Wind and Structures, *Vol. 21, No. 4 (2015) 407-424*
DOI: http://dx.doi.org/10.12989/was.2015.21.4.407

Numerical investigation on the wind stability of super long-span partially earth-anchored cable-stayed bridges

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(Received April 22, 2015, Revised October 9, 2015, Accepted October 10, 2015)

Abstract. To explore the favorable structural system of cable-stayed bridges with ultra-kilometer main span, based on a fully self-anchored cable-stayed bridge with 1400 m main span, a partially earth-anchored cable-stayed bridge scheme with the same main span is designed. Numerical investigation on the dynamic characteristics, aerostatic and aerodynamic stability of both two bridge schemes is conducted, and the results are compared to those of a suspension bridge with similar main span, and considering from the aspect of wind stability, the feasibility of using partially earth-anchored cable-stayed bridge in super long-span bridges with ultra-kilometer main span is discussed. Moreover, the effects of structural design parameters including the length of earth-anchored girder, the number of auxiliary piers in side span, the height and width of girder, the tower height etc on the dynamic characteristics, aerostatic and aerodynamic stability of a partially earth-anchored cable-stayed bridge are analyzed, and their reasonable values are proposed. The results show that as compared to fully self-anchored cable-stayed bridge and suspension bridge with similar main span, the partially earth-anchored cable-stayed bridge has greater structural stiffness and better aerostatic and aerodynamic stability, and consequently becomes a favorable structural system for super long-span bridges with ultra-kilometer main span. The partially earth-anchored cable-stayed bridge can achieve greater stiffness and better wind stability under the cases of increasing the earth-anchored girder length, increasing the height and width of girder, setting several auxiliary piers in side span and increasing the tower height.

Keywords: partially earth-anchored cable-stayed bridge; dynamic characteristics, aerostatic stability; aerodynamic stability; structural design parameters

1. Introduction

Since the completion of the Stromsund Bridge in Sweden in 1955, because of its strong spanning capacity and good mechanical performance, the cable-stayed bridge has been rapidly developed in the world. The Stonecutters Bridge in Hongkong and the Sutong Yangtze River Bridge in China with a main span of 1018 m and 1088 m respectively have been completed in 2008, which means the implementation main span of cable-stayed bridge of kilometer-scale breakthrough. In 2012, the Russky Island Bridge in Russia with a main span of 1104 m is completed. At present, the world bridge engineering is entering a new era of building the sea-crossing bridges, and the span length of cable-stayed bridge continues to grow (Xiang 2012). However, with the continuous increase of span length of cable-stayed bridges, several important

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http://www.techno-press.org/?journal=was&subpage=8 ISSN: 1226-6116 (Print), 1598-6225 (Online)

problems such as the wind stability, the strength and rigidity of super long stay cables, the excessive axial compression in the girder at the junction of tower and girder and also the resulting girder buckling etc arise, which will significantly restrict further development of cable-stayed bridges. Aiming to these problems, researchers have put forward some resolutions. Instead of the traditional fully self-anchored cable-stayed bridge, Gimsing and Georgakis (2012) developed the design concept of partially earth-anchored cable-stayed bridge to decrease the excessive compression in the girder. It is a new structural system of cable-stayed bridges, through setting several stay cables near the bridge ends to be earth-anchored, the horizontal component of stay cables near the midspan provides the tension in the girder, which helps to reduce significantly the excessive compression in the girder at the junction of tower and girder and make the axial force in the girder distribute uniformly. As compared to the fully self-anchored cable-stayed bridge, the partially earth-anchored cable-stayed bridge has less compression in the girder, greater structure stiffness and better structural stability.

In recent years, comprehensive investigations on structural system and mechanical performance of partially earth-anchored cable-stayed bridge have been conducted. Muller (1991) brought forward the concept of applying prestress to the central part of the girder which was earth-anchored and subjected to tension, and also the term of “Bi-stayed”. Xia (2010) and Won *et al.* (2008a) studied the construction method of partially earth-anchored cable-stayed bridge. Sun (2008), Sun *et al.* (2010), Won *et al.* (2008b), Xia (2010), Xiao *et al.* (2013) and Zhang *et al.* (2011) investigated the static performance and its parametric effect of the partially earth-anchored cable-stayed bridge in completion. Chen *et al.* (2013) proposed an approximate calculation formulation of nature frequency of partially earth-anchored cable-stayed bridges. Won *et al.* (2008c) investigated the buffeting response of a partially earth-anchored cable-stayed bridge under the dynamic wind action. Unfortunately, few investigations on the wind stability of partially earth-anchored cable-stayed bridge have been done. As is known to all, the cable-stayed bridge is a flexible structural system and susceptible to the wind action, and the wind stability therefore becomes an important factor for its design.

In this work, based on a fully self-anchored cable-stayed bridge with 1400 m main span, a partially earth-anchored cable-stayed bridge scheme with the same main span is designed, and the dynamic characteristics, aerostatic and aerodynamic stability of both two bridge schemes are investigated numerically, and the results are compared with those of a suspension bridge with similar main span, and considering from the aspect of wind stability, the feasibility of using the partially earth-anchored cable-stayed bridge in super long-span bridges with ultra-kilometer main span is discussed. In addition, the effects of structural design parameters including the length of earth-anchored girder, the number of auxiliary piers in side spans, the height and width of girder, the tower height etc on the dynamic characteristics, aerostatic and aerodynamic stability of the partially earth-anchored cable-stayed bridge are analyzed, and their reasonable values are proposed.

2. Descriptions of the example bridges and finite element models

2.1 The cable-stayed bridge schemes

Fig. 1(a) shows the side view of a 1400 m fully self-anchored cable-stayed bridge model(Nagai *et al*. 2004). Center and side spans are assumed to be 1400 m and 680 m respectively. For each side span, 3 intermediate piers are installed at a distance of 100 m in order to increase in-plane flexural rigidity of the bridge. The four stay cable planes are fan-shaped, and in each stay cable planes, there are 2×34 stay cables. The deck 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. The tower is an A-shaped frame, its height is 327 m above from the ground and 280 m from deck level, which is one-fifth of the center span length.

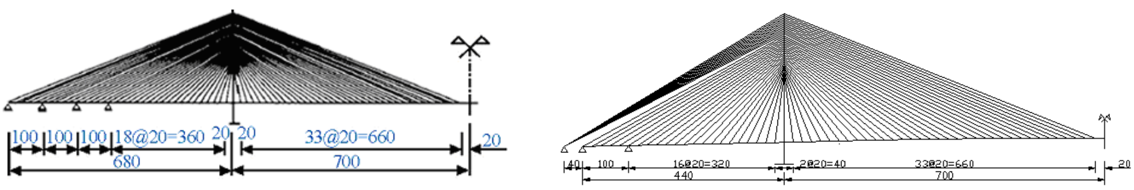
Based on the above fully self-anchored cable-stayed bridge, a partially earth-anchored cable-stayed bridge scheme is designed as shown in Fig. 1(b), in which 2×12 stay cables near the bridge ends in each side span are earth-anchored, and the others are remained to be anchored to the girder. The bridge consists of a main span of 1400 m and two side spans of 440 m, and an auxiliary pier is installed in each side span. As for the main span, the earth-anchored girder is 480 m long that locates in the central part of main span, and the other 920 m girder segment is self-anchored.

2.2 The suspension bridge

To illustrate the feasibility of using the partially earth-anchored cable-stayed bridge in super long-span bridges with ultra-kilometer main span, a suspension bridge with the similar main span-the Jiangyin Bridge over the Yangtze River, is also taken as example as shown in Fig. 2. The Jiangyin Bridge stretching from Jingjiang to Jiangyin in Jiangsu Province of China, has a main span of 1385 m between Jingjiang tower in the north and Jiangyin tower in the south, the length of the Jingjiang side span is 336 m, and the length of the Jingyin side span is 309 m. The cable sag-to-span ratio is 1/10.5, the lateral distance of two cables is 32.5 m, and the interval of hangers is 16 m. The deck is an aerodynamically shaped closed box steel girder of 3.0 m high and 36.9 m. The two towers are both door-shaped frames and differ in the height, the height of Jingjiang tower is 184 m, and for the Jingyin tower, it is 187 m high.

2.3 Finite element models

Three three-dimensional finite element models have been established for the above bridges, as plotted in Fig.3. Three-dimensional beam elements are used to model the bridge towers and girders. The stay cables, main cables and hangers are modeled by three-dimensional truss element. The bridge decks are all represented by a single beam and the cross-section properties of the bridge deck are assigned to the beam as equivalent properties. The rigid diaphragms are provided to model the connections between the deck and stay cables or hangers, other connections between bridge components and the supports of the bridge are also properly modeled. Structural geometric nonlinearity due to the cable sag and initial internal force is fully considered.



(a) Fully self-ancored scheme

(b) Partially earth-anchored scheme

Fig. 1 General layout of super long-span cable-stayed bridge with 1400 m main span(half bridge)(unit: m)

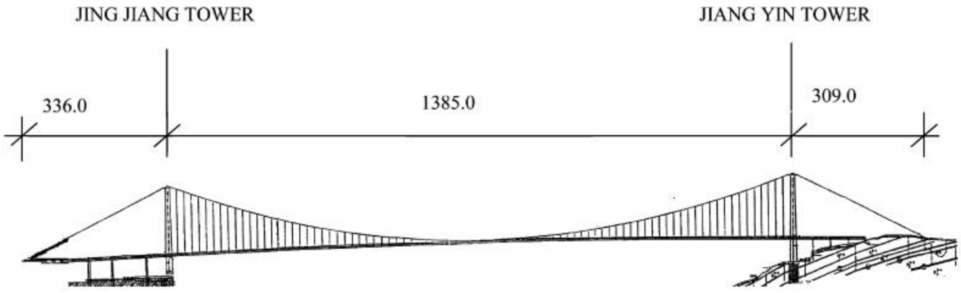
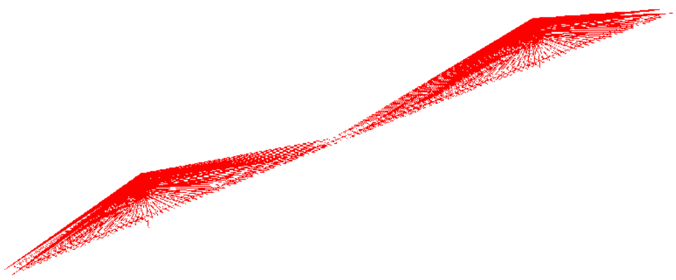
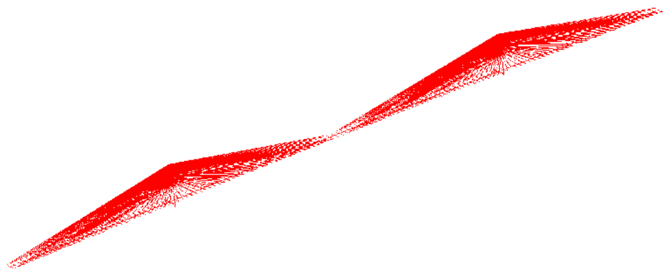


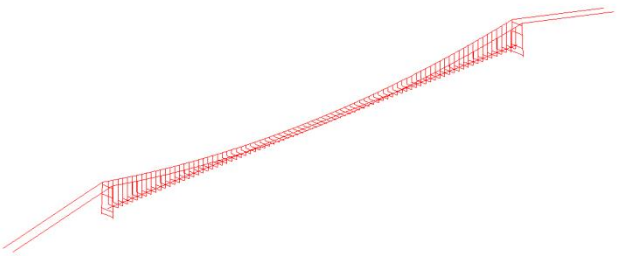
Fig. 2 General layout of the Jiangyin Bridge over the Yangtze River (unit: m)



(a) Partially earth-anchored cable-stayed bridge(called PEA for short)



(b) Fully self-anchored cable-stayed bridge(called FSA for short)



(c) Suspension bridge(called SB for short)

Fig. 3 Three-dimensional finite element models of the example bridges

Table 1 The modal properties of the girder

Mode	Natural frequency(Hz)			Modal shape
	PEA	FSA	SB	
Vertical bending	0.2027	0.1821	0.1341	1-S
	0.1591	0.2116	0.1044	1-AS
	0.2769	0.2646	0.1874	2-S
	0.2927	0.3034	0.2000	2-AS
	0.3839	0.3771	0.2575	3-S
	0.3168	0.4290	0.3100	3-AS
Lateral bending	0.0632	0.0572	0.0521	1-S
	0.1722	0.1662	0.1236	1-AS
	0.3193	0.3136	-	2-S
	0.5229	0.5079	-	2-AS
Torsion	0.4261	0.4153	0.2730	1-S
	0.5637	0.5453	0.2678	1-AS

3. Dynamic characteristics analysis

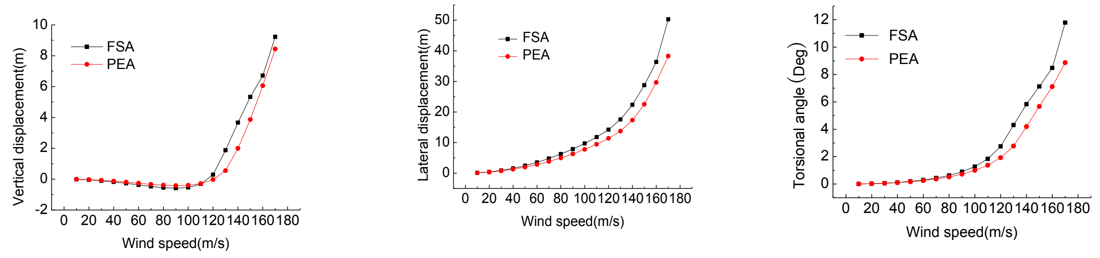
On the computed equilibrium position of the above three example bridges in completion, the first 20 modes are calculated by three-dimensional structural dynamic characteristics finite element analysis based on the subspace iteration method, and the modal properties of the girder are provided in Table 1.

As found in Table 1, with comparison of fully self-anchored cable-stayed bridge with same main span, the natural frequencies of partially earth-anchored cable-stayed bridge is improved, especially the vertical bending and torsional frequency, which indicates that the overall stiffness of cable-stayed bridge has been enhanced by setting several earth-anchored stay cables. Similarly, as compared to the suspension bridge with similar main span, the natural frequencies of partially earth-anchored cable-stayed bridge are significantly increased, especially the torsional frequency, and it is concluded that in the case of similar main span, the partially earth-anchored cable-stayed bridge has greater structural stiffness.

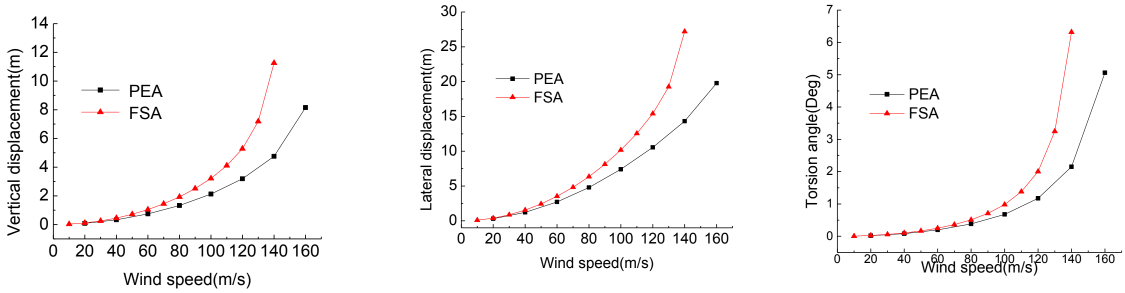
To sum up, as for the bridge with ultra-kilometer main span, the partially earth-anchored cable-stayed bridge has better stiffness characteristics.

4. Aerostatic analysis

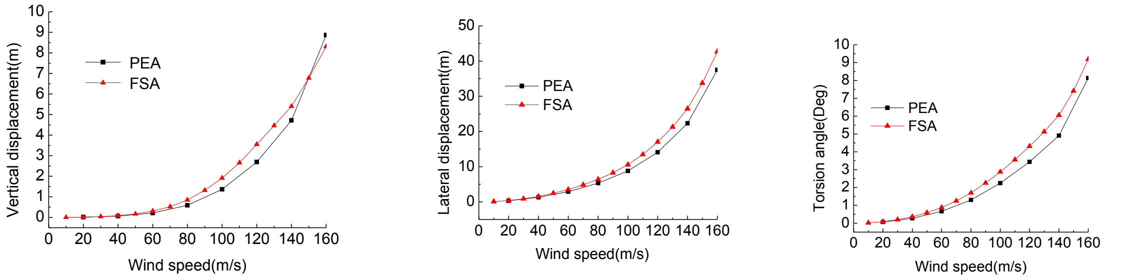
Under the wind attack angles of 0° and ±3°, the aerostatic behavior of fully self-anchored and partially earth-anchored cable-stayed bridges is investigated numerically by three-dimensional nonlinear aerostatic analysis(Zhang 2007), and the evolutions of girder displacements at midspan with increasing wind speed are plotted in Fig. 4. The aerostatic drag, lift and twist moment components are considered for the girder, because the girder aerodynamic shape of the example bridges is very similar to that of the Taizhou Bridge over the Yangtze River, and the aerostatic coefficients of the Taizhou Bridge are employed herein (Chen 2006); for stay cables and towers, only the aerostatic drag component is considered, and the corresponding drag coefficient is 0.8 for stay cables and 2.0 for towers.



(a) 0° wind attack angle



(b) -3° wind attack angle



(c) +3° wind attack angle

Fig. 4 Comparison of the girder displacement at midspan between the fully self-anchored and partially earth-anchored cable-stayed bridges under different wind attack angles

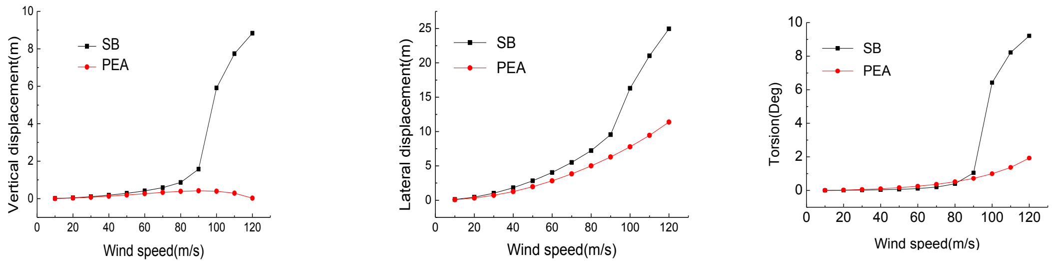
As shown in Fig. 4, as the wind speed is low, the girder displacements of the two bridges are relatively small and identical, and both increase linearly with wind speed; as the wind speed increases to a certain value, the girder displacements increase dramatically in a nonlinear manner, and the difference increases significantly. In the case of the same wind speed, the girder displacement of partially earth-anchored cable-stayed bridge is less than that of fully self-anchored cable-stayed bridge under all the wind attack angles. Under the wind attack angle of 0°, as for the fully self-anchored cable-stayed bridge, when the wind speed is above 110 m/s, the girder displacement increases sharply, and the turning point appears, which means that the bridge begins to become unstable; but for the partially earth-anchored cable-stayed bridge, the starting wind speed of aerostatic instability is greater than 120m/s; under the wind attack angle of -3°, the turning point of displacement curves of self-anchored cable-stayed bridge appears at the wind speed of about 110 m/s, and but for the partially earth-anchored cable-stayed bridge, it is about 130 m/s; under the wind attack angle of +3°, the starting wind speed of aerostatic instability about 70 m/s for the self-anchored cable-stayed bridge , and it is about 90 m/s for the partially earth-anchored cable-stayed bridge. Therefore under the condition same main span, the partially earth-anchored cable-stayed bridge is proved to be more stable aerostatically than the fully self-anchored cable-stayed bridge.

In order to illustrate the applicability of partially earth-anchored cable-stayed bridge to super long-span bridge with ultra-kilometer main span, the aerostatic stability of a suspension bridge-the Jiangyin Yangtze River Bridge with main span of 1385m is analyzed under the wind attack angle of 0° and ±3°, the aerostatic coefficients of girder are taken from the model wind tunnel test results(Xiang and Lin 1996), the evolutions of the girder displacements at midspan with increasing wind speed are shown in Fig. 5.

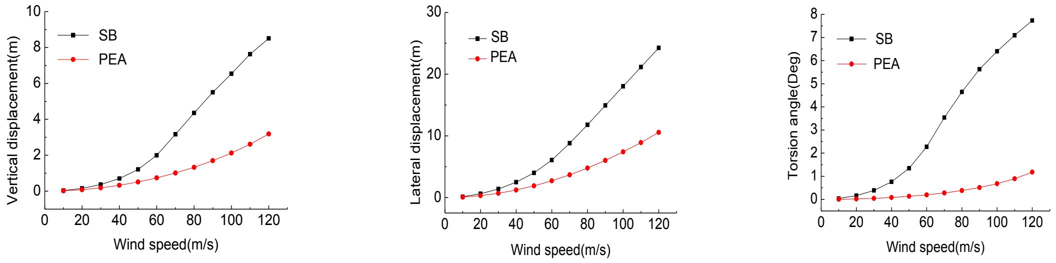
As shown in Fig. 5, under different wind attack angles, the girder displacement of partially earth-anchored cable-stayed bridge is much less than that of the suspension bridge. Within the calculated wind speed, the girder displacement of partially earth-anchored cable-stayed bridge increases monotonously, and no turning point exists in the displacement curves. But for the suspension bridge, there exists obvious turning points in the displacement curves. As the wind speed is beyond a certain value, the girder displacement increases sharply, and the bridge becomes unstable aerostatically. Therefore under the condition of similar main span, it is concluded that the partially earth-anchored cable-stayed bridge is more stable aerostatically than the suspension bridge, and therefore it is favorable aerostatically for super longs-span bridge with ultra-kilometer main span.

5. Aerodynamic analysis

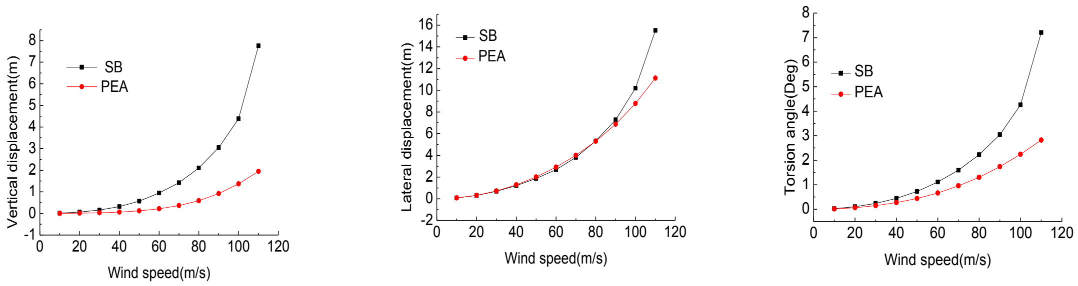
Under wind attack angles of 0° and ±3°, the aerodynamic stability of the example bridges is investigated numerically by three-dimensional nonlinear aerodynamic stability analysis (Zhang 2007), and the critical wind speeds of aerodynamic instability are presented in Table 2. In the analysis, the aerodynamic derivatives of girder are obtained from the wind tunnel test of the Taizhou Bridge (Chen 2006), and for the suspension bridge, they are obtained from the wind tunnel test of the Jiangyin Bridge (Xiang and Lin 1996), and the modal damping ratio is assumed as 0.5 %.



(a) 0° wind attack angle



(b) -3° wind attack angle



(c) +3° wind attack angle

Fig. 5 Comparison of the girder displacement at midpoint between the partially earth-anchored cable-stayed bridge and suspension bridge under different wind attack angles

Table 2 The critical wind speed of aerodynamic instability(m/s)

Wind attack angle	PEA	FSA	SB
-3°	123.1	120.9	62.2
0°	118.7 (125.2)	111.8 (117.9)	67.3 (79.3)
+3°	98.5	97.3	48.9

Note: The values in bracket are calculated by using the aerodynamic derivatives of an ideal plate, the same below

As found in Table 2, the critical wind speeds of aerodynamic instability of partially earth-anchored cable-stayed bridge are all slightly greater than those of fully self-anchored cable-stayed bridge, which indicates that aerodynamic stability of cable-stayed bridge can be improved by using of the earth-anchored stay cables. The fact can be attributed to the higher vertical bending and torsional frequencies obtained for partially earth-anchored cable-stayed bridge, as shown in Table 1. Similarly, the critical wind speeds of aerodynamic instability of partially earth-anchored cable-stayed bridge are nearly 2 times those of the suspension bridge with the similar main span. It can be also explained in Table 1 that under the similar main span, higher vertical and lateral bending frequencies and especially the torsion frequency are achieved for the partially earth-anchored cable-stayed bridge.

Therefore, it is concluded that even if the main span exceeds 1000 m, the partially earth-anchored cable-stayed bridge is more stable aerodynamically, and becomes favorable aerodynamically for super long-span bridges with ultra-kilometer main span.

6. Parametric analysis

In order to fully understand the wind stability of partially earth-anchored cable-stayed bridge, based on the partially earth-anchored cable-stayed bridge scheme as plotted in Fig. 1(b), through adjusting design parameters including the length of earth-anchored girder, the number of auxiliary piers in side spans, the height and width of girder, the tower height etc, their effects on the dynamic characteristics, aerostatic and aerodynamic stability of partially earth-anchored cable-stayed bridge are investigated, and their reasonable values are also proposed. Due to the limitation of paper length and also the similarity of results, only the results under wind attack angle of 0° are presented for the aerostatic analysis.

6.1 Length of earth-anchored girder

In the partially earth-anchored cable-stayed bridge, the girder segment supported elastically by the earth-anchored stay cables is called the earth-anchored girder, its length is an important structural parameter and has significant influence on the mechanical performance. Based on the example bridge, remaining the main span length unchanged, two case bridges with the earth-anchored girder length of 280 m and 680 m respectively are designed through decreasing or increasing number of earth-anchored stay cables and adjusting the side span length and also the auxiliary piers. In the case of the earth-anchored girder length of 280 m, 2×7 stay cables near the bridge ends in each side span are earth-anchored, and the others are anchored to the girder, and two side spans are adjusted to 540 m, and an auxiliary pier is installed in each side span. As for the earth-anchored girder length of 680 m, 2×17 stay cables near the bridge ends in each side span are earth-anchored, and the others are anchored to the girder, and two side spans are adjusted to 340 m, and no auxiliary pier is installed in each side span. The impact of earth-anchored girder length on the dynamic characteristics, aerostatic and aerodynamic stability of the bridge is analyzed, and the results are shown in Table 3, Fig. 6 and Table 4 respectively.

It can be seen in Table 3 that with increasing the earth-anchored girder length, the vertical bending, lateral bending and torsional frequency are all increased, which indicates the overall stiffness of the bridge is enhanced. However, with the further increase of the earth-anchored girder length, the growth of natural frequency is reduced, and thus there exists an optimal earth-anchored girder length for improving structural stiffness of partially earth-anchored cable-stayed bridge.

At the same wind speed, as shown in Fig.6, the girder displacement decreases with the increase of earth-anchored girder length, but the displacement difference between the earth-anchored girder length of 480 m and 680 m is very small. Therefore, increasing the length of earth-anchored girder is beneficial to improve the aerostatic stability of partially earth-anchored cable-stayed bridge, and but there also exits an optimal earth-anchored girder length.

Under 0° wind attack angle as found in Table 4, with the increase of the earth-anchored girder length, the critical flutter wind speed increases rapidly as the earth-anchored girder length increases from 280 m to 480 m, but after that, the increase is significantly reduced; under +3° and -3° wind attack angles, the critical flutter wind speed is the highest in the case of earth-anchored girder length of 480 m. On the whole, the bridge gains the best aerodynamic stability in the case of the earth-anchored girder length of 480 m. Therefore, it is proved once again that there exists an optimal earth-anchored girder length for improving the aerodynamic stability of partially earth-anchored cable-stayed bridge.

Table 3 Effect of the earth-anchored girder length on natural frequency (Hz)

Modes	280 m	480 m	680 m	Modal shape
Vertical bending	0.1877	0.2027	0.2069	1-S
	0.1471	0.1591	0.1610	1-AS
Lateral bending	0.0567	0.0631	0.0601	1-S
	0.1641	0.1721	0.1781	1-AS
Torsion	0.3964	0.4261	0.4327	1-S
	0.5411	0.5637	0.5719	1-AS

Table 4 Effect of the earth-anchored girder length on the critical flutter wind speed (m/s)

Wind attack angle	280 m	480 m	680 m
-3°	117.5	123.05	121.64
0°	105.39(121.56)	114.73（125.16）	118.36(127.81)
+3°	95.16	98.52	94.61

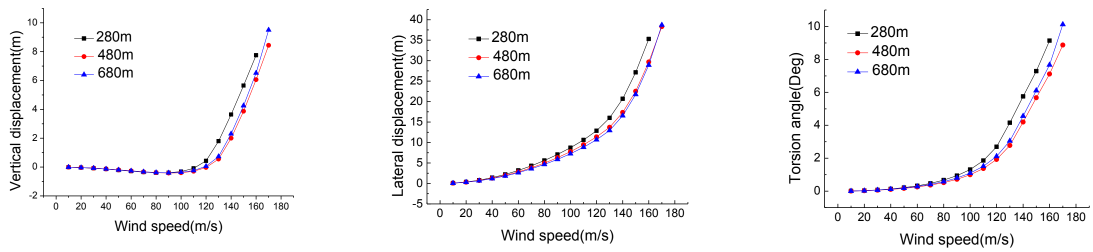


Fig. 6 Effect of the earth-anchored girder length on the girder displacement at midspan

In general, increasing the length of earth-anchored girder is favorable to improve the overall stiffness and the wind stability of partially earth-anchored cable-stayed bridge, but the optimal earth-anchored girder length should be determined through detailed analysis.

6.2 Number of the auxiliary piers

In order to improve structural behavior and construction safety, several auxiliary piers are usually installed in the side span of cable-stayed bridge. To investigate the effect of auxiliary piers in the side span on the wind stability of partially earth-anchored cable-stayed bridge, based on the example bridge, two case bridges with 0 and 2 auxiliary piers in side span are designed. In the case of two auxiliary piers in side span, the two auxiliary piers are installed at a distance of 100 m departing from the bridge end. The influence of auxiliary piers in side span on the dynamic characteristics, aerostatic and aerodynamic stability of the bridge is analyzed and shown in Table 5, Fig. 7 and Table 6 respectively.

It is found in Table 5 that with the installation of auxiliary piers in side span, the vertical bending, lateral bending and torsional frequency are all increased, which indicates that the auxiliary piers in side span can effectively improve the overall stiffness of partially earth-anchored cable-stayed bridge. However, the effect is not proportional to the number of auxiliary piers. As compared to the case of without auxiliary piers, the natural frequency is significantly increased for the bridge with an auxiliary pier in side span. However, as the number of auxiliary piers continues to increase, the growth of natural frequency becomes little. Therefore, the number of auxiliary piers has an optimal value for improving structural stiffness of partially earth-anchored cable-stayed bridge.

Table 5 Effect of the auxiliary piers on structural natural frequency (Hz)

Modes	0	1	2	Modal shape
Vertical bending	0.1800	0.2027	0.2054	1-S
	0.1107	0.1591	0.1692	1-AS
Lateral bending	0.0583	0.0631	0.0648	1-S
	0.1588	0.1721	0.1774	1-AS
Torsion	0.4085	0.4261	0.4335	1-S
	0.5380	0.5637	0.5808	1-AS

Table 6 Effect of the auxiliary piers on the critical flutter wind speed (m/s)

Wind attack angle	0	1	2
-3°	120.03	123.05	121.09
0°	117.52(126.02)	114.73（125.16）	117.66(128.20)
+3°	95.78	98.52	94.37

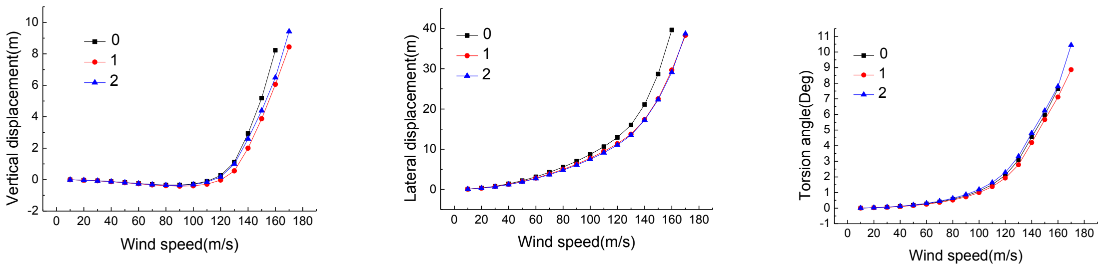


Fig. 7 Effect of the auxiliary piers on the girder displacement at midspan

As seen from Fig. 7, the number of auxiliary piers has significant impact on the lateral and vertical displacements of the girder, but it has little effect on the torsional displacement. With the installation of auxiliary piers in side span, the girder displacement decreases, which indicates that the overall stiffness of the bridge is improved as explained in Table 5. However, the girder displacement decreases monotonously with the increase in the number of auxiliary piers. On the whole, the minimum girder displacement is achieved under the case of an auxiliary pier. As shown in Table 6, the influence of auxiliary piers on the aerodynamic stability of partially earth-anchored cable-stayed bridge is not obvious, and the bridge is the most stable aerodynamically as only an auxiliary pier is installed in side span.

In summary, the auxiliary piers in side span are helpful to improve structural stiffness and wind stability of partially earth-anchored cable-stayed bridge, but the optimal number of auxiliary piers should be determined by comprehensive consideration of the economy and construction safety.

6.3 Width of the girder

The girder width is generally determined by the design traffic volume, but it has influence on the stiffness and aerodynamic performance of the girder and also the bridge. In order to investigate the effect of girder width on the wind stability of partially earth-anchored cable-stayed bridge, based on the example bridge, two case bridges with the girder width of 28 m and 32 m respectively are designed, the variations of cross-sectional properties with the girder width are presented in Table 7. Their dynamic characteristics, aerostatic and aerodynamic stability are analyzed, and the results are given in Table 8, Fig. 8 and Table 9 respectively.

Table 7 The cross-sectional properties of the girder with different width

Girder width	A (m^2)	Ix (m^4)	Iy (m^4)	Iz (m^4)	W (KN/m)
35 m	1.761	8.33	3.939	193.2	258.4
28 m	1.433	6.542	2.849	102.6	223.1
32 m	1.642	7.583	3.269	151.5	212.7

Notes: A-area, Ix-torsional moment of inertia, Iy-lateral bending moment of inertia, Iz-vertical bending moment of inertia, W- the girder gravity unit length.

Table 8 Effect of the girder width on structural natural frequency (Hz)

Modes	28 m	32 m	35 m	Modal shape
Vertical bending	0.2188	0.2086	0.2027	1-S
	0.1659	0.1599	0.1591	1-AS
Lateral bending	0.0541	0.0589	0.0631	1-S
	0.1438	0.1593	0.1721	1-AS
Torsion	0.3824	0.4081	0.4261	1-S
	0.5157	0.5408	0.5637	1-AS

Table 9 Effect of the girder width on critical flutter wind speed (m/s)

Wind attack angle	28 m	32 m	35 m
-3°	115.47	118.28	123.05
0°	96.80(100.47)	112.50（119.31）	114.73（125.16）
+3°	88.98	92.97	98.52

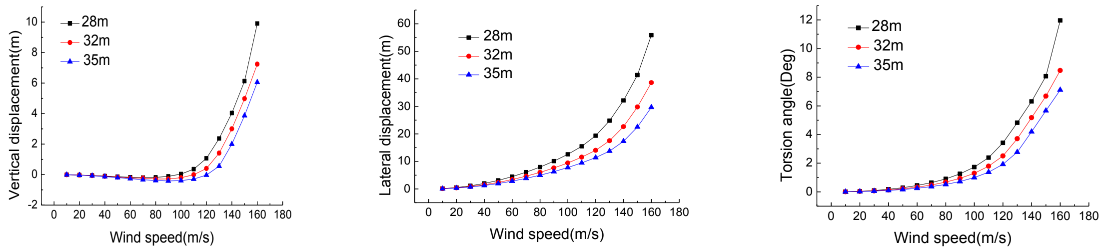


Fig. 8 Effect of the girder width on the girder displacement at midspan

As can be seen from Table 8, as the girder width increases, the vertical bending frequency is decreased slightly, but the lateral bending and torsional natural frequency is significantly increased. The reason is that with the increase of girder width, the vertical bending stiffness and mass of the girder are linearly increased, but the lateral bending stiffness is increased in a cubic manner. Therefore, the increase of girder width can effectively improve the lateral and torsional stiffness of the bridge, but has little impact on the vertical stiffness.

With the increase of the girder width, as shown in Fig. 8, the vertical, lateral displacement and torsion angle are all remarkably reduced, the aerostatic stability of he bridge is thus improved significantly. The fact can be attributed to the improvement of structural stiffenss as explained in Table 8. Furthermore as seen in Table 9, the critical flutter wind speed of partially earth-anchored cable-stayed bridge is monotonously increased with the increase of girder width, the aerodynamic stability of the bridge is significantly improved. It can be explained from the significant increase of torsional frequency as shown in Table 8.

Therefore, as viewed from the aspect of wind stability, increasing the girder width is favorable, but the girder width should be also determined by the traffic volume and economy.

6.4 Depth of the girder

The girder depth is another important parameter affecting structural stiffness and aerodynamic performance of the girder and also the bridge. Based on the example bridge, two case bridges with the girder depth of 3 m and 4 m respectively are designed, and the variations of cross-sectional properties with the girder depth are presented in Table 10. The effect of girder depth on dynamic characteristics, aerostatic and aerodynamic stability is analyzed, and the results are given in Table 11, Fig. 9 and Table 12 respectively.

Table 10 The cross-sectional properties of the girder with different depth

Girder depth	A(m2)	Ix(m4)	Iy(m4)	Iz(m4)	W(KN/m)
3.5 m	1.761	8.330	3.939	193.20	258.4
3 m	1.709	6.201	2.875	186.82	254.1
4 m	1.815	10.741	5.176	199.58	265.5

Notes: A-area, I_x-torsional moment of inertia, Iy-lateral bending moment of inertia, Iz-vertical bending moment of inertia, W- the girder gravity unit length

Table 11 Effect of the girder depth on the natural frequency (Hz)

Modes	3 m	3.5 m	4 m	Modal shape
Vertical bending	0.2055	0.2027	0.2019	1-S
	0.1568	0.1591	0.1594	1-AS
Lateral bending	0.0626	0.0631	0.0625	1-S
	0.1711	0.1721	0.1812	1-AS
Torsion	0.4186	0.4261	0.4362	1-S
	0.5463	0.5637	0.5880	1-AS

Table 12 Effect of the girder depth on the critical flutter wind speed (m/s)

Wind attack angle	3 m	3.5 m	4 m
-3°	116.88	123.05	127.81
0°	109.33(120.47)	114.73（125.16）	120.92(129.77)
+3°	92.11	98.52	102.5

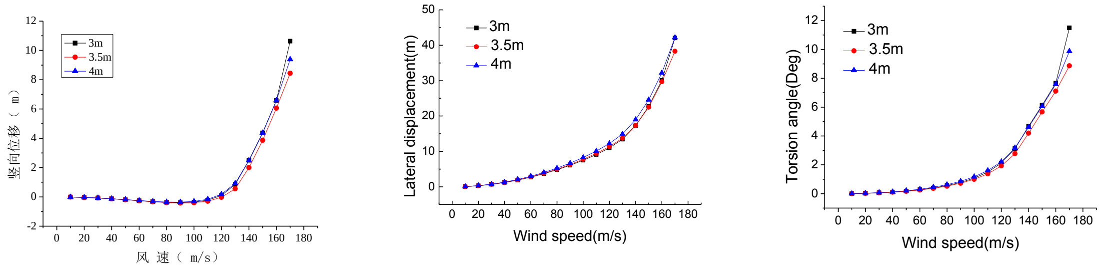


Fig. 9 Effect of the girder depth on the girder displacement at midspan

As can be seen from Table 11, with the increase of girder depth, the vertical bending, lateral bending and torsional frequency are all increased slightly. Although the increase of girder depth can improve the girder stiffness, the vertical stiffness of the bridge is mainly contributed by the elastic supporting of stay cables, the little improvement of vertical stiffness is counteracted by the increase of structural mass, which results in the little change of vertical bending frequency. As for the lateral bending and torsional frequency, the effect is the same. Therefore, increasing the girder depth can improve structural stiffness, but the effect is limited.

Similar phenomenon happens in the aerostatic analysis. As seen in Fig. 9, the girder displacement is little affected by the girder depth, the displacement curves under different girder depth coincide basically, which indicates that the girder depth has little effect on the aerostatic stability of partially earth-anchored cable-stayed bridge. In contrast, as seen in Table 12, the girder depth has remarkable influence on the aerodynamic stability. With the growth of girder depth, the critical flutter wind speed is increased greatly, which indicates that increasing girder depth is favorable to improve aerodynamic stability of partially earth-anchored cable-stayed bridge.

6.5 Height of the tower

The tower height is generally calculated above from the deck, which is closely related to main span length, the cable plane arrangement and the inclined angle of stay cables, and has an important influence on structural performance of cable-stayed bridge. The tower height-to-span ratio is generally between 1/4 and 1/7, and mostly close to 1/5. In order to investigate the effect of tower height on the wind stability of partially earth-anchored cable-stayed bridge, remaining the other design parameters unchanged, two case bridges with the tower height-to-span ratios of 1/6 and 1/4 respectively are designed, and their dynamic characteristics, aerostatic and aerodynamic stability are analyzed, and the results are given in Table 13, Fig. 10 and Table 14 respectively.

As can be seen from Table 13, increasing the tower height can significantly increase the vertical bending and torsional frequency of partially earth-anchored cable-stayed bridge, but the lateral bending frequency decreases slightly. With the increase of the tower height, the inclined angle of stay cable increases, the vertical supporting stiffness of stay cables for the girder is significantly enhanced, which results in the improvement of the vertical and torsional stiffness of the bridge. In contrast, the lateral bending stiffness of the tower decreases with the growth of tower height, which leads to the reduction of the lateral bending frequency.

Similarly as seen in Fig. 10, the tower height has significant influence on the vertical and torsional displacement of partially earth-anchored cable-stayed bridge, and but for the lateral displacement, the effect is little. With the increase of tower height, the vertical and torsional displacements are both decreased remarkably, and the aerostatic stability of the bridge is therefore improved. In the same way, as found in Table 14, the critical flutter wind speed is increased significantly with the increase of tower height, which indicates that the aerodynamic stability of partially earth-anchored cable-stayed bridge can be significantly improved by increasing the tower height.

From the aspects of structural rigidity and wind stability, increasing the tower height is favorable, but it has adverse affect on the economy, and therefore the tower height should be determined by comprehensively considering structural mechanics, wind stability and economy.

Table 13 Effect of the tower height-to-span ratio on the natural frequency (Hz)

Modes	1/6	1/5	1/4	Modal shape
Vertical bending	0.1762	0.2027	0.2282	1-S
	0.1514	0.1591	0.1641	1-AS
Lateral bending	0.0651	0.0631	0.0627	1-S
	0.1749	0.1721	0.1695	1-AS
Torsion	0.3614	0.4261	0.4639	1-S
	0.5015	0.5637	0.5823	1-AS

Table 14 Effect of the tower height-to-span ratio on the critical flutter wind speed (m/s)

Wind attack angle	1/6	1/5	1/4
-3°	105.23	123.05	145.47
0°	97.89(109.92)	114.73（125.16）	133.67(135.08)
+3°	82.89	98.52	117.11

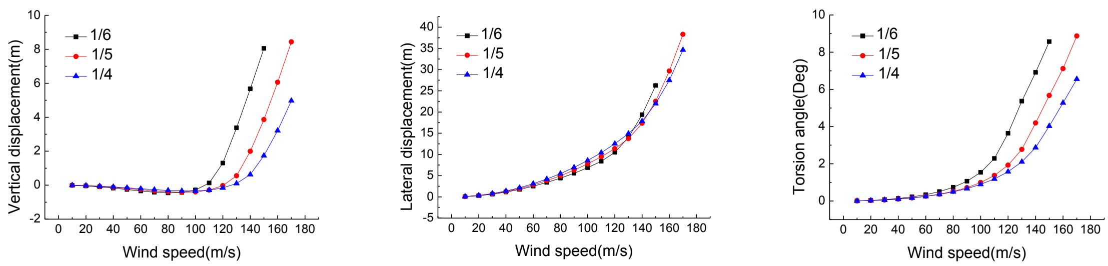


Fig. 10 Effect of the tower height-to-span ratio on the girder displacement at midspan

7. Conclusions

In this work, the dynamic characteristics and wind stability of a partially earth-anchored cable-stayed bridge with 1400m main span is investigated numerically, and the results are also compared to those of a suspension bridge with similar main span, and considering from the aspect of wind stability, the feasibility of applying partially earth-anchored cable-stayed bridge to super long-span bridges with ultra-kilometer main span is discussed. Moreover, the effects of design parameters including the length of earth-anchored girder, the number of auxiliary piers in side span, the height and width of girder, the tower height etc on the dynamic characteristics and wind stability of a partially earth-anchored cable-stayed bridge are investigated, and some conclusions are drawn as follows:

(1) As compared to the fully self-anchored cable-stayed bridge and the suspension bridge with similar main span, the partially earth-anchored cable-stayed bridge has greater structural stiffness and better wind stability, and consequently becomes a favorable structural system for super long-span bridges with ultra-kilometer main span.

(2) With the increase of the earth-anchored girder length, the natural frequency is increased, the overall stiffness is enhanced, and the wind stability is also significantly improved. However, there exists an optimal earth-anchored girder length for improving the wind stability of partially earth-anchored cable-stayed bridge.

(3) The auxiliary piers in side span are helpful to improve structural stiffness and wind stability of partially earth-anchored cable-stayed bridge, but the optimal number of auxiliary piers should be determined by the economy and construction safety.

(4) Increasing the girder width is helpful to improve the lateral and torsional stiffness of partially earth-anchored cable-stayed bridge, especially the wind stability, but the girder width should be also determined by the traffic volume.

(5) The girder depth has little effect on the natural frequency and the aerostatic stability of partially earth-anchored cable-stayed bridge, but increasing girder depth can improve the aerodynamic stability of the bridge.

(6) The tower height has significant effect on structural stiffness and wind stability. With the increase of tower height, the natural frequency and also wind stability are improved remarkably. However, the tower height should be determined by comprehensively considering structural mechanics, wind stability and economy.

(7) In a word, the partially ground-anchored cable-stayed bridge can gain greater structural stiffness and better aerostatic and aerodynamic stability through increasing the ground-anchored segment length, inceasing the height and width of girder, setting several auxiliary piers in side spans and increasing the height-span ratio of the bridge towers.

Acknowledgments

The research described in this paper is financially supported by the Zhejiang Provincial Natural Science Foundation(Grant No. LY15E080020), which is gratefully appreciated.

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