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Study of seismic performance and favorable structural system of suspension bridges

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Abstract. By taking the Runyang Highway Bridge over the Yangtze River with 1490 m main span as example, structural response of the bridge under the horizontal and vertical seismic excitations is investigated by the response spectrum and time-history analysis of MIDAS/Civil software respectively, the seismic behavior and the influence of structural nonlinearity on the seismic response of the bridge are revealed. Considering the aspect of seismic performance, the suitability of employing the suspension bridge in super long-span bridges is investigated as compared to the cable-stayed bridge and cable-stayed-suspension hybrid bridge with the similar main span. Furthermore, the effects of structural parameters including the span arrangement, the cable sag to span ratio, the side to main span ratio, the girder height, the central buckle and the girder support system etc on the seismic performance of the bridge are investigated by the seismic response spectrum analysis, and the favorable earthquake-resistant structural system of suspension bridges is also discussed.

Keywords: suspension bridge; seismic performance; structural system; response spectrum analysis; time-history analysis; structural parameters

1. Introduction

Suspension bridge, which consists of the deck, main cables, hangers, towers and anchor blocks etc, is an important structural type of the cable-supported bridges. Until now, it is still the most competitive scheme of the bridge whose main span exceeds 1000 meters. Currently, the longest suspension bridge is the Akashi Kaikyo Bridge in Japan with main span of 1990 m. In the 21st century, many bridges across the straits are being planned around the world, and among them several long and particularly super long-span suspension bridges are schemed, for example, the Messina Strait Bridge with a main span of 3300 m and the Gibraltar Bridge with a main span of 5000 m (Gimsing and Georgakis 2012). In recent years, the cable-stayed bridge has been developed rapidly, the Stonecutters Bridge (1018 m) and Sutong Bridge (1088 m) implement the main span of cable-stayed bridge of kilometer-scale breakthrough, and they are followed by the Russky Island Bridge in Russia with a main span of 1104 m completed in 2012. Furthermore, the cable-stayed bridge scheme with 1400 m main span has been studied (Nagai, Fujino *et al.*2004). The research on the span limit of cable-stayed bridge shows that the most favorable main span is

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below 1200 m, however 1200 to 1500m main span is still competitive for the cable-stayed bridge (Xiang 2012). To overcome the shortage of the cable-stayed bridge or suspension bridge, the cable-stayed-suspension hybrid bridge is put forward in recent decades, and its main span is also very long (Sun, Cai *et al*. 2013). Therefore, below the main span of 1500 m, the suspension bridge is faced with the competition of other long-span bridges such as the cable-stayed bridge and cable-stayed-suspension hybrid bridge.

As is well known to all, the suspension bridge is a structural system of great flexibility, it is very susceptible to the dynamic action such as wind and earthquake etc., and the seismic performance becomes an important problem of its design. Up to now, a few researches on the seismic performance of long-span earth-anchored suspension bridges have been conducted. Feng, Xiang *et al*. (2005) established a dynamic model and the equilibrium equation of multi-support excitations for a super-large-span suspension bridge based on the large mass method and the pseudo-static displacement conception, and analyzed the dynamic characteristics and seismic response of the bridge under the multi-support excitations, and finally investigated the effects of soil-foundation-structure interaction and the traveling-wave effect on the seismic response of the bridge. Xu (2006) proposed a feasibility research scheme of the Qiongzhou Strait suspension bridge based on the static performance, and investigated the seismic response of the scheme subjected to consistent and multi-support earthquake excitations by the time-history analysis. Pen (2007) investigated the influence of the center buckle, the elastic connection rigidity of the girder ends, the vertical earthquake excitation and the traveling-wave effect on the seismic response of the Aizhai Suspension Bridge. Yan (2007) conducted the linear and nonlinear seismic response analysis of two long-span suspension bridges, and revealed the effect of geometrical nonlinearity on the seismic response of long-span suspension bridge. Deng and Jia (2008) performed the linear seismic response analysis of two long-span suspension bridges by the response spectrum method, and investigated the effect of higher vibration modes on the seismic response of long -span suspension bridge. Apaydin (2010) took the Fatal Sultan Mehmet and Bosporus suspension bridges with main span of 1090 and 1074 m respetively in Istanbul as example, evaluated their seismic performance under the multi-support scenario earthquake excitation by the non-linear 3D finite element time history analysis. By using penalty function and first-order optimization theory, Wang, Li *et al*. (2010) proposed a new optimal placement method of dampers to ensure the anti-earthquake performance of super long-span suspension bridges. Yang, Chen *et al*. (2011) investigated experimentally the seismic response reduction performance of magnetorheological (MR) damper for a suspension bridge. Adanur, Altunisik *et al*. (2012) investigated and compared the geometrically nonlinear earthquake behavior of the first and second Bosporus suspension bridges built in Istanbul in Turkey subjected to the near-fault and far-fault ground motion. Sgambi, Garavaglia *et al*. (2014) used a probabilistic approach (Monte Carlo simulation) to carry out the seismic analysis of a long-span suspension bridge to take into account the variability of certain factors relating to the seismic input. The above researches mainly focus on the effects of the earthquake excitation, structural nonlinearity, the connection of girder and the damper on the seismic performance of long-span suspension bridge. However, the seismic performance comparison of suspension bridge with the cable-stayed bridge or the cable-stayed-suspension hybrid bridge with the similar main span is not made, and the favorable earthquake-resistant structural system of suspension bridge is also not studied.

In this work, by taking the Runyang Highway Bridge over the Yangtze River with main span of 1490 m as example, structural response of the bridge under the horizontal and vertical seismic excitations is investigated by the response spectrum and time-history analysis respectively, the seismic behavior and the effect of structural nonlinearity on the seismic response of the bridge are revealed. Considering the aspect of seismic performance, the suitability of employing suspension bridge in super long-span bridges is investigated as compared to the cable-stayed bridge and cable-stayed-suspension hybrid bridge with the similar main span. Furthermore, the effects of structural parameters including the span arrangement, the cable sag to span ratio, the side to main span ratio, the girder height, the central buckle and the girder support system etc on the seismic response of the bridge are investigated by the seismic response spectrum analysis, and the favorable earthquake-resistant structural system of suspension bridges is also discussed.

2. Description of the example bridge

The Runyang Highway Bridge over the Yangtze River completed in 2005 in China, which is taken as the example bridge herein, is a single-span two-hinged steel suspension bridge with main span of 1490 m and two side spans of 470 m as shown in Fig. 1 (Ji and Zhong 2006). The cable sag to span ratio is 1/10, the lateral distance of two main cables is 34.3 m, and the interval of vertical hangers is 16 m. The deck is a streamlined steel box girder, its depth at the bridge centerline is 3 m and the total width is 38.7 m (including the inspection and maintenance sidewalk). The tower is a door-shaped frame with 3 transverse beams, its height is about 210 m above from the ground level. The cross-sectional and material properties of the example bridge are given in Table 1.

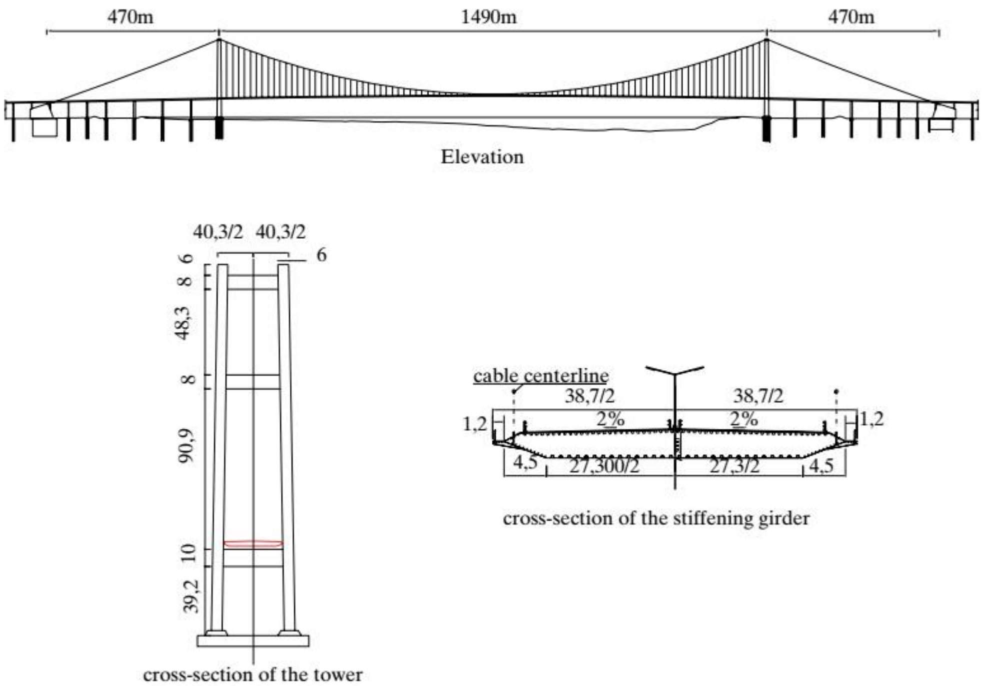

Fig. 1 General layout of the Runyang Highway Bridge over the Yangtze River

Table 1 The cross-sectional and material properties of the example bridge

Members		*E* (Mpa)	*A* (m^2)	J_d (m^4)	*Iz* (m^4)	*Iy* (m^4)	*M* (kg/m^3)
Girder		2.1×10^5	1.2262	5.133	132.790	1.967	16013
Main cable(single)		2.0×10^5	0.4735	0.0	0.0	0.0	8400
Hanger(single)		2.0×10^5	0.00214	0.0	0.0	0.0	7850
Tower's column		3.5×10^4	24.88~65.18	173.28~512.07	145.91~646.38	96.91~186.09	2600
Tower's stransverse beam	Upper	3.5×10^4	19.14	146.66	75.30	149.60	2600
	Middle	3.5×10^4	20.58	195.32	111.13	168.30	2600
	Bottom	3.5×10^4	26.12	402.75	226.09	346.51	2600

Notes: *E*: elastic modulus; *A*: cross-sectional area; J_d: torsional moment of inertia; *Iz*: vertical bending moment of inertia; *Iy*; lateral bending moment of inertia; *M*: mass density.

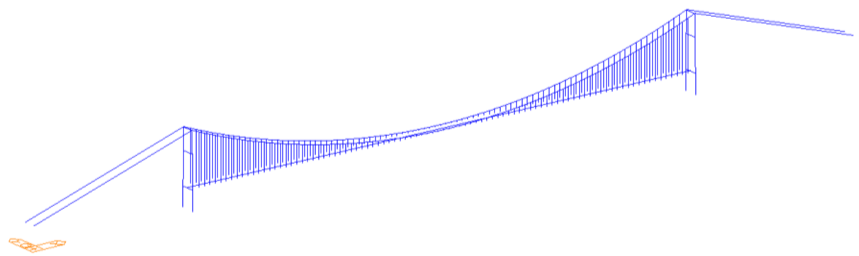

Fig. 2 3D finite element model of the example bridge

3 Finite element model and dynamic characteristic of the example bridge

3.1 Finite element modeling

The example bridge is discretized into a three-dimensional skeleton finite element model as plotted in Fig. 2, in which the stiffening girder is modeled by the single-girder model, the stiffening girder and towers are modeled by 3D beam elements, the hangers and main cables are modeled by 3D bar elements, and the rigid diaphragms are provided to model the connections between the bridge deck and the hangers. The suspension bridge is a flexible structure, and exhibits strong geometric nonlinearity due to: (1) the combined effects of axial force and bending moment in the girder and towers; (2) the nonlinear behavior of cables caused by cable sag and gravity effects; and (3) the bridge geometry change due to large displacement. All sources of geometric nonlinearities are considered in the following analysis. Both the outer and inner boundary conditions are added to the finite element model. The main cables are fixed at the tower upper ends and also the anchorage blocks. The tower bottoms are fixed at the bases. As for the girder at the tower, it is supported vertically by the bottom transverse beams of the towers, the vertical (Z) and lateral (Y) movements and the rotation about *X*-axis of the girder are subordinate to the corresponding nodes of the tower bottom transverse beams, while the longitudinal (X) movement and the rotations about *Y*-axis and *Z*-axis of the girder are left free.

Table 2 The girder's modal properties of the example bridge

Modes	Frequency(Hz)	Modal shape*
Vertical bending	0.1275	1-S
	0.0822	1-AS
	0.1695	2-S
	0.1884	2-AS
	0.2492	3-S
	0.3045	3-AS
Lateral bending	0.0508	1-S
	0.1225	1-AS
Torsion	0.2384	1-S
	0.2926	1-AS

* S: symmetric; AS: anti-symmetric; the value denotes the mode sequence number.

3.2 Dynamic characteristics

On the computed equilibrium state of the example bridge in completion, the dynamic characteristics of the example bridge are analyzed by MIDAS/Civil software based on the subspace iteration method. Table 2 shows the girder's modal properties of the example bridge.

As seen in Table 2, some features on the dynamic behavior of suspension bridge can be concluded as follows: (1) the fundamental period is 12.2s, it is very long, which demonstrates that the suspension bridge is a structural system with great flexibility; (2) the lateral bending mode comes firstly, and then the longitudinal floating-vertical bending coupled mode comes the next, the frequency ratio of the fundamental in-plane and out-of-plane modes is 1.618:1, which indicates the out-of-plane structural stiffness is less than that in plane, and the bridge becomes more susceptible to the lateral and longitudinal actions such as wind and earthquake; (3) the vibration frequency distributes densely within a narrow frequency band, and the coupling among modes is remarkable, and therefore the CQC method should be used for modal combination in the seismic response analysis of suspension bridge.

4. Seismic response analysis of the example bridge

4.1 Earthquake ground motion

4.1.1 Seismic acceleration response spectrum

According to the guidelines for seismic design of highway bridges(JTGT B02-01 2008), the bridge type and the geological condition of bridge site, the seismic fortification intensity is 7, and the basic design acceleration of ground motion is 0.15g; the site is classified as Class Ⅱ, its characteristic period is 0.40s, and structural damping ratio is taken as 2%. Under the earthquake action E1, the design horizontal seismic acceleration response spectrum is plotted in Fig.3, and for the vertical design seismic acceleration response spectrum, it is taken as 65% the horizontal seismic acceleration response spectrum.

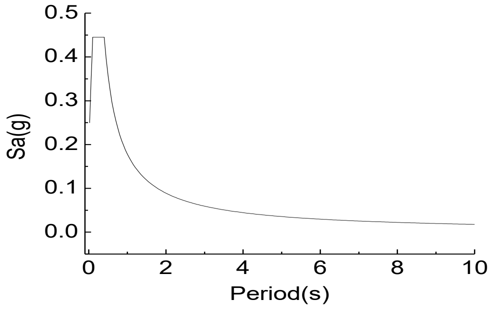

Fig. 3 The horizontal seismic design acceleration response spectrum under earthquake action E1

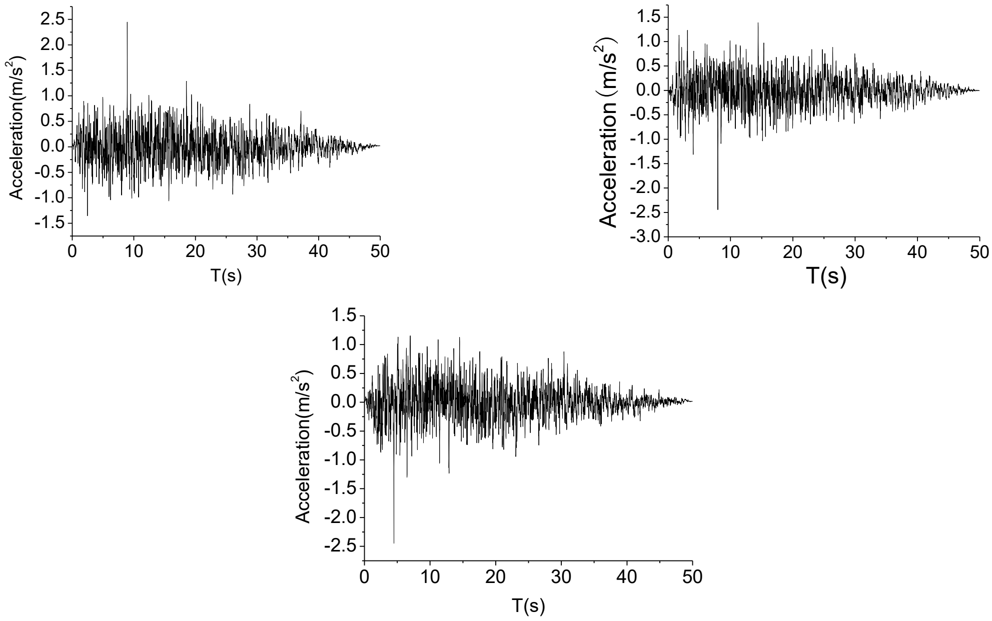

Fig. 4 Three artificial seismic acceleration time-history curves under earthquake action E1

4.1.2 The artificial seismic acceleration time-history curves

By taking the above design response spectrum as target spectrum, three artificial seismic acceleration time-history curves as shown in Fig. 4 are generated by the trigonometric series superposition method, which are the seismic excitations of nonlinear seismic response time-history analysis as follows.

4.2 Seismic response spectrum analysis

Under the longitudinal, lateral and vertical seismic excitations, structural response of the example bridge is investigated numerically by multimode response spectrum analysis of MIDAS/Civil software. Due to the dense distribution of natural frequency of the bridge, the modal coupling effect is remarkable, and the CQC method is thus used for modal combination. Due to the length limitation, only the maximum seismic responses are given in Table 3.

Table 3 The maximum seismic response values of the example bridge under earthquake action E1

Seismic excitations	Members	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Vertical	Lateral
Longitudinal	Tower	1.165×10^6	1.313×10^4	1.091×10^4	608.2	-	-
	Girder	1.328×10^5	6.178×10^3	1.359×10^4	574.1	225.6	-
	Main cable	-	-	1.653×10^5	817.5	149.8	-
Lateral	Tower	2.935×10^5	1.448×10^4	2.736×10^4	-	-	125.7
	Girder	1.332×10^6	9.193×10^3	-	-	-	905.3
	Main cable	-	-	1.701×10^5			918.6
Vertical	Tower	4.471×10^4	-	1.240×10^5	25.0	-	-
	Girder	7.382×10^4	3.010×10^3	2.958×10^3	1.0	123.9	-
	Main cable	-	-	1.574×10^5	146.7	143.9	-

Note: under the longitudinal and vertical seismic excitations, the tower's bending moment and shear force are both in longitudinal direction, and as for the girder, they are in vertical direction; under the lateral seismic excitation, the bending moment and shear force are both in lateral direction; the same as follows.

As observed from the analysis results, the seismic behavior of suspension bridge can be concluded as follows:

(1) Under the longitudinal seismic excitation, the towers are undergoing the longitudinal vibration, and the girder and main cables are undergoing the longitudinal and vertical vibration. As for the towers, the maximum longitudinal displacement occurs at one third of tower height departing from the tower upper end, and there exists the maximum longitudinal bending moment and shear force at the tower bottom section. For the girder, the longitudinal displacement is basically the same along the bridge axis, and at the two quarter points, there exists the maximum vertical displacement and also the vertical bending moment, however the maximum shear and axial forces occur in the sections near the tower and at midspan respectively. Generally, the seismic response of the tower is much greater than that of the girder, therefore the longitudinal seismic excitation is unfavorable for the tower, and more attention should be paid to the seismic design of the tower bottom section.

(2) Under the lateral seismic excitation, the tower, girder and main cables are all undergoing the lateral vibration. The girder maximum lateral displacement happens at midspan, and but its maximum lateral bending moment and shear force occur at the section near the tower. The tower bends laterally, the maximum lateral displacement occurs at the tower upper end, and its maximum lateral bending moment, shear and axial force occur at the tower bottom section. The main cables move laterally with the girder, their maximum lateral displacements are basically the same. As compared to the tower, greater seismic response is achieved for the girder, and the girder sections near the tower and at midspan become the key sections, which should be paid more attention to its seismic design.

(3)Under the vertical seismic excitation, the tower bends longitudinally, and the girder and main cables move longitudinally and deflect vertically. As for the girder, the maximum vertical displacement and bending moment occur at the midpoint of main span, and there exists the maximum shear and axial forces in the sections near the tower and at midspan respectively. The inertial forces of the girder and main cables under the vertical seismic excitation are transferred to the foundation through the towers and anchorage blocks, the axial force in the tower is thus

Table 4 The peak values of time-history seismic response under E1 seismic action

Seismic excitations	Members	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Vertical	Lateral
Longitudinal	Tower	1.284×10^6	1.913×10^4	1.204×10^4	776.3	-	-
	Girder	1.553×10^5	6.962×10^3	1.878×10^4	625.3	259.3	-
	Main cable	-	-	1.817×10^5	891.1	169.2	-
Lateral	Tower	3.382×10^5	1.666×10^4	2.986×10^4	-	-	147.4
	Girder	1.377×10^6	1.029×10^4	-	-	-	966.3
	Main cable	-	-	1.832×10^5	-	-	1157.2
Vertical	Tower	4.981×10^4	-	1.468×10^4	32.2	-	-
	Girder	8.226×10^4	3.298×10^3	3.462×10^3	5.7	144.7	-
	Main cable	-	-	1.717×10^5	151.6	234.2	-

increased remarkably, and due to the longitudinal bending of the towers, large longitudinal bending moment and shear force occur at the tower bottom section.

(4) Through the comparison of results given in Table 3, it can be found that structural responses under the longitudinal and lateral seismic excitations are both much greater than those under the vertical seismic excitation, and therefore the seismic performance of suspension bridge under the horizontal earthquake action should be emphasized. The seismic excitation produces great structural response for the tower bottom and the girder sections near the tower, at quarter point and midspan, and therefore more attentions should be paid to the seismic design of these sections.

4.3 Nonlinear seismic response time-history analysis

To investigate the effect of structural nonlinearity on the seismic performance of suspension bridge, the seismic response of the bridge under the horizontal and vertical earthquake ground motions is conducted by nonlinear time-history analysis of MIDAS/Civil software, and the peak displacement and internal force of the tower, the girder and main cables are given in Table 4. In the analysis, structural geometric nonlinearity is considered, and three acceleration time-history curves plotted in Fig. 4 are taken as the seismic excitation separately, and the peak values are taken from the corresponding three seismic response curves.

It can be found from the nonlinear time-history analysis that the peak values and their positions of seismic response of the tower, girder and main cables are basically consistent to those of response spectrum analysis. In general, the seismic responses obtained by nonlinear time-history analysis are greater than those of response spectrum analysis as shown in Table 3. As compared to the linear response spectrum analysis, with introducing the nonlinear effect, structural stiffness is reduced, and thus greater response is obtained under the same seismic excitation. Therefore for long-span suspension bridge, the nonlinear time-history analysis is proposed to accurately predict its seismic response.

5. Comparison of the seismic performance with other bridge structures

In order to investigate the applicability of suspension bridge in super long-span bridge with main span over 1000 m from the aspect of seismic performance, a cable-stayed bridge and a cable-stayed-suspension hybrid bridge both with 1400 m main span are taken as comparison bridges, their dynamic characteristics is analyzed firstly, and then their seismic responses under the same seismic excitation are analyzed by the multimode response spectrum method.

5.1 The cable-stayed bridge

Fig. 5(a) shows the side view of a cable-stayed bridge scheme (Nagai, Fujino *et al*. 2004). The center and side spans are assumed to be 1,400 and 680 m respectively. For the side span, three intermediate piers are installed at a distance of 100 m in order to increase in-plane flexural rigidity of the bridge. The deck shown in Fig. 5(b) is a streamlined steel box girder of 35 m wide and 3.5 m high, and is suspended by diagonal stays anchored to the girder at 20 m intervals. As shown in Fig. 5(c) at the edge of the cross section, the thickness of the plate is increased to cope with the large bending moment from wind load in the girder near the tower. The required distance for reinforcement from the tower is defined as Xu seen in Fig. 5(a), which is 80 m herein. Fig. 5(d) shows the front view and the assumed cross section of the tower. Its height from deck level is 280 m, which is one-fifth of the center span length. Table 5 gives the cross-sectional and material properties of the cable-stayed bridge.

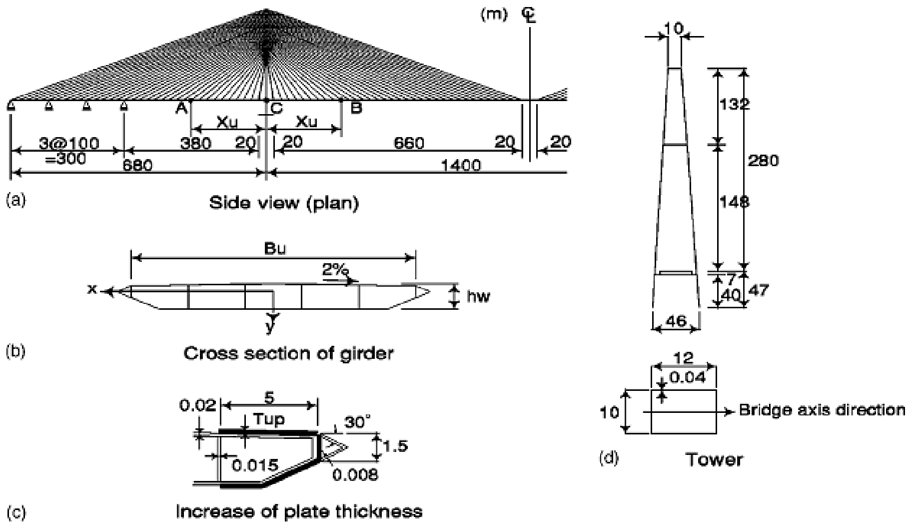

Fig. 5 1400 m cable-stayed bridge (Unit: m)

Table 5 The cross-sectional and material properties of the cable-stayed bridge

Members	*E* (Mpa)	*A* (m^2)	J_d (m^4)	*Iz* (m^4)	*Iy* (m^4)	*M* (Kg/m^3)
Girder	2.1×10^5 (2.1×10^5)	1.761 (2.046)	3.939 (4.432)	8.330 (9.739)	193.2 (261.1)	14673.0 (13705.0)
Stay cable	2.0×10^5	0.0087~0.038	0.0	0.0	0.0	7850.0
Tower	2.1×10^5	1.76	30.67	39.27	40.32	10773.0

Note: Values in parentheses are reinforced values.

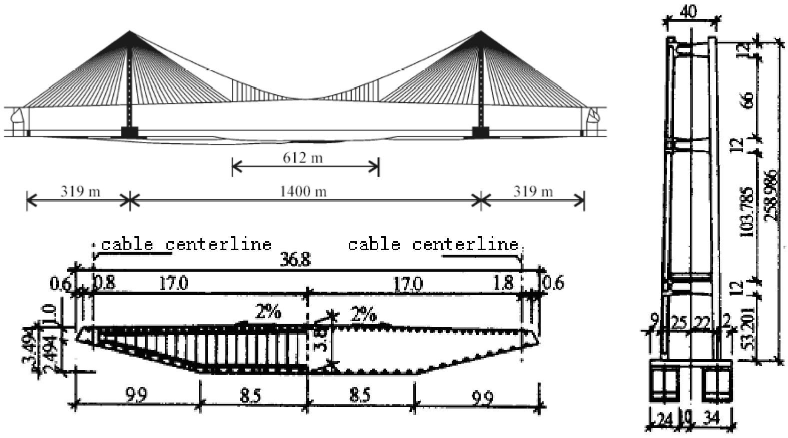

Fig. 6 Elevation of the cable-stayed-suspension hybrid bridge (Unit: m)

Table 6 The cross-sectional and material properties of the cable-stayed-suspension hybrid bridge

Members		E (Mpa)	A (m^2)	J_d (m^4)	Iz (m^4)	Iy (m^4)	M (Kg/m^3)
Girder		2.1×10^5	1.2481	5.034	1.9842	137.754	14732.0
Main cable(single)	CS	2.0×10^5	0.3167	0.0	0.0	0.0	8400.0
	SS	2.0×10^5	0.3547	0.0	0.0	0.0	8400.0
Hanger(single)		2.0×10^5	0.0064	0.0	0.0	0.0	7850.0
Stay cable(single)		2.0×10^5	0.008	0.0	0.0	0.0	7850.0
Tower	C	3.3×10^4	30.0	350.0	320.0	220.0	2600.0
	TB	3.3×10^4	10.0	150.0	70.0	70.0	2600.0

Notes: CS: the center span; SS: the side span; C: the tower's Column; TB: the tower's transverse beam.

5.2 The cable-stayed-suspension hybrid bridge

The earth-anchored cable-stayed-suspension hybrid bridge consists of a main span of 1400 m and two side spans of 319 m as shown in Fig. 6, which was proposed in the east channel of Lingding Strait in China (Zhang 2007). The central span consists of the cable-stayed segment of 788 m and the suspension segment of 612 m. The lateral distance of two main cables is 34 m, the cable sag to span ratio is 1/10, and the interval of hangers is 18 m. The stay cables are anchored to the girder at 18 m intervals in the central span and 14 m in the side spans. The deck is a steel streamlined box steel girder of 36.8 m wide and 3.8 m high. The towers are door-shaped frame with three transverse beams, and their height above the ground level is about 259 m. The cross-sectional and material properties of the bridge are given in Table 6.

5.3 Comparison of the dynamic characteristics

As observed in Table 7, it is found that: (1) the fundamental periods for three bridge structures are all very long, and therefore they are demonstrated to be structural system with great flexibility; (2) for all three bridge structures, the lateral bending mode comes firstly, and then the longitudinal

Table 7 The comparison of natural frequencies (Hz) of different bridge structures

Modes	Suspension bridge	Cable-stayed bridge	Cable-stayed-suspension hybrid bridge	Modal shape
Vertical bending	0.1275	0.1703	0.1858	1-S
	0.0822	0.1928	0.0972	1-AS
	0.1695	0.2503	0.2171	2-S
	0.1884	0.2936	0.1837	2-AS
	0.2492	0.3583	0.3142	3-S
	0.3045	0.4096	0.2849	3-AS
Lateral bending	0.0508	0.0568	0.0621	1-S
	0.1225	0.1655	0.1467	1-AS
Torsion	0.2384	0.3969	0.3359	1-S
	0.2926	0.5124	0.3657	1-AS

Table 8 Comparison of the seismic response peak values of the towers of different bridge structures

Bridge strutures	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)	
					Longitudinal	Lateral
Suspension bridge	Longitudinal	1.165×10^6	1.313×10^4	1.091×10^4	608.2	-
	Lateral	2.935×10^5	1.448×10^4	2.736×10^4	-	125.7
	Vertical	4.471×10^4	-	1.240×10^5	25.0	-
Cable-stayed bridge	Longitudinal	3.770×10^6	3.656×10^4	5.312×10^4	963.6	-
	Lateral	3.695×10^5	3.156×10^4	5.942×10^4	-	234.2
	Vertical	6.234×10^4	-	4.262×10^5	32.3	-
Cable-stayed-suspension hybrid bridge	Longitudinal	1.644×10^6	1.430×10^4	3.394×10^4	891.8	-
	Lateral	1.780×10^5	3.137×10^4	4.675×10^4	-	177.1
	Vertical	5.272×10^4	-	2.142×10^5	62.1	-

floating-vertical bending coupled mode comes the next, which indicates the out-of-plane structural stiffness is less than that in plane, and they are all susceptible to the lateral and longitudinal actions; (3) The cable-stayed bridge has the greatest natural frequencies, then the cable-stayed-suspension hybrid bridge, and for the suspension bridge, it has the least natural frequencies. Therefore under the similar main span, the suspension bridge is the most flexible structural system among the three bridge structures.

5.4 Comparison of the seismic performance

As found in Tables 8 and 9, under the similar main span and the same seismic excitations, the maximum seismic response occurs for the cable-stayed bridge, and whereas the suspension bridge has the minimum seismic response, and as for the cable-stayed-suspension hybrid bridge, it is between the cable-stayed bridge and suspension bridge and but more close to the suspension bridge. Therefore as viewed from the seismic performance, the suspension bridge is superior to both the cable-stayed bridge and the cable-stayed-suspension hybrid bridge, and therefore it

Table 9 Comparison of the seismic response peak values of the girders of different bridge structures

Bridge structures	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
Suspension bridge	Longitudinal	1.328×10^5	6.178×10^3	1.359×10^4	574.1	-	225.6
	Lateral	1.332×10^6	9.193×10^3	-	-	905.3	-
	Vertical	7.382×10^4	3.010×10^3	2.958×10^3	1.0	-	123.9
Cable-stayed bridge	Longitudinal	9.962×10^5	3.522×10^4	4.416×10^4	1180.2	-	650.1
	Lateral	3.873×10^6	3.082×10^4	-	-	983.2	-
	Vertical	1.464×10^5	6.210×10^3	1.533×10^4	20.8	-	226.9
Cable-stayed-suspension hybrid bridge	Longitudinal	4.833×10^5	1.232×10^4	1.910×10^4	864.9	-	300.1
	Lateral	2.184×10^6	1.662×10^4	-	-	915.9	-
	Vertical	1.045×10^5	5.833×10^3	2.062×10^4	10.2	-	201.5

becomes the most suitable bridge structure for super long-span bridges with kilometer-scale main span.

6. Parametric study on the seismic performance of suspension bridge

To explore the favorable earthquake-resistant structural system of suspension bridge, under the horizontal and vertical seismic excitations, the effects of structural parameters including the span arrangement, the cable sag to span ratio, the side to main span ratio, the girder depth, the central buckle and the girder supporting system etc (Zhang and Sun 2004, Zhang and Fu 2014) on the seismic performance of suspension bridge are investigated by multimode response spectrum analysis of MIDAS/Civil software, and the favorable values of these design parameters are proposed.

6.1 The span arrangement

The suspension bridge generally has two kinds of span arrangements, one is single span, and the other is three spans, and the latter is commonly employed in practice. However in the case of deep water and shallow beach, to save the cost of substructure, the suspension bridge is usually designed as single-span structure through increasing the main span length. Under the same span length, the vertical stiffness of single-span suspension bridge is generally greater than that of the three-span one. Based on the example bridge, a three-span continuous suspension bridge scheme is designed, which has the same main and side span length as the example bridge, and its seismic response is analyzed and given in Tables 10 and 11.

It is found that the span arrangement has important influence on the seismic response, especially under the longitudinal and lateral seismic excitations. Under the same seismic excitation, the seismic response of three-span suspension bridge is much less than that of single-span one, and better seismic performance is achieved for the three-span suspension bridge. Therefore as viewed from the aspect of seismic performance, three-span arrangement is more favorable for long-span suspension bridge.

Table 10 Effect of the span arrangement on the seismic response of tower

The span arrangement	Seismic excitation	Bending moment(kN.m)	Shear force (kN)	Axial force(kN)	Displacement(mm)	
					Longitudinal	Lateral
Single-span	Longitudinal	1.165×10^6	1.313×10^4	1.091×10^4	608.2	-
	Lateral	2.935×10^5	1.448×10^4	2.736×10^4	-	125.7
	Vertical	4.471×10^4	-	1.240×10^5	25	-
Three-span	Longitudinal	9.568×10^5	1.021×10^4	9.153×10^3	534	-
	Lateral	2.324×10^5	1.112×10^4	2.617×10^4	-	100.4
	Vertical	4.025×10^4	-	1.065×10^5	21.6	-

Table 11 Effect of the span arrangement on the seismic response of girder

The span arrangement	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
Single-span	Longitudinal	1.328×10^5	6.178×10^3	1.359×10^4	574.1	-	225.6
	Lateral	1.332×10^6	9.193×10^3	-	-	905.3	-
	Vertical	7.382×10^4	3.010×10^3	2.958×10^3	1.0	-	123.9
Three-span	Longitudinal	9.287×10^4	5.186×10^3	1.251×10^4	529.3	-	198.2
	Lateral	9.263×10^5	8.327×10^3	-	-	845.6	-
	Vertical	3.623×10^4	4.833×10^3	1.713×10^3	2.1	-	101.7

6.2 The cable sag to span ratio

The cable sag to span ratio is another important design parameter for long-span suspension bridge, which affects the economy and structural stiffness of the bridge. Generally, the sag to span ratio ranges from 1/9 to 1/11. To understand how the cable sag affects the seismic behavior of suspension bridge, based on the example bridge, through remaining the girder alignment and the positions of main cables at midspan unchanged and also adjusting the tower height and the sections of main cables and hangers, two bridge schemes with the cable sag to span ratio of 1/9 and 1/11 are assumed respectively, the seismic response analysis is performed, and the effect of cable sag to span ratio on the seismic response of the tower and girder is shown in Tables 12 and 13.

With increasing the cable sag to span ratio, as found in Tables 12 and 13, the seismic responses of both the tower and girder are significantly reduced, and the seismic performance of suspension bridge is thus improved. Therefore, the large cable to span ratio is favorable for the seismic performance of long-span suspension bridge. Although the small cable sag to span ratio is favorable to improve the static performance of suspension bridge, it leads to bad seismic performance. In conclusion, it should consider both the static and dynamic performance to determine the cable sag to span ratio of suspension bridge.

6.3 The side to main span ratio

The side to main span ratio is also an important parameter affecting the economy and structural

Table 12 Effect of the cable sag to span ratio on the seismic response of tower

The cable sag to span ratio	Seismic excitation	Bending moment(kN.m)	Shear force (kN)	Axial force(kN)	Displacement(mm)	
					Longitudinal	Lateral
1/9	Longitudinal	1.105×10^6	9.933×10^3	9.283×10^3	591.6	-
	Lateral	2.968×10^5	1.434×10^4	2.679×10^4	-	125.7
	Vertical	3.258×10^4	-	9.573×10^4	23.6	-
1/10	Longitudinal	1.165×10^6	1.313×10^4	1.091×10^4	608.2	-
	Lateral	2.935×10^5	1.448×10^4	2.736×10^4	-	132.7
	Vertical	4.471×10^4	-	1.240×10^5	25.0	-
1/11	Longitudinal	1.925×10^6	1.934×10^4	2.329×10^4	689.6	-
	Lateral	2.956×10^5	1.469×10^4	2.743×10^4	-	133.3
	Vertical	5.982×10^4	-	1.537×10^5	29.5	-

Table 13 Effect of the cable sag to span ratio on the seismic response of girder

The cable sag to span ratio	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
1/9	Longitudinal	1.224×10^5	3.536×10^3	1.092×10^4	502.6	-	205.9
	Lateral	1.219×10^6	9.029×10^3	-	-	882.6	-
	Vertical	7.136×10^4	2.673×10^3	2.158×10^3	0.9	-	103.2
1/10	Longitudinal	1.328×10^5	6.178×10^3	1.359×10^4	574.1	-	225.6
	Lateral	1.332×10^6	9.193×10^3	-	-	905.3	-
	Vertical	7.382×10^4	3.010×10^3	2.958×10^3	1.0	-	123.9
1/11	Longitudinal	1.722×10^5	8.620×10^3	1.434×10^4	583.6	-	312.4
	Lateral	1.571×10^6	9.152×10^3	-	-	937.6	-
	Vertical	7.310×10^4	3.158×10^3	3.244×10^3	3.2	-	145.9

Table 14 Effect of the side to main span ratio on the seismic response of tower

The side to main span ratio	Seismic excitation	Bending moment(kN.m)	Shear force (kN)	Axial force(kN)	Displacement(mm)	
					Longitudinal	Lateral
0.2	Longitudinal	9.753×10^5	1.029×10^4	9.781×10^3	533.8	-
	Lateral	3.132×10^5	1.782×10^4	2.958×10^4	-	128.5
	Vertical	5.813×10^4	-	1.009×10^5	24.3	-
0.315	Longitudinal	1.165×10^6	1.313×10^4	1.091×10^4	608.2	-
	Lateral	2.935×10^5	1.448×10^4	2.736×10^4	-	132.7
	Vertical	4.471×10^4	-	1.240×10^5	25.0	-
0.4	Longitudinal	1.592×10^6	1.431×10^4	1.329×10^4	700.1	-
	Lateral	2.756×10^5	1.269×10^3	2.343×10^4	-	135.8
	Vertical	2.086×10^4	-	1.532×10^5	26.3	-

stiffness of suspension bridge. With increasing the side span length, the cable sag in side span is increased simultaneously, the longitudinal constraint for the center span and thus structural

Table 15 Effect of the side to main span ratio on the seismic response of girder

The side to main span ratio	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
0.2	Longitudinal	1.288×10^5	5.785×10^3	1.291×10^4	524.2	-	155.2
	Lateral	1.122×10^6	8.996×10^3	-	-	883.5	-
	Vertical	7.212×10^4	2.603×10^3	2.786×10^3	0.8	-	113.6
0.315	Longitudinal	1.328×10^5	6.178×10^3	1.359×10^4	574.1	-	225.6
	Lateral	1.332×10^6	9.193×10^3	-	-	905.3	-
	Vertical	7.382×10^4	3.010×10^3	2.958×10^3	1.0	-	123.9
0.4	Longitudinal	1.622×10^5	6.202×10^3	2.414×10^4	629.6	-	282.6
	Lateral	1.415×10^6	9.427×10^3	-	-	937.6	-
	Vertical	7.314×10^4	5.558×10^3	2.478×10^3	2.4	-	145.3

Table 16 The girder cross-sectional properties with different girder depth

The girder depth(m)	3.0	3.5	4.0
A (m^2)	1.2481	1.3095	1.3214
I_y (m^4)	137.75	139.12	141.15
I_z (m^4)	1.9842	2.8662	3.7425
J_d (m^4)	5.034	7.394	9.323
m (Kg/m)	18386.5	19013.2	19134.6

stiffness are reduced. The side to main span ratio of suspension bridge mainly ranges from 0.2 to 0.4, and rarely exceeds 0.4. Generally, the small side to main span ratio is favorable to decrease structural deformation and improve the economy and dynamic performance. The side to main span ratio for the example bridge is 0.315, through remaining the main span unchanged and adjusting the side span length, two bridge schemes with the side to main span ratio of 0.2 and 0.4 respectively are designed, and their seismic responses are analyzed and given in Tables 14 and 15.

With the increase of side span length, the longitudinal seismic response of tower increases significantly, while the lateral and vertical seismic responses are little affected. As for the girder, the longitudinal, lateral and vertical seismic responses all increases significantly. Therefore, the shorter side span is favorable to improve the seismic performance of suspension bridge.

6.4 The girder depth

In practice, the streamlined steel box girder is commonly employed to enhance the wind stability for long-span suspension bridges with single deck. Generally, the girder depth ranges from 3 m to 5 m, and the depth to span length ratio is less than 1/300. To a certain extent, the increase of girder depth can improve the vertical stiffness and decrease the vertical deflection. To investigate the influence of the girder depth on the seismic performance of suspension bridge, through remaining the girder width the same and changing the girder depth, two box girders with depth of 3.5 m and 4.0 m respectively are assumed, and the corresponding bridge schemes are designed, the cross-sectional properties of the girder with different depth are given in Table 16. The seismic responses of both two bridge schemes are analyzed, and the effect of girder depth on

Table 17 Effect of the girder depth on the seismic response of tower

The girder depth(m)	Seismic excitation	Bending moment(kN.m)	Shear force (kN)	Axial force(kN)	Displacement(mm)	
					Longitudinal	Lateral
3.0	Longitudinal	1.165×10^6	1.313×10^4	1.091×10^4	608.2	-
	Lateral	2.935×10^5	1.448×10^4	2.736×10^4	-	132.7
	Vertical	4.471×10^4	-	1.240×10^5	25.0	-
3.5	Longitudinal	1.116×10^6	1.268×10^4	1.174×10^4	593.6	-
	Lateral	2.986×10^5	1.528×10^4	2.702×10^4	-	138.2
	Vertical	4.428×10^4	-	1.325×10^5	25.7	-
4.0	Longitudinal	1.092×10^6	1.231×10^4	1.329×10^4	588.2	-
	Lateral	3.106×10^5	1.609×10^4	2.633×10^4	-	145.3
	Vertical	4.326×10^4	-	1.431×10^5	26.2	-

Table 18 Effect of the girder depth on the seismic response of girder

The girder depth(m)	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
3.0	Longitudinal	1.328×10^5	6.178×10^3	1.359×10^4	574.1	-	225.6
	Lateral	1.332×10^6	9.193×10^3	-	-	905.3	-
	Vertical	7.382×10^4	3.010×10^3	2.958×10^3	1.0	-	123.9
3.5	Longitudinal	1.387×10^5	6.728×10^3	1.796×10^4	582.3	-	225.6
	Lateral	1.465×10^6	9.873×10^3	-	-	912.6	-
	Vertical	7.452×10^4	3.117×10^3	2.963×10^3	1.1	-	126.4
4.0	Longitudinal	1.510×10^5	6.952×10^3	1.834×10^4	590.6	-	212.8
	Lateral	1.715×10^6	1.527×10^4	-	-	925.7	-
	Vertical	7.612×10^4	3.258×10^3	2.972×10^3	1.2	-	126.3

the seismic response of the tower and girder is presented in Tables 17 and 18.

With the increase of girder depth, the longitudinal displacement, the bending moment and shear force of the tower are reduced slightly, however structural response of the tower under the lateral and vertical seismic excitations are increased a little. The girder depth has significant influence on structural response of the girder under the longitudinal and lateral excitations, but for the vertical excitation, the influence is little. As the girder depth increases, under the longitudinal seismic excitation, the vertical displacement decreases slightly, however the longitudinal displacement and especially the inner force increase greatly; under the lateral seismic excitation, the seismic response of girder increases remarkably. In conclusion, the main seismic response increases with the increase of the girder depth, and the increase of girder depth is not favorable for the seismic performance of suspension bridge.

6.5 The central buckle

Instead of the short hangers, the rigid central buckle at the midspan is used in the example bridge to connect the girder and main cables, which optimizes the stress state of the shorter

Table 19 Effect of the central buckle on the seismic response of tower

The central buckle	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)	
					Longitudinal	Lateral
With	Longitudinal	1.165×10^{6}	1.313×10^{4}	1.091×10^{4}	608.2	-
	Lateral	2.935×10^{5}	1.448×10^{4}	2.736×10^{4}	-	132.7
	Vertical	4.471×10^{4}	-	1.240×10^{5}	25.0	-
Without	Longitudinal	1.535×106	1.658×104	1.373×104	683.7	-
	Lateral	2.972×10^{5}	1.486×10^{4}	2.746×10^{4}	-	133.5
	Vertical	4.578×10^{4}	-	1.431×10^{5}	30.6	-

Table 20 Effect of the central buckle on the seismic response of girder

The central buckle	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
With	Longitudinal	1.328×10^{5}	6.178×10^{3}	1.359×10^{4}	574.1	-	225.6
	Lateral	1.332×10^{6}	9.193×10^{3}	-	-	905.3	-
	Vertical	7.382×10^{4}	3.010×10^{3}	2.958×10^{3}	1.0	-	123.9
Without	Longitudinal	1.625×10^{5}	7.226×10^{3}	1.598×10^{4}	581.9	-	312.4
	Lateral	1.372×10^{6}	9.218×10^{3}	-	-	912.1	-
	Vertical	7.496×10^{4}	3.158×10^{3}	3.244×10^{3}	2.1	-	145.9

hangers and enhances the whole rigidity of suspension bridge. The central buckle is a triangle truss and consists of the cable clip, the inclined and vertical bars, and the girder segment at midspan. Based on the example bridge, a bridge scheme is designed through replacing the rigid central buckle with the short hangers at midspan, and its seismic response is analyzed and shown in Tables 19 and 20.

It is found that the central buckle has little influence on the lateral seismic action, however has significant effect on the longitudinal and vertical seismic actions. As compared to the short hangers at midspan, the longitudinal displacement and internal force of the tower, the longitudinal and vertical displacements and internal force of the girder are all reduced significantly in the case of the central buckle set at midspan, and the seismic performance is thus improved. Therefore, the rigid central buckle is an efficient countermeasure to improve the seismic performance of long-span suspension bridge.

6.6 The girder supporting system

The girder supporting system refers to the connection between the girder and towers. For the single-span suspension bridge, both two ends of the stiffening girder are hinge-supported on the tower transverse beams, which is called as single-span two-hinged system herein. As for the three-span suspension bridge, the stiffening girder can be made continuous or not continuous along the whole bridge span, and the former is called as three-span continuous system, whereas the latter is called as three-span two-hinged system. For three-span suspension bridge, whether the stiffening girder is continuous or not has small influence on the quantity of material used and the global

Table 21 Effect of the girder supporting system on the seismic response of tower

The girder supporting system	Seismic excitation	Bending moment(kN.m)	Shear force (kN)	Axial force(kN)	Displacement(mm)	
					Longitudinal	Lateral
Single-span two-hinged system	Longitudinal	1.165×10^6	1.313×10^4	1.091×10^4	608.2	-
	Lateral	2.935×10^5	1.448×10^4	2.736×10^4	-	132.7
	Vertical	4.471×10^4	-	1.240×10^5	25.0	-
Three-span continuous system	Longitudinal	9.568×10^5	1.021×10^4	9.153×10^3	534.2	-
	Lateral	2.324×10^5	1.112×10^4	2.617×10^4	-	100.4
	Vertical	4.025×10^4	-	1.065×10^5	21.6	-
Three-span two-hinged system	Longitudinal	9.753×10^5	1.101×10^4	9.833×10^3	540.1	-
	Lateral	2.428×10^5	1.131×10^4	2.688×10^4	-	104.7
	Vertical	4.132×10^4	-	1.147×10^5	22.3	-

Table 22 Effect of the girder supporting system on the seismic response of girder

The girder supporting system	Seismic excitation	Bending moment(kN.m)	Shear force(kN)	Axial force(kN)	Displacement(mm)		
					Longitudinal	Lateral	Vertical
Single-span two-hinged system	Longitudinal	1.328×10^5	6.178×10^3	1.359×10^4	574.1	-	225.6
	Lateral	1.332×10^6	9.193×10^3	-	-	905.3	-
	Vertical	7.382×10^4	3.010×10^3	2.958×10^3	1.0	-	123.9
Three-span continuous system	Longitudinal	9.287×10^4	5.186×10^3	1.251×10^4	529.3	-	198.2
	Lateral	9.263×10^5	8.327×10^3	-	-	845.6	-
	Vertical	3.623×10^4	4.833×10^3	1.713×10^3	2.1	-	101.7
Three-span two-hinged system	Longitudinal	9.307×10^4	5.223×10^3	1.269×10^4	535.2	-	200.6
	Lateral	9.481×10^5	9.231×10^3	-	-	856.3	-
	Vertical	3.872×10^4	4.993×10^3	2.136×10^3	2.4	-	103.2

deformation. But in the case of continuous deck, riding is smooth and comfortable. To investigate the influence of the girder supporting system on the seismic performance of suspension bridge, two case bridges of three-span continuous system and three-span two-hinged system are designed respectively, and their seismic responses are analyzed and given in Tables 21 and 22.

For three-span suspension bridge, whether the girder is continuous or not has little influence on the seismic response, the seismic response of three-span two-hinged system is slightly greater than that of three-span continuous system, and their seismic response are both less than that of single-span two-hinged system. Therefore, the three-span continuous system has the best seismic performance, then the three-span two-hinged system, and the worst is the single-span two-hinged system. Considering from the seismic performance, the three-span continuous system is favorable for long-span suspension bridge.

7. Conclusions

By taking the Runyang Highway Bridge over the Yangtze River with main span of 1490 m as example, structural response of the bridge under the horizontal and vertical seismic excitations is investigated by the response spectrum and time-history analysis of MIDAS/Civil software respectively, the seismic performance and the effect of structural nonlinearity on the seismic response of the bridge are revealed. Considering the aspect of seismic performance, the feasibility of using the suspension bridge in super long-span bridges is investigated with compared to the cable-stayed bridge and cable-stayed-suspension hybrid bridge with the similar main span. Under the horizontal and vertical seismic excitations, the effects of structural parameters including the span arrangement, the cable sag to span ratio, the side to main span ratio, the girder depth, the central buckle and the girder support system etc on the seismic response of suspension bridge are investigated by the seismic response spectrum analysis, and the favorable earthquake-resistant structural system is also discussed. Some conclusions can be drawn as follows:

(1) The horizontal seismic excitation produces significant seismic response of the girder and tower, there exists great seismic response for the tower bottom and the girder sections near the tower, at quarter point and midspan, and therefore particular attention must be given to the seismic design of these sections.

(2) Structural nonlinearity has significant influence on the seismic response of suspension bridge, and thus the nonlinear time-history analysis is favorable for the seismic response evaluation of long-span suspension bridges.

(3) As compared to the cable-stayed bridge and cable-stayed-suspension hybrid bridge with the similar main span, the suspension bridge has the least seismic response, and becomes an ideal earthquake-resistant structural system for super long-span bridges with kilometer-scale main span.

(4) better seismic performance is achieved for long-span suspension bridge through using the three-span continuous system, increasing the cable sag to span ratio, reducing the side span length and the height of the stiffening girder, and setting rigid central buckle at midspan.

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