SEISMIC CONCEPTUAL DESIGN OF LONG-SPAN CABLE-STAYED BRIDGE

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SUMMARY

For a long-span cable-stayed bridge, the seismic performance is highly dependent on the seismic conceptual design instead of numerical design. In the paper, based on the seismic response analysis of more than ten long-span cable-stayed bridges, the seismic conceptual design is discussed in the following fore aspects:
1. Choice of deck type: Composite deck, hybrid deck composed of composite deck in the main span and concrete deck in side spans, are compared from a seismic design viewpoint.
2. Choice of deck-tower connection manner: Three connection manners-- no connection, elastic connection and rigid connection are discussed. The effect of elastic stiffness on the seismic response of cable-stayed bridges is analyzed, and a suitable stiffness is proposed.
3. Arrangement of side piers: Considering that several side piers are often adopted in hybrid cable-stayed bridges, the effect of the arrangement of side piers on dynamic behaviors is analyzed.
4. Choice of deck-side pier connection manner: The deck-side pier connection manner in the transverse direction is discussed from a seismic design viewpoint. For a cable-stayed bridge with several side piers, the best connection manner is analyzed and discussed.
The conclusions of the paper will provide guidance and reference for the seismic design of long-span cable-stayed bridges.

INTRODUCTION

In China, cable-stayed bridges are becoming very popular. Quite a lot of cable-stayed bridges have been constructed, more and more long-span cable-stayed bridges are under construction, or in the design and consideration processes. In order to assure seismic safety of these bridges, it is essential to carry out studies on seismic design of long-span cable-stayed bridges.

At present, the structure of a long-span cable-stayed bridge is usually designed based solely on service load, the earthquake resistance and aerodynamic stability are considered in isolation by special studies. This is unlikely to be the best solution. The performance (including static and dynamic performance) of a cable-stayed bridge is highly dependent on the choice of structural system. Therefore, in the conceptual design phase, the structural form should be adopted based on static considerations, seismic resistance and aerodynamic stability.

The seismic conceptual design (conceptual design from a seismic design viewpoint), in particular, will be discussed in the paper. Damage to bridges in recent earthquakes indicates that seismic conceptual design is even more important than numerical design. Because of the randomness of earthquakes, the complexity of structures and the uncertainty of other factors, the seismic performance of a long-span cable-stayed bridge is highly dependent on the conceptual design instead of numerical design.

In the last ten years, the seismic response analysis of more than ten long-span cable-stayed bridges have been completed by the research group of the State Key Laboratory for Disaster Reduction in Civil Engineering of China, and some achievements have been obtained. In the paper, the seismic conceptual design is discussed based on these achievements.

For a long-span cable-stayed bridge, although structural options for seismic resistance are subjected to many nonseismic constraints, there are still many alternatives. In the paper, seismic design alternatives are analyzed and compared in four aspects: 1) deck type; 2) deck-tower connection manner; 3) arrangement of side piers; and 4) deck-side pier transverse connection manner.

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CHOICE OF DECK TYPE

At the conceptual design stage of a long-span cable-stayed bridge, there are four deck types can be considered: concrete deck, composite deck, steel deck and hybrid deck (steel or composite deck in main span and concrete deck in side spans). The cable-stayed bridge with hybrid deck (hybrid cable-stayed bridge), in particular, is attracting more interests with its superior static performance and construction speed. Many hybrid cable-stayed bridges have been constructed or under construction. So, it is essential to compare the dynamic behavior of hybrid cable-stayed bridge with other cable-stayed bridges. In the chapter, Xupu Bridge in Shanghai is taken as an example to carry out the study.

Xupu Bridge is a hybrid cable-stayed bridge with two A shaped towers, its spans are 2×40m+3×39m+45m+590m+45m+3×39m+2×40m. The deck system is composed of composite deck in main span and prestressed concrete deck in side spans. The spherical hinged movable bearings are erected on the anchor piers, and the pot rubber bearings are erected on the other side piers. Besides, there are limiters erected between the deck and side piers in the transverse direction. The spacing between deck and anchor pier is 200mm, the spacing between deck and the other side piers is 10~20mm. Another alternative of Xupu Bridge is a composite cable-stayed bridge with span of 96m+142m+590m+142m+96m. Apart from the deck type, the other design is as same as the existing Xupu Bridge.

In order to analyze and compare the dynamic behavior of the two alternatives, two 3-D analytical models are constructed. The boundary conditions adopted are as follows: all towers and piers are fixed at the base; the deck can move freely in the longitudinal direction, but in the transverse direction, the deck is movable at anchor pier, while unmovable at the other side piers and towers.

The fundamental frequencies of the two alternatives are listed in Table 1, and the seismic responses are shown in Table 2. In the seismic response analysis, the same site response spectrum with a horizontal factor of 0.1g is adopted.

Table 1: Fundamental frequencies of two alternatives

Vibration mode	Frequency (Hz)	
	Hybrid alternative	Composite alternative
1st floating mode	0.0944	0.0989
1st vertical flexure mode	0.3118	0.2889
1st lateral flexure mode	0.3383	0.3026
1st torsion mode	0.6072	0.6006

Table 2: Maximum seismic responses of two alternatives

Case	Position of section	Hybrid alternative		Composite alternative	
		Axial force P (kN)	Bending moment M (kN.m)	Axial force P (kN)	Bending moment M (kN.m)
I	Bottom of tower	7.039×10^3	3.827×10^5	6.507×10^3	3.627×10^5
	Main girder	8.106×10^3	7.663×10^4	7.753×10^3	7.603×10^4
	Bottom of anchor pier	1.070×10^3	6.617×10^4	1.208×10^3	6.617×10^4
	Bottom of other side pier	1.991×10^3	3.131×10^4	2.794×10^3	3.131×10^4
II	Bottom of tower	6.308×10^4	3.703×10^5	5.495×10^4	3.503×10^5
	Main girder	7.475×10^4	9.154×10^5	7.034×10^4	7.688×10^5
	Bottom of anchor pier	2.900×10^3	4.103×10^4	3.249×10^3	4.591×10^4
	Bottom of other side pier	9.073×10^3	1.078×10^5	1.048×10^4	1.156×10^5

Note: 1. Case I --- input in both longitudinal direction and vertical direction,
Case II --- input in both lateral direction and vertical direction;
2. The response of other side pier of hybrid alternative is the largest one.

Table 1 shows that, due to the larger weight of deck in side spans, the frequency of the 1st floating mode of the hybrid alternative is a little lower than that of the composite alternative. However, frequencies of the 1st vertical and lateral flexure mode of the hybrid alternative are obviously higher than that of the composite alternative, because of the larger restriction of side spans. Moreover, the weight of deck in side spans has little effect on the 1st torsion mode.

As for the seismic response, it can be seen from Table 2 that the response of the hybrid alternative is a little larger than that of the composite alternative. The results should be attributed to the larger weight of deck system and the higher frequencies of the hybrid alternative.

Based on the foregoing analysis, it can be concluded that composite cable-stayed bridge and steel cable-stayed bridge are superior over the hybrid cable-stayed bridge in dynamic behavior.

CHOICE OF DECK-TOWER CONNECTION MANNER

In the design of a cable-stayed bridge, there are three deck-tower connection manners can be adopted, they are no connection (floating system), elastic connection and rigid connection. When the center-span length increases, however, no connection will result in considerable large displacement of deck, while the rigid connection will result in considerable large force in the tower, so these two are not the best choices. For a long-span cable-stayed bridge, the elastic connection may be the best choice, but the suitable elastic stiffness is hard to determine. In order to provide a reference for the determination of suitable elastic stiffness, the effect of elastic stiffness on seismic response of cable-stayed bridges are investigated in the chapter.

In the investigation, three long-span cable-stayed bridges are taken as examples: Mingjiang Bridge in Fujian province, Shantou Queshi Bridge in Guangdong province and the 2nd Nanjing Bridge in Jiangsu province. The main parameters of these three bridges are listed in Table 3.

Table 3: Main parameters of three cable-stayed bridges

Parameter	Mingjiang Bridge	Queshi Bridge	2nd Nanjing Bridge
Spans(m)	40+250+605+250+40	2×47+100+518+100+2×47	58.5+246.5+628+246.5+58.7
Tower shape	A shape	A shape	Inverse Y shape
Width of bridge (m)	29	30.35	33.6
Deck type	composite	hybrid (steel+concrete)	steel
Depth of deck (m)	2.5	3.0	3.5
Number of cable plane	2	2	2
Fundamental frequency (Hz)	0.0947	0.1510	0.0757

Note: The fundamental frequency in the table is corresponding to no connection manner.

The spectra used in the seismic response analysis of three bridges are illustrated in Figure 1. In the analysis, the spectrum is input in both longitudinal direction and vertical direction (with a factor of 2/3).

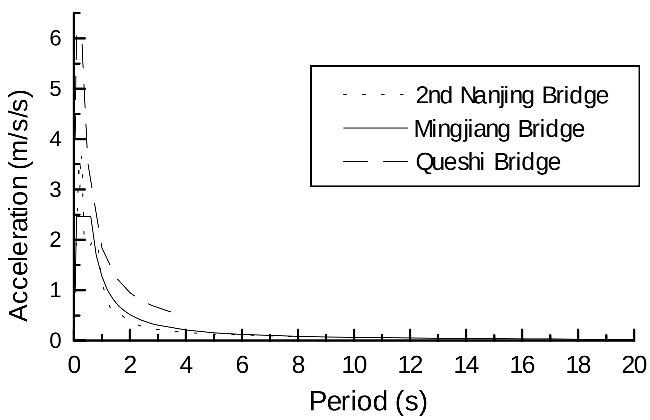

Figure 1: Response spectra used in the analysis

In order to investigate the effect of elastic stiffness on seismic response, a series of elastic stiffness are adopted: 1.0e-10 kN/m, 1.0e3 kN/m, 5.0e3 kN/m, 1.0e4 kN/m, 5.0e4 kN/m, 1.0e5 kN/m and 1.0e10 kN.m. After a lot of seismic response analysis, the effect of elastic stiffness on seismic response of cable-stayed bridges is illustrated in Figure2 ~ Figure 4. In the figures, “B1” represents Mingjiang Bridge, “B2” represents Queahi Bridge, and “B3” represents 2nd Nanjing Bridge.

When the elastic stiffness increases, the deck-tower connection becomes stronger, so the longitudinal displacement of the deck and the longitudinal displacement at the top of tower decrease obviously, just as shown in Figure 2 and Figure 3.

Figure 4 and Figure 5 indicate that, in a large range of stiffness (1.0e3 kN/m ~ 1.0e5 kN/m), the shear force and bending moment at the bottom section of tower are not very sensitive to elastic stiffness. The tendency is as same as that obtained in the seismic response analysis of the Tatara Bridge in Japan[4].

It can also be found From Figure2~Figure 4 that for different bridge, the sensitivity of seismic response to elastic stiffness is different, it depends on the dynamic characteristics of the bridge and response spectrum of the bridge site. In generally, for a long-span cable-stayed bridge with a main span of about 600m, a stiffness of 1.0e4 kN/m can be taken as a reference.

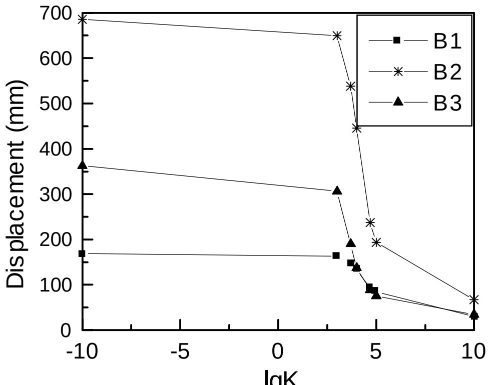

Figure 2: Displacement at the top of tower
(K: elastic stiffness)

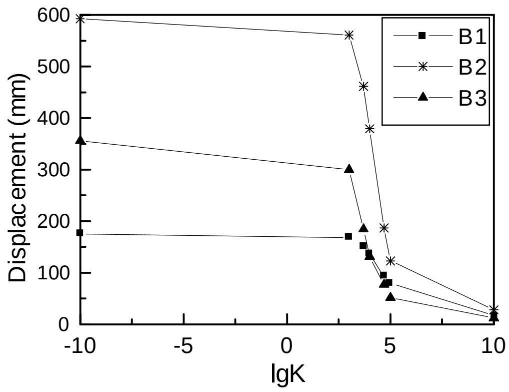

Figure 3: Displacement of the deck
(K: elastic stiffness)

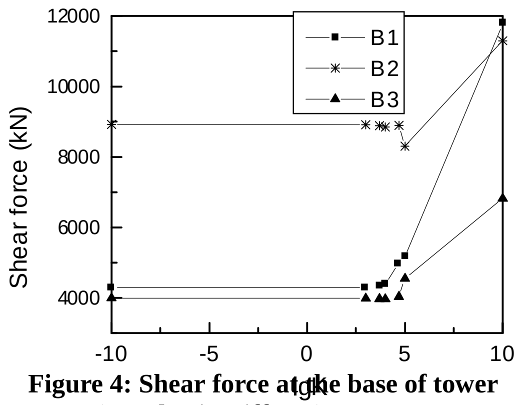

Figure 4: Shear force at the base of tower
(K: elastic stiffness)

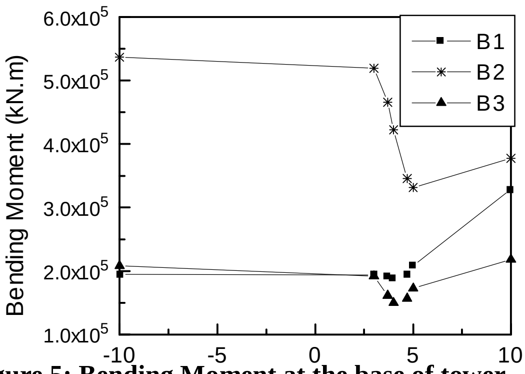

Figure 5: Bending Moment at the base of tower
(K: elastic stiffness)

ARRANGEMENT OF SIDE PIERS

In the design of a long-span cable-stayed bridge, especially a hybrid cable-stayed bridge, several side piers are often arranged. Obviously, the arrangement of side piers will have effect on the dynamic behavior of the cable-stayed bridge. In the chapter, Xupu bridge in Shanghai, which is a hybrid cable-stayed bridge with five side piers at each side, is taken as an example to investigate the effect. The arrangement of side piers in Xupu Bridge is illustrated in Figure 5(e). The other four alternatives with one to four side piers are designed for the analysis, as illustrated in Figure 5(a) ~ Figure 5(d). The dynamic characteristics of cable-stayed bridges with these five alternatives are analyzed, and fundamental frequencies are illustrated in Figure 6, in which "1" represents the 1st floating frequency, "2" represents the 1st vertical flexure frequency, "3" represents the 1st lateral flexure frequency, and "4" represents the 1st torsion frequency.

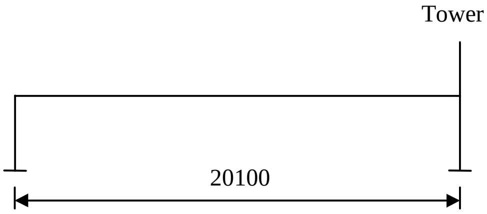

Figure 5(a): With one side pier (unit: cm)

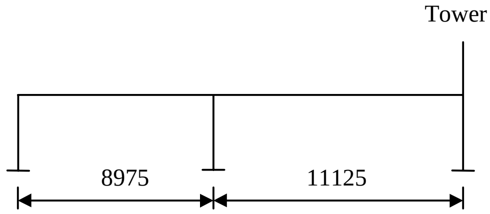

Figure 5(b): With two side piers (unit: cm)

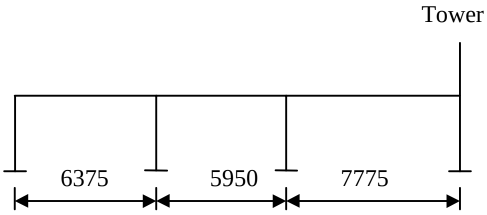

Figure 5(c): With three side piers (unit: cm)

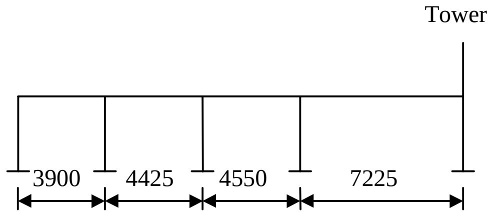

Figure 5(d): With four side piers (unit: cm)

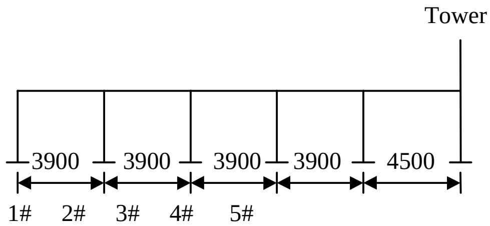

Figure 5(e): With five side piers (unit: cm)

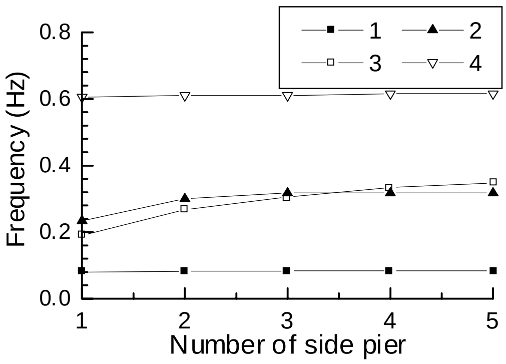

Figure 6: The effect of side pier number on the fundamental frequencies

It can be found from Figure 6 that the arrangement of side piers has little influence on the first floating frequency, because the deck is movable freely in all cases. The first lateral flexure frequency is sensitive to the arrangement because of the restriction of side piers in the transverse direction. The first vertical flexure frequency will be changed obviously when side pier number is changed from one to two, then remain almost the same value. Besides, the arrangement of side piers has little effect on the first torsion frequency of main span.

CHOICE OF DECK-SIDE PIER TRANVERSE CONNECTION MANNER

In the seismic design of long-span cable-stayed bridges, enough attention is seldom paid to the seismic resistance of the anchor pier in the transverse direction, which depends on the deck-side pier connection manner in the transverse direction. When the response spectrum analysis method is adopted, in particular, the response of the anchor pier in the transverse direction will be badly underestimated unless enough modes is taken into consideration. Seismic response analyses of many long-span cable-stayed bridges indicate that anchor pier is vulnerable in the transverse direction. On the one hand, the response of anchor pier is usually very large because the side pier is often designed to restrain the deck. On the other hand, the anchor pier is designed based on service load, which results in a small force in the transverse direction, so the design of the anchor pier is not strong enough.

The seismic behavior of Yangpu Bridge in Shanghai is a good example. Yangpu Bridge is a composite cable-stayed bridge with a main span of 602m. In the transverse direction, the top of anchor pier and deck are restrained each other. When subjected to the earthquake with 10% probability of exceedance in 50 years, the maximum bending moment at the bottom section of anchor pier will be 105900kN.m, which have been exceeded the transverse yield bending moment of 73750kN.m. For assuring the seismic safety of Yangpu Bridge, a steel bar with an ultimate tension force of 2000kN was erected between the top of anchor pier and deck. The steel bar will provide restraint under service load and wind load, but will fail when the force exceeds 2000kN in the earthquake. Then, the bending moment at the bottom section of anchor pier will be reduced to 47790kN.m (<73750kN.m) even subjected to the earthquake with 10% probability of exceedance in 100 years. So the seismic safety will be assured.

In the seismic analysis of the 2nd Nanjing Bridge in Jiangsu province, the same problem appeared in Yangpu Bridge was found, so a buffering device is advised to be erected between the deck and the anchor pier in the transverse direction.

In the 1995 Kobe earthquake, the Higashi Kobe Bridge, a cable-stayed bridge with a center span of 485m, was reported to be damaged at a deck-side pier connection. A pendel - type bearing pin at the end anchored pier on Kobe side had dropped off. It seems that the main cause is the effects of combine action by vertical and transverse earthquake shaking.

When several side piers are arranged, as usually in hybrid cable-stayed bridges, the problem will be more complex. For a single side pier, it can be free or be restrained with deck. But for several side piers, it should be decided how many piers to be restrained, and which one be restrained, the best combination should be found. To solve the problem, Xupu Bridge with one anchor pier and four auxiliary piers is taken as an example. Four cases are considered: Case I: 2# ~5# side piers offer transverse restraint; Case II: 3# and 5# side piers offer transverse restraint; Case III: 3# side piers offer transverse restraint; Case IV: No side pier offers transverse restraint.

The maximum bending moment at the bottom section of tower and side piers, the maximum relative displacement between the top of pier and deck are listed in Table 4.

When all side piers except anchor pier offer transverse restraint, the force responses of these side piers are more even, the relative displacement between anchor pier and deck is smaller, and the bending moment at the bottom section of tower is smaller too. However, when some side pier is free, the others must share the inertia force of deck undertaken by this pier, so the force of other side piers and tower will become larger, as shown in Table 4. Therefore, for the force and displacement response of all piers and towers, case I is the best choice.

In general, for a cable-stayed bridge with several side piers, it is benefit for deformation and force that all side piers except anchor pier offer transverse restraint.

Table 4:Effect of transverse restraint on earthquake response

Case	Seismic response	1# pier	2# pier	3# pier	4# pier	5# pier	Tower
I	Relative displacement (mm)	166	0	0	0	0	0
	Bending moment (kN.m)	3.71×10^4	1.51×10^5	1.19×10^5	8.84×10^4	5.77×10^4	4.46×10^5
II	Relative displacement (mm)	512	392	0	176	0	0
	Bending moment (kN.m)	3.68×10^4	2.94×10^4	3.26×10^5	2.95×10^4	1.03×10^5	5.55×10^5
III	Relative displacement (mm)	522	402	0	183	97	0
	Bending moment (kN.m)	3.67×10^4	2.92×10^4	3.33×10^5	2.94×10^4	2.95×10^4	5.91×10^5
IV	Relative displacement (mm)	440	345	250	162	88	0
	Bending moment (kN.m)	3.41×10^4	2.68×10^4	2.70×10^4	2.70×10^4	2.73×10^4	6.94×10^5

Note: Position of piers is illustrated in Figure 5(e).

CONCLUSION

Based on the foregoing analysis, the following conclusions can be made:

1. In dynamic behavior, composite cable-stayed bridge and steel cable-stayed bridge are superior over the hybrid cable-stayed bridge. Therefore, from a seismic design viewpoint, composite deck and steel deck are better choice than hybrid deck.
2. For a long-span cable-stayed bridge, the best deck-tower connection in the longitudinal direction is elastic connection. The displacement of deck and tower decrease obviously with the increase of elastic stiffness, while the shear force and bending moment of tower are not very sensitive to elastic stiffness in a large range. In general, when the main span is about 600m, an elastic stiffness of 1.0e4 kN/m may be suitable.
3. For a floating cable-stayed bridge, arrangement of side piers has little effect on the first floating frequency and the first torsion frequency. The first lateral flexure frequency is sensitive to the arrangement. The first vertical flexure frequency will be changed obviously when side pier number is changed from one to two, then remain almost the same value.
4. The anchor pier of a long-span cable-stayed bridge is vulnerable in the transverse direction when it is designed to restrain the deck, so special attention should be paid to the design of anchor pier.
5. In general, for a cable-stayed bridge with several auxiliary piers, it is benefit for deformation and force of the structure that all side piers offer transverse restraint.

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