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Wind characteristics at bridge site in a deep-cutting gorge by wind tunnel test

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ABSTRACT

To study the wind characteristics at bridge site in a deep-cutting gorge, a gigantic bridge site terrain model was made in a wind tunnel. The effects of different oncoming wind directions on the wind characteristics over the bridge site were investigated in the simulated atmospheric boundary layer. Results show that the perpendicular wind speed profiles along the bridge main beam can be generally divided into two parts. The shapes of the wind speed profiles at the two bridge towers are much closer to the power law and log law than those of the bridge main beam. The wind attack angle required for the wind resistant design of the bridge should be determined in the range of −6° to 2°, which obviously exceeds the range of −3° to 3° that is usually considered in the homogeneous terrain. When the oncoming wind is from southwest, the wind power spectra at 1/4 span, mid-span and 3/4 span points match well with the spectra values by the Kaimal model. For two measurement points of the same distance, the decay factor of the coherence function varies along the bridge main beam as well as the bridge towers depending on their positions.

1. Introduction

For the mountain-gorge terrain, there exist many rolling mountains and deep-cutting gorges. When the wind flows over it, the wind will be obstructed and deflected by the mountains, and the flow separation usually occurs behind the mountains. In addition, non-synoptic winds, like thunderstorms, occur frequently in the mountain-gorge terrain. The wind speed and wind direction always change when the wind flows along the gorges. As a result, the wind characteristics over the mountain-gorge terrain are very complex. For the long-span bridge building in the mountain-gorge terrains, they always straddle the deep-cutting gorges. Therefore, the wind characteristics at the bridge site are greatly influenced by the deep-cutting gorge terrain, and the wind characteristics around the bridge main beam and tower are very complicated. For these reasons, the local mountain-gorge and other non-synoptic winds at bridge site are likely to affect the dynamic behaviors of the bridge structures and occupy an important position in the wind-resistant designs. However, the current design standards and codes are made generally based on the homogeneous terrain, which are not applicable for these long-span bridges (Chock and Cochran, 2005). On the other hand, more and more long-span bridges straddling the deep-cutting gorges have been built in recent years, especially in the west regions of China due to the well-known strategy of developing the western region. Therefore, there is a critical need to better investigate the wind characteristics at the bridge site in a deep-cutting gorge, and these wind characteristics attract ever-increasing attention of the wind engineering researchers (Hu et al., 2015).

Although the wind characteristics over the mountain-gorge terrain could be investigated in many methods, it is still a difficult task to perform. Theoretical studies are not only limited by the inherent difficulties to treat real mountain-gorge terrain geometries, but also limited by the complexity of the model equations that try to mimic the most important physical phenomena presented in the atmospheric boundary layer. Therefore, the theoretical studies mainly focus on the smooth and isolated hill rather than the real mountain-gorge terrain (Jackson and Hunt, 1975; Mason and Sykes, 1979; Hunt et al., 1988). Field measurements are extremely expensive to be carried out and easily affected by the environment condition, which become a real problem to be solved (Hui et al., 2009a). Simultaneously to the development of theoretical studies and field measurements, the numerical simulation method by computational fluid dynamics (CFD) has been more and more widely adopted to analyze the wind characteristics over the mountain-gorge terrain, due to the convenience of controlling and changing the test conditions. Iizuka and Kondo

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(2004, 2006) analyzed the wind characteristics over a 2-D hill by the large-eddy simulations (LES) method, and compared these simulated results with those from the corresponding wind tunnel tests. Cao et al. (2012) performed the LES to study the turbulent boundary layer over the steep and low hills with and without surface roughness, and also compared the computed results over the hills with the wind tunnel data. Tamura et al. (2007) performed the LES method to study the turbulent boundary-layer type of flows over a 3-D steep hill model, and discussed the effects of surface condition on the turbulence statistics of the hill. Maurizi et al. (1998) investigated the wind flow over a mountainous area in a region of 15.0 km×14.0 km based on the solution of the fluid flow with k-ε turbulence model and using a non-orthogonal three-dimensional grid system. The results showed that it is possible to obtain three-dimensional simulations of the atmospheric flow over the complex terrain, within a reasonable amount of computer time. Differences of about 10% of the wind speed measured 30 m above the ground could occur as a result of different grid resolutions or flow inlet conditions. Uchida and Ohya (2003) carried out the calculation of turbulent flow over a real complex terrain in a horizontal region of 9.5 km×5.0 km by the LES method, and found that the wind field in this research region was strongly influenced by the wake region generated behind a mountain with the height of 244 m. Furthermore, the numerical results demonstrated that the changes induced on the wind field by the topographic effects, such as the local wind acceleration and the flow separation, were successfully simulated. However, the current commonly used turbulence models such as LES and RANS are still difficult to simulate the real turbulent flow. Also, Cochran and Derickson (2011) pointed out that it is critical in CFD method to have the numerical inflow boundary conditions match the mean and turbulent inflow conditions of the prototype, and the inflow turbulent conditions for these turbulence models are the most difficult factors in the CFD simulation. Generally, the turbulence characteristics results obtained by numerical simulation method are usually less accurate than the mean wind characteristics results (Cao et al., 2012; Hu et al., 2016), and the numerical results should be validated before conducting more numerical simulations.

Compared with the theoretical study, field measurement and numerical simulation methods, the wind tunnel test method not only has such advantages as easy modeling, and conveniently control, change and repeat of the test conditions, but can also simulate the turbulent flow on the inlet and over the complex terrain with a high accuracy. Actually, the wind tunnel test has become the main method to analyze the wind characteristics over the mountain-gorge terrain. Carpenter and Locke (1999) investigated the wind flow over 1:1000 scale 2-D hills in a simulated atmospheric boundary layer, and measured the mean wind speed and longitudinal turbulence over a variety of hill geometries which included shallow sinusoidal hills, steep sinusoidal hills, consecutive hills and an irregularly shaped hill. Miller and Davenport (1998) studied the boundary layer flow over a number of 2-D complex surfaces by wind tunnel tests, and compared the observed speed-ups with those predicted by the current Canadian and UK codes of practice. The results showed that the velocity speed-ups in complex terrain were reduced when compared to those found in the isolated hills or ridges. Furthermore, the application of the simple guidelines used in several codes of practice to features located in complex terrain would lead to conservative results for design purposes as the speed-up is over predicted. Note that the above complex terrains are generally simple hills, it can be regarded as the simplified form of the real mountain-gorge terrain. Therefore, the above research conclusions may be not directly applied to the engineering practices, such as the long-span bridges straddling the deep-cutting gorges as discussed above. Li et al. (2010) made a real mountain-gorge terrain model in a scale of 1:500 with a diameter of 4 m in the wind tunnel, and the terrain model centered on a long-span bridge which straddled a typical deep-cutting gorge. Then the wind characteristics along the bridge main beam were investigated in detail. The results showed that the mean wind speed profiles, power law exponents of the mean wind speed profiles and wind attack angles in the gorge all varied greatly with both the measuring points and the oncoming wind directions due to the effects of the deep-cutting gorge. Furthermore, the mean value of the attack angle along the bridge main beam was 4.7°, which exceeded the range −3° to 3° that is usually required for the wind resistant design of bridges. The longitudinal turbulence intensities in the gorge were generally smaller than the corresponding value of the oncoming wind, which may mainly be caused by the speed-up effect of the gorge terrain. Although, the research by Li et al. (2010) revealed the generally variation of wind characteristics at bridge site in a deep-cutting gorge to a certain degree, it did not investigate the wind characteristics at the bridge tower, and the wind power spectra and wind coherence at the bridge site were not studied, either. On the other hand, the wind characteristics at bridge site in a deep-cutting gorge are excessively complicated, and much more research should be done.

As discussed earlier, the wind tunnel test method has many advantages to study the wind characteristics over the mountain-gorge terrain, and it has become the main method in this field. However, there is an inherent problem when modeling the mountain-gorge terrain model in a wind tunnel: since the terrain domain chosen to be analyzed is always limited, its range is generally determined by truncating the boundless mountain-gorge terrain at an appropriate distance from the bridge site. As we known, the mountain-gorge terrain usually has a high altitude and the elevations on the boundary may be significantly different. Therefore, the sudden elevation jump between the edge top of the terrain model and the wind tunnel floor normally exists. Furthermore, the jump usually varies significantly around the edge of the terrain model. If the wind flows over this untreated model, the flow obstruction and separation will occur over the terrain model edge, which contradicts the real flow pattern and the significant errors will be introduced. To make the oncoming wind flows over the edge of the terrain model smoothly and reasonably, a transition section from the wind tunnel floor to the edge top of the terrain model must be established. Although Maurizi et al. (1998) and Hu et al. (2006) used a ramp transition section to simulate a more realistic oncoming wind field in order to predict the wind field over a mountainous terrain, the applicability and effectiveness of the ramp transition section were not validated. To study the appropriate transition section shape for mountain-gorge terrain model in wind tunnel test, Hu et al. (2015) derived a type of theoretical curves serving as the transition section shape for the mountain-gorge terrain model based on the potential flow theory around a circular cylinder, and validated the curved transition section has a better flow transition performance than the traditional ramp transition section by wind tunnel tests. Furthermore, it was found that the wind attack angles at the end of the curved transition section are much smaller than those at the end of the traditional ramp transition section based on the research by the CFD numerical simulation method (Hu et al., 2013). Note that the 2-D (two-dimensional) curved transition section proposed by Hu et al. (2015) can be only applied to the platform terrain which has the same elevation. Therefore, it cannot directly apply to the real mountain-gorge terrain due to the variable elevations on the terrain edge.

In this paper, to study the wind characteristics at bridge site in a deep-cutting gorge, the Longjiang Bridge with the main span of 1196 m which straddles a deep-cutting gorge was employed as a typical example. The terrain model centered on the bridge site, with a diameter of 15 km, was made in the wind tunnel using a 1:1000 scale. More importantly, a new transition section called the 3-D gradual curved transition section was developed to especially serve as the boundary transition section of the bridge site terrain model. Then the effects of different oncoming wind directions on the wind characteristics over the bridge site were investigated in the simulated atmospheric boundary layer, and the wind parameters such as the mean wind speeds, power law exponents of the mean wind speed, wind attack angles, turbulence intensity, wind power spectra and wind coherence around the bridge