mode shape	Period (s)	Mode shape	Period (s)	Mode shape
1	7.751	Longitudinal floating (main bridge)	7.978	Longitudinal floating (main bridge)	8.188	Longitudinal floating (main bridge)
2	3.494	Symmetric vertical vibration (main bridge)	3.374	Lateral vibration (high tower)	3.281	Lateral vibration (high tower)
3	3.333	Lateral vibration (high tower)	3.222	Symmetric vertical vibration (main bridge)	3.221	Symmetric vertical vibration (main tower)
4	2.597	Lateral vibration (main bridge)	2.635	Lateral vibration (main bridge)	2.834	Lateral vibration (low tower)
5	2.442	Asymmetric vertical vibration (main bridge)	2.411	Lateral vibration (low tower)	2.572	Lateral vibration (main bridge)

3.3. Setting of Auxiliary Pier

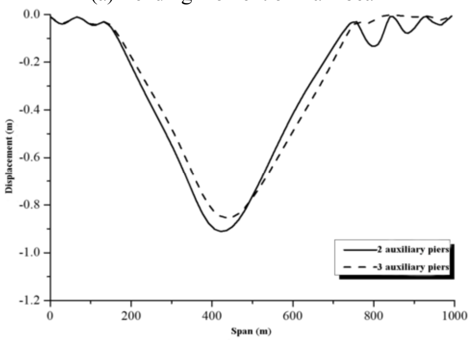
Adding auxiliary piers is a better method to improve the mechanical performance of CSB structures. In general, adding auxiliary piers at the side spans of long-span CSBs can improve the mechanical status of structures, such as the horizontal displacement of tower top, bending moment at pylon bottom, and internal force of main beams. At the same time, it can also improve the mechanical status of the process for construction. After the structural system is determined, the internal force of the CSB under dead load can be optimized by adjusting the cable force of the stay cable. Then the stress and deformation state of the structure under the action of live load are the control factors of structural optimization design. For Shunxing Bridge, due to geographical location and other control factors, two or three auxiliary piers are set at the side of the high tower to study the influence of the layout of auxiliary piers on the mechanical performance of the CSB with unequal-height towers.

The comparison of the internal force and displacement of the main beam with the number of auxiliary piers are illustrated in Figure 4. As shown, the internal force and displacement of the main beam are basically the same due to the consistent layout of the auxiliary piers on the low tower side, while the internal force and displacement of the main beam are quite different due to the different layout of the auxiliary piers on the high tower side. Comparison to the side main girder of the high tower with 2 auxiliary piers, the bending moment and displacement of the side main girder of the high tower with 3 auxiliary piers are greatly reduced. It can be seen from Figure 4 (a) that when 2 auxiliary piers are set, the bending moment at the top of the auxiliary pier is larger, reaching 90968 kN·m and 75643 kN·m. When 3 auxiliary piers are set, the bending moment at the top of the auxiliary pier is 48339 kN·m, 41207 kN·m, and 43884 kN·m, respectively, which is 36%~54% lower than that of the 2 auxiliary piers. It can be seen from Figure 4 (b) that, due to the setting of auxiliary piers can increase the overall structural stiffness of the

CSBs with high-low tower. When the auxiliary pier is added, the vertical displacement of the side span and middle span girder of the high tower decreases significantly, while the vertical displacement of the middle span and side span girder of the low tower has little change. When 3 auxiliary piers are set, the maximum vertical displacement of the side span main beam of the high tower is 3.6 cm, which is 73% less than the vertical displacement (13.3 cm) of the side span main beam with the 2 auxiliary piers.



(a) Bending moment of main beam



(b) Displacement of main beam

Figure 4. Influence of number of auxiliary piers.

4. Conclusion

Taking Shunxing Bridge as an example, for the asymmetry of the bridge structure with two unequal-height pylons, the structural optimization design is studied from the structural system, the ratio of side span to main span, and the setting of auxiliary pier. Furthermore, the purpose of appropriate structural layout and reasonable stress is achieved. The main conclusions are as follows:

(1) In order to adapt to hydrological, geological, and topographic conditions as well as obtain a reasonable span layout, the CSB with high-low pylons can be designed. Although its asymmetry is more novel than the traditional CSB in aesthetics, it also causes the asymmetry distribution of the mass and stiffness for the bridge, and the optimization design of the structure needs to be analyzed.

(2) Temperature load is the key factor to determine the use of unconsolidated system for the CSB with high-low pylons of Shunxing Bridge. Moreover, the use of unconsolidated system is also related to the height of the lower tower column. The lower

tower column height of Shunxing Bridge is all less than 20 m, and the lower tower column does not have enough flexibility, so the semi-floating system is adopted.

(3) A reasonable ratio of side span to main span can decrease the static and dynamic response of the CSBs with high-low towers. If the ratio of side span to main span of the structure is too small, the bending moment of the main beam will be relatively large under the action of live load and temperature load, and it is necessary to set a large range and concentration of weights to prevent the beam from being pulled up.

(4) The setting of auxiliary piers can increase the overall structural stiffness of CSB with two unequal-height pylons, and has a greater influence on the vertical deformation and stress of the main beam of the side span, while has a relatively small influence on the middle span and the other side span.

Acknowledgement

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