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Wind stability of a structurally non-symmetric suspension bridge under erection

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1. Introduction

Currently, the commonly built suspension bridges are single or three-span symmetric structural system. To well suit with the natural conditions, several two-span non-symmetric suspension bridges have been built such as the Tsingma Bridge in Hongkong, the Xihoumen Bridge in China etc. It is well known that the wind stability of suspension bridges during erection becomes a subject of major concern. Up to now, comprehensive investigations on the wind stability of structurally symmetric suspension bridges under erection have been conducted, and some wind stability improvement measures have been proposed. (Cobo del Arco and Aparicio 2001, Ge and Tanaka 2000, Zhang 2004). Unfortunately, few investigations on the wind stability of structurally non-symmetric suspension bridge during erection have been done.

The present paper focuses its attention on how the wind stability varies during deck erection, and also attempts to find an optimized erection sequence for a structurally non-symmetric suspension bridge. By taking the world's longest structurally non-symmetric suspension bridge-the Xihoumen Bridge as example, evolutions of the aerostatic and aerodynamic stability limits through the deck erection stage following three different erection sequences has been produced by 3D nonlinear aerostatic and aerodynamic analysis, and the favorable deck erection sequence is discussed with respect to the wind stability.

2. Descriptions of the example bridge and deck erection sequences

The Xihoumen Bridge as shown in Fig. 1 is taken as the example bridge. The bridge is a two-span structurally non-symmetric structural system with main span of 1650 m and two side spans of 578 m and 485 m respectively. The deck is two-span continuous steel twin-box girder with height of 3.51 m and width of 36 m. The pylons are door-shaped concrete structures with height of 211 m. The cable sag to span is 1/10, and the standard interval of hangers is 18 m.

To gain a favorable deck erection sequence with respect to the wind stability for structurally non-symmetric suspension bridges, three deck erection sequences commonly used for structurally symmetric

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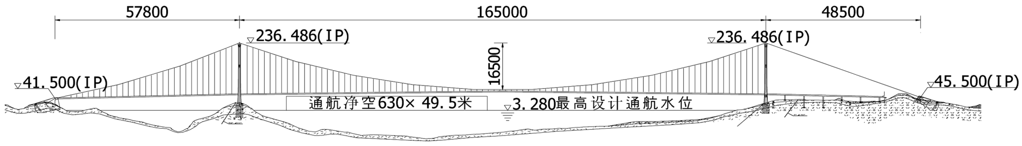
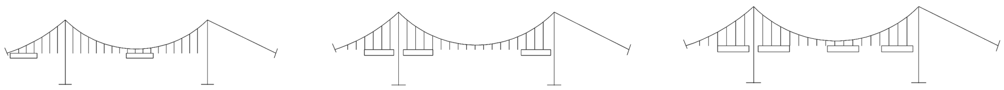


Fig. 1 Vertical layout of the Xihoumen Bridge



(a) Midspan to pylons (b) Pylons to midspan (c) Five working fronts

Fig. 2 The deck erection sequences

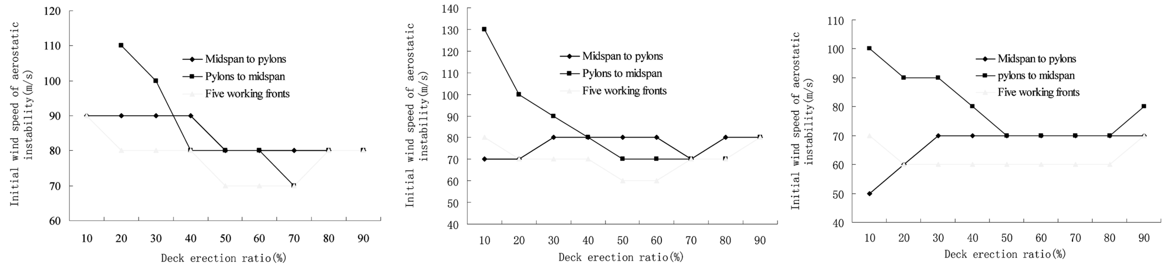
suspension bridges as shown in Fig. 2 are analyzed for the bridge: (1) Midspan to pylons. In center span, the erection starts from the midspan and extends symmetrically toward the two pylons, and in side span, it starts from the bridge end to pylon; (2) Pylons to midspan. In contrast to the above scheme, the process starts simultaneously from the two pylons to the midspan in center span, and in side span, it starts from the pylon to the bridge end; (3) Five working fronts. This is a combination of the two aforementioned configurations. Following this sequence, the deck of a suspension bridge is erected simultaneously from the midspan and the two pylons toward quarter-points of the center span and the bridge end with five working fronts.

3. Aerostatic stability

Under the wind attack angles of 0^{o} and $\pm 3^{o}$, with the experimentally obtained aerostatic coefficients (Ge 2005), the aerostatic behaviors of the example bridge following three different erection sequences are investigated numerically by three-dimensional nonlinear aerostatic analysis (Zhang, *et al*. 2002). In the analysis, the bridge is idealized to a 3D finite element model, in which the deck is modeled by the single-girder model, the deck and pylons are modeled by 3D beam elements, the hangers and cables are modeled by 3D bar elements, and rigid diaphragms are provided to model the connections between the deck and hangers. It is found from the dynamic characteristics analysis that good agreement of the natural frequencies of the single-girder model with those of the exact double-girder model is achieved. This fact gives some confidence in the use of single-girder model for the following analysis as well.

It should be mentioned here that because the aerostatic coefficients are not sufficient, the true aerostatic instability conditions can not be found analytically. In order to compare the aerostatic stability of the bridge under different erection sequences, the term "the initial wind speed of aerostatic instability" is introduced, and defined as the wind speed at which structural displacements increase rapidly, and the bridge starts to become aerostatically unstable. Therefore, the true wind speed of aerostatic instability is higher than the initial wind speed of aerostatic instability defined herein. The evolutions of initial wind speed of aerostatic instability during deck erection are plotted in Fig. 3.

As found in Fig. 3, the initial wind speeds of aerostatic instability are all greater than the design wind speed against aerostatic instability in the construction stage (56.4 m/s) (Ge 2005), and



(a) Wind attack angle of -3^o (b) Wind attack angle of 0^o (c) Wind attack angle of +3^o

Fig. 3 Evolutions of the initial wind speeds of aerostatic instability during deck erection

therefore the bridge is aerostatically stable during deck erection.

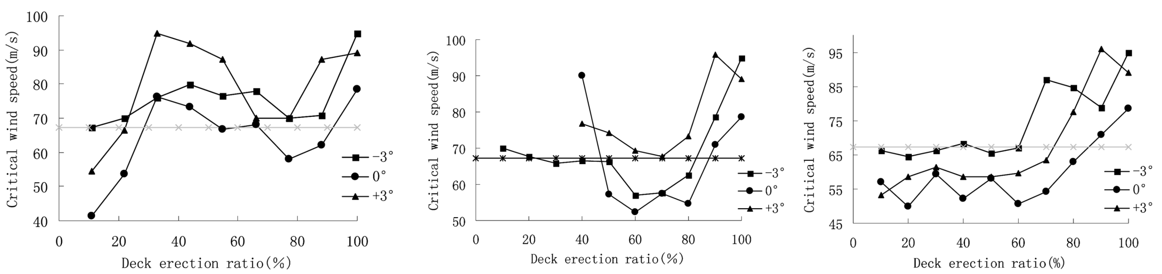
Following three different erection sequences, the evolutions of initial wind speeds of aerostatic instability are found to be considerably different. Under the erection sequences of pylons to midspan and five working fronts, the initial wind speed of aerostatic instability both varies as a U-shaped curve, and but for the erection sequence of midspan to pylons, it varies smoothly. Before 30% of the deck is completed under the erection sequence of pylons to midspan, the initial wind speeds of aerostatic instability tend to be very high, and the bridge has the best aerostatic condition among the three cases. Thereafter, the erection sequence of midspan to pylons becomes relatively more aerostatically stable than other two erection sequences. Throughout the deck erection, the erection sequence of five working fronts has given the worst aerostatic condition.

Considering the less structural stiffness at the relatively early stages, the erection sequence of pylons to midspan seems to be more aerostatically favorable.

4. Aerodynamic stability

Under wind attack angles of 0^o and ±3^o, with the experimentally obtained flutter derivatives (Ge 2005), the aerodynamic stability of the bridge under erection is investigated numerically by three-dimensional nonlinear aerodynamic stability analysis (Zhang, *et al*. 2002), and the evolutions of critical wind speeds of aerodynamic instability during deck erection are plotted in Fig. 4.

Following the three different erection sequences, the evolutions of aerodynamic stability limits are



(a) Midspan to pylons (b) Pylons to midspan (c) Five working fronts

Fig. 4 Evolutions of the critical wind speeds of aerodynamic instability during deck erection also found to be considerably different as shown in Fig. 4. Under the erection sequence of midspan to pylons, the worst condition happens at very early stages, and also when nearly 70% of the deck is suspended, the bridge becomes less aerodynamically stable. Except the two stages, the critical wind speeds are all greater than the design wind speed against flutter in the construction stage (67.14 m/s) (Ge 2005). The critical wind speed varies as a U-shaped curve as observed in the previous aerostatic stability analysis under the sequence of pylons to midspan, the worst aerodynamic condition happens as 50-80% of the deck is suspended. Within this range, the critical wind speeds at wind attack angles of 0^o and $+3^o$ are both lower than the design wind speed against flutter in the construction stage, and but at other erection stages, the critical wind speed tends to be very high. Under the erection sequence of five working fronts, the critical wind speeds increase monotonically as the deck erection proceeds. Before nearly 70% of the deck is completed, the critical wind speeds increase slightly, and all lower than the design wind speed against flutter in the construction stage, and thereafter they increase significantly and become higher than the design wind speed against flutter in the construction stage.

In comparison with other two erection sequences, at great part of the erection stages, the bridge is relatively more aerodynamically stable under the sequence of midspan to pylons, whereas at the aforementioned disadvantageous stages, some efficient measures should be provided to improve the wind stability of the bridge under erection.

5. Conclusions

In this work, following three different erection sequences, evolutions of the aerostatic and aerodynamic stability throughout the deck erection process for a structurally non-symmetric suspension bridge are investigated numerically by 3D nonlinear aerostatic and aerodynamic analysis. The results show that the erection sequence of five working fronts is confirmed analytically to be unfavorable for the bridge with respect to the wind stability; the best aerostatic stability is achieved under the deck erection sequence of pylons to midspan; as compared to the aerostatic stability, the bridge becomes more unstable aerodynamically during the deck erection process, and therefore on the whole, the deck erection sequence of midspan to pylons seems to be more favorable with respect to the wind stability.

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