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Field monitoring and validation of vortex-induced vibrations of a long-span suspension bridge

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ABSTRACT

To investigate full-scale wind-induced vibrations of a long-span suspension bridge with a central span of 1650 m, a long-term wind and wind effect monitoring system was created. The basic wind field characteristics along the span-wise direction of the investigated bridge were analyzed. It was found that the wind field along the span-wise direction was inhomogeneous. The full-scale wind pressure distribution around the lower surface of the twin-box girder was also obtained. From the power density functions (PSDs) of the fluctuating pressures, the vortex shedding frequency of the full-scale twin-box girder was determined. A field visualization test was performed, and the flow pattern around the lower surface was obtained. Thirty-seven vortex-induced vibration (VIV) events were observed during the monitoring period. The corresponding wind conditions and vibrations were analyzed in detail. In addition to the wind direction and inflow turbulence, it was found that the inhomogeneity of the wind field along the span-wise direction of the bridge is also a critical factor that affects VIVs of full-scale bridge. The VIVs from a section model test and the full-scale bridge were compared, and it was found that the vertical VIV amplitude of the section model was much smaller than that from the field monitoring results. Moreover, torsional VIVs appeared in the section model test, whereas it was not observed in the full-scale bridge.

1. Introduction

Although vortex-induced vibrations (VIVs) of a bluff body have been widely investigated, they are still not completely understood due to the complexity of the nonlinear interaction between the fluid and motion of the bluff body. Because this problem extensively exists in actual structures and negatively affects their safety. Comprehensive fundamental studies have been performed (Bearman, 1984; Gabbai and Benaroya, 2005; Sarpkaya, 2004; Williamson and Govardhan, 2004). A rough definition of VIVs can be expressed as “when flow passes through a bluff body, vortex shedding occurs in the wake. If the vortex shedding frequency is close to the natural frequency of the bluff body, large-amplitude vibrations will occur”. However, it is well known that this simple definition cannot adequately describe VIVs. VIVs exhibit extremely complex fluid dynamic characteristics. In recent decades, most studies have primarily focused on a bluff body with a simple configuration, such as in the aforementioned studies, for example, circular cylinders and rectangular prisms. However, little is understood on the VIV mechanism and flow patterns for more complicated configurations, for example, a stream-like box girder, which is extensively used in modern long-span cable-supported bridges. For long-span cable-supported bridges, three special characteristics significantly affect the VIVs of a bridge deck. First, as the span size increases, the modes of the bridge become more and more dense, and the corresponding damping becomes smaller. For example, the lowest vertical frequency of a suspension bridge, whose main span size is 1650 m, is 0.09766 Hz, and the frequency interval between modes is approximately 0.04 Hz. The vertical modal damping is less than 0.60% (Li et al., 2011). Second, as the span size increases, the wind field along the bridge may become inhomogeneous. Finally and most importantly, the flow field around the stream-like box girder is more complicated than that around a circular cylinder due to separation and reattachment phenomena. Moreover, to improve the aerodynamic stability for a super-long span cable-supported bridge, twin- or multi-box girders have been extensively used in actual bridges, such as the Xihoumen suspension bridge (main span: 1650 m, China), Hong Kong Stonecutters cable-stayed bridge (main span: 1018 m, China), Gwangyang suspension bridge (main span: 1545 m, Korea), and the Strait of Messina Bridge (main span: 3000 m, Italy). Due to the gap between the separated box girders, the mechanism behind VIVs becomes more complicated. The VIVs of twin-or multi-box girders have been investigated through wind tunnel tests (Diana

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et al., 2006; Ge et al., 2011; Ge, 2011; Larsen et al., 2008; Xu, 2004; Zhang et al., 2008). Although the wind tunnel test is a powerful tool to investigate VIVs of long-span suspension bridges, it cannot simulate actual wind dynamics and structural dynamic characteristics due to the size effects in the wind tunnel, i.e., the characteristics of the natural wind field at the bridge site, high Reynolds numbers and structural damping. It is known that these factors significantly affect the VIVs of long-span cable-supported bridges. However, field monitoring techniques can overcome the limitations of wind tunnel tests and provide insights into VIV behaviors of full-scale bridges. Moreover, it also can validate the wind tunnel test results. Larsen et al. (2000) discussed the VIVs of the Great Belt East Bridge observed during the final phases of deck erection and surfacing of the suspended spans, and the guide vanes were designed and implemented to mitigate the VIV oscillations of Great Belt East Bridge. Frandsen (2001) measured the wind pressures and accelerations of the Great Belt East Bridge simultaneously. In the field measured period, some VIV events on the Great Belt East Bridge were observed. It was found that the cross-wind VIVs of the Great Belt East Bridge occurred in smooth flow and low wind speeds (approximately 8 m/s) with a direction nearly perpendicular to the bridge axis. The time-average pressure coefficients on the top trailing edge were near zero and the correlation of span-wise pressures became large when VIV was occurring. Fujino and Yoshida (2002) observed that the first vertical VIV mode of a ten-span continuous single steel box-girder bridge (the Trans-Tokyo Bay Crossing Bridge) occurred in the wind direction within $\pm 20^{\circ}$ to the transverse axis of the bridge and the wind velocity approximately16–17 m/s. To control the vertical mode vibrations of the bridge, a new type of tuned mass damper (TMD) was implemented in the girder, and effective vibration control was achieved. Although successful examples on the studies of VIVs of full-scale long-span bridges through short-term field monitoring have been presented as mentioned above, it is necessary to do comprehensive studies on VIVs of full-scale long-span bridges through long-term field monitoring. Fortunately, more and more wind and wind effect long-term monitoring systems have been implemented on full-scale long-span bridges, and many VIV events from actual bridges have been recorded. Thus, it is possible to create comprehensive studies on VIVs of full-scale long-span bridges. Based on the above viewpoint, the primary objective of this paper is to investigate wind field characteristics and the VIV behaviors of a long-span suspension bridge with separated twin-box girder based on long-term field monitoring results. The VIVs of this long-span suspension bridge had been investigated in a previous article (Li et al., 2011) based on 2-month (9/29/2009–11/30/2009) field monitoring results. However, in the following 4-year monitoring process, the wind and wind effect monitoring system has been expanded and upgraded, and the accumulated field monitoring results are much more abundant than the previous article.

The organization of the paper is as follows: in Section 2, the investigated bridge and corresponding wind and wind effect monitoring system are introduced. In Section 3, the wind characteristics at the bridge site are analyzed in detail. In Section 4, the flow field characteristics around the twin-box girder are presented. In Section 5, the VIVs of the full-scale twin-box girder are investigated, and finally, the conclusion is presented.

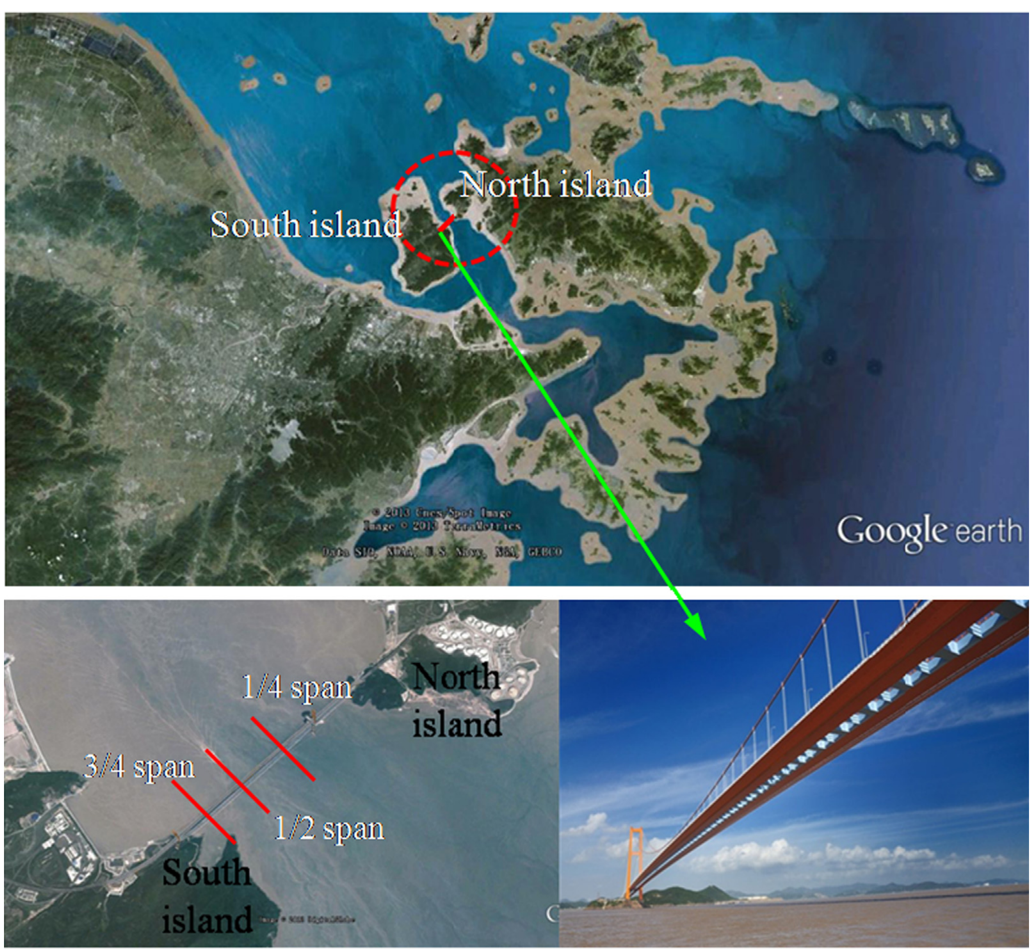

Fig. 1. Location of the investigated long-span suspension bridge.