INVESTIGATION ON WIND CHARACTERISTICS FOR A BRIDGE WITHIN A MOUNTAINOUS AREA VIA WIND TUNNEL TEST OF TERRAINT MODEL

Lei Yan 1, Zhen-Shan Guo 2, Le-Dong Zhu 3

1 PhD Candidate of Department of Bridge Engineering, Tongji University, Shanghai 200092, China, yanlei0519@gmail.com

2 Senior engineer of Department of Bridge Engineering / Key Laboratory for Wind Resistance Technology of Bridges of Ministry of Transport, Tongji University, Shanghai 200092, China, guo@tongji.edu.cn

3 Professor of State Key Laboratory of Disaster Reduction in Civil Engineering / Key Laboratory for Wind Resistance Technology of Bridges of Ministry of Transport / Department of Bridge Engineering, Tongji University, Shanghai, China, Ledong@tongji.edu.cn

ABSTRACT

Wind tunnel tests of a 1/2200 scale mountainous terrain model have been carried out to investigate local wind characteristics at a bridge site in southeast Tibet, China. Flows past 5 key sites of the bridge at the deck level in 26 directions were measured. Flow was also measured at each pylon at 32 additional different levels in these directions. It was observed that profiles of wind characteristics (including mean wind velocity, overall turbulence intensity, yaw angle and wind attack angle) at each pylon vary significantly depending on the approaching wind direction, and the majority of mean wind profiles cannot be presented by the normal profile. The wind attack angle at the deck level measured in the study fluctuated between -16° and +18°, and mean wind velocity to the reference wind was small when the wind attack angle was large, especially at positive wind attack angles. The design standard wind speed and the minimum critical wind speed for flutter rely on the wind attack angle and should be determined by results of the tests.

Keywords: Mountainous terrain, Wind direction, Mean wind profile, Interval of wind attack angle

1 Introduction

More and more cable-supported bridges with a mountainous area have been built to connect two districts. Polonggou Bridge is located at the G318 Shanghai-Lhasa Expressway, belonging to Hengduan Mountains, the southeast part of Tibet. It is a cable-stayed bridge with the mid-span of 430 m with an altitude of 2090.089 m. The height of the tower near Chengdu side above the bearing platform upper surface is 146.7 m, and the other near Lhasa side is 139.7 m. However, the altitudes of the two towers are same and equal to 2184.249 m. The general layout of Polonggou Bridge is shown in Figure 1.
The surrounding terrain within a radius of 5 km comprises three large mountains at altitudes of approximately 4,160 m, 4,020 m and 3,560 m at the summit. These are located in the north, west and east side of the bridge site, with one comparatively small mountain situated eastwards with an altitude of 3,460 m. There are four valleys between each two mountains. The location of bridge and its surrounding topography is shown in Figure 2.

Mountains and valleys often act as physical blocks to the flow and significantly interrupt the normal global atmospheric circulation and form the local wind circulation. The speed and direction of wind dramatically change and a far more turbulent wake region forms, especially in the lee of the mountain. Most of conducted researches focused on wind speed-up effects, and little suggestion has been provided for the turbulence intensity, yaw angle and wind attack angle at a mountainous terrain.

Several empirical speed-up prediction algorithms have been published to provide formulae or look-up tables to predict speed-up for simple orography. BS EN 1991-1-4 (2005) adopted an orography factor accounts for the increase of mean wind speed over isolated hills and escarpments (not undulating and mountainous regions). As for a bridge built in a complex terrain, JTG/T D60-01 (2004) suggested designers should adopt numerical simulations, field measurements or wind-tunnel simulations to predict wind speed-up and determine design standard wind speed of bridge.

There have been great progresses in the numerical evaluation of wind flow over different types of topographies. Bitsuamlak et al. (2004) demonstrated that numerical simulations could give generally good speed-up predictions on the upstream but problematic predictions on the downstream areas of the complex terrain.

Field measurement results of local wind characteristics of a specific site may not be available in situations of complex terrain. Cermak and Isyumov (1998) noted that in such situations small-scale topographic models, constructed at scales in the range of 1:1000 to 1:5000, which can be effective for estimating the full-scale mean flow field. Wind tunnel tests [Teunissen et al. (1987)] over Askervein Hill at three different length scales have been successfully carried out and results compared with full-scale data through bench-mark testing well. Bowen, A. J. (1998, 2003) discussed some significant issues that affect the accuracy of wind-tunnel simulations of the wind over complex terrain.
As for flexible cable-supported bridges built in mountainous areas, the special wind characteristics indicate a new and complicated challenge for the wind-resistance research. In this study, the wind-tunnel simulation was adopted to investigate on wind characteristics at bridge site and obtain wind parameters for bridge, including design standard wind speeds at different levels and minimum critical wind speeds for flutter.

2 Overview of the wind tunnel tests

2.1 Selection of model scale

In selecting the model scale, it is important to minimize the influence of wind-tunnel walls and excessive blockage of the test section. Goh, CB. (1981) concluded that the roof height should be greater than 3 times that half-length of the hill (L) so that the deflected flow stream-lines over the hill model are insignificantly unaffected by the roof. Cermak and Isyumov (1998) noted that for a blockage ratio of 5% and less, distortion effects are negligible and a correction for the speed-up of the flow at the model is sufficient. Selecting the model scale should also consider measurement errors. There are two main sources of error: errors due to the position of the probe being slightly off from its correct measurement location, and errors due to the wind-tunnel simulation itself.

The mountainous terrain chosen extended to 6.7 km to avoid an abrupt change of the approaching flow. The terrain for model included only the topography above an elevation of 2000 m, then the highest summit in the terrain was 2160 m, average height and overall diameter of the terrain was 3184.4 m and 12.1 km respectively. In consideration of blockage effects completely, the ideal model scale should be 1: 5000.

However, it was found with a 1:5000 model [D. Neal (1982)], that measurements close to the ground at a particular site are significantly inaccurate due to these gross errors in local terrain. The deck upper surface at the mid-span and tower top would be 18.0 mm and 29.7 mm respectively on the ideal model scale, then measurement errors may be out of control.

In a compromise between blockage effects and the measurement accuracy, the terrain model was constructed at a geometric scale of 1 to 2200 by 10 mm thick high-density foam sheets and the average wind tunnel blockage ratio was 9.87%. There were some local sections, especially summits where the effective blockage ratio behaved closer to 50% and flow stream-lines over the summit were definitely deflected by the roof. However, the region of highest interest to the study was mainly below 84 mm (corresponding to the level of tower top) so the deflecting influence was likely to be small.

2.2 Wind tunnel equipments

Wind tunnel tests were carried out in Tongji University (China), TJ-3 Wind Tunnel, which is a closed-circuit vertical return tunnel at Tongji University. Wind speed within the tunnel is continuously variable between 1.0 and 17.6 m/s. The working section is 14.0 m long, 15.0 m wide and 2.0 m high. A three-dimensional traversing system mounted to the ceiling allows for precise placement of a sensor at any point with an accuracy of 0.5 mm within the test section. The test region is 1.5 m high by 3 m wide by 3 m long.

The Cobra Probe is a multi-hole pressure probe that provides dynamic, 3-component velocity and local static pressure measurements in real-time. Cobra Probes in the wind tunnel tests were available in various ranges for use between 2 m/s and 40 m/s and measured flow angles in a ±45° cone. The standard posture of Cobra Probe was adopted, yaw angle was positive when approaching flow came westerly in the wind tunnel. The original yaw angle needed to be adjusted to make sure the validity of sample data because the main direction will change dramatically with the shift in the position. The accuracy of one Cobra Probe is shown in Table 1.
Table 1: The accuracy of one Cobra Probe

<table>
<thead>
<tr>
<th>Test velocity</th>
<th>Pitch-Yaw ±24°</th>
<th>Pitch-Yaw Error</th>
<th>Velocity Error</th>
<th>Pitch-Yaw ±45°</th>
<th>Pitch-Yaw Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 m/s</td>
<td>±0.1 m/s</td>
<td>±1°</td>
<td>±0.3 m/s</td>
<td>±3°</td>
<td></td>
</tr>
<tr>
<td>12 m/s</td>
<td>±0.2 m/s</td>
<td>±0.3°</td>
<td>±0.3 m/s</td>
<td>±1°</td>
<td></td>
</tr>
<tr>
<td>40 m/s</td>
<td>±0.3 m/s</td>
<td>±0.2°</td>
<td>±0.6 m/s</td>
<td>±1°</td>
<td></td>
</tr>
</tbody>
</table>

A Cobra Probe was supported on the end of a steel fastener to measure mean velocity and turbulence intensity, which in turn was secured to the internal traversing system. The other Cobra Probe was situated upstream of the terrain model at the height of 1000 mm, which measured simultaneously a reference wind velocity, \( U_{\text{ref}} \). The reference wind velocity and overall turbulence intensity was approximately 10.5 m/s and 4.8% respectively, which could represent the approaching flow of the terrain model with minimum disturbance. Cobra Probe measurements were taken at 1000 Hz for 65.536 s. A photograph of the general layout of the wind tunnel tests is shown in Figure 3.

Fig. 3 A photograph of the general layout of the wind tunnel tests

2.3 Measurement sites

To obtain systematic wind characteristics, flows past 5 key sites of the bridge at various heights were measured in 24 basic directions with an interval of 15°. Two additional directions perpendicular to the longitudinal axis of the bridge were considered. The terrain model was fixed on the wooden wheel with a diameter of 6.7 m, which allowed for measurements in different wind directions. Wind direction of 0° was defined as the North Wind, and the wind direction increased in a clockwise direction, namely, wind direction of 90° signified the East wind. The 5 key sites were: the location of each pylon and 2 points at the quarter-point of the main-span and the center of the main-span. As for site 2, 3 and 4, the height was 41 mm in the wind tunnel tests, corresponding to the deck upper surface of mid-span. The heights of site 1 and 5 were from 17 mm high above the basic ground (corresponding to the bearing platform upper surface of tower near Chengdu side) up to 1,000 mm (over the highest mountain). When the height was below 84 mm (corresponding to the level of tower top), which was the interested height, the basic increment was 5 mm. However, the basic increment rose to 50 mm with the height exceeding 100 mm. The layout of the 5 key sites is shown in Figure 4, and the measurement positions of site 1, 5 below tower top is shown in Figure 5.
3 Major test results

3.1 Wind characteristics in three typical approaching wind directions

There are 26 kinds of wind characteristics at bridge site in approaching wind direction, which include mean wind velocity, overall turbulence intensity, yaw angle and wind attack angle. Three typical profiles of wind characteristics are described in this paper, for the approaching wind directions of 335.2°, 75° and 270° respectively. Cross-sections in these three approaching wind directions are given in Figures 6.

The mean wind profile is presented in the form of $U / U_{ref}$. Mean wind profiles and overall turbulence intensity profiles of site 1, 5 are given in Figures 7 to 8. The measured yaw angle should add the original yaw angle to represent the actual difference in the horizontal plane. Yaw angle profiles and wind attack angle profiles are given in Figures 9 to 10.

In the first approaching wind direction, the Power Law can fit both mean wind profiles well, and the wind velocity of site 5 is smaller below tower top. Both overall turbulence intensities decrease with height, and the value of site 5 is larger at the corresponding heights due to the comparatively smaller wind velocity. The approaching flow is parallel to the direction of valley 4, both yaw angles are smaller and the value of site 1 retains $-10^\circ$ below tower top. Site 1 situates on the edge of Mountain D, which basically only change the yaw angle of the approaching flow. However, Site 5 is located at the base of Mountain A, the approaching flow descends from the previous high lump and result in a big negative wind attack angle.
In the second approaching wind direction, the Power Law can fit mean wind profile of site 1 well, and the wind velocity of site 5 increases to the maximum wind velocity with height quickly. Both overall turbulence intensities decrease with height, but the value of site 5 is smaller between the heights of 150 mm and 600 mm. The direction of approaching flow changes dramatically below 150 mm, two average yaw angles are -35° and -25° respectively, which means the local approaching flow basically parallel to the direction of valley 1 and presumably causes a big overall turbulence intensity of site 5. The wind attack angle of site 5 is significantly larger between 100 mm and 400 mm, which presumably result in a big wind velocity and small overall turbulence intensity in the corresponding heights.

In the last approaching wind direction, both mean wind profiles resemble an “S” shape and both overall turbulence intensity profiles resemble a reverse “S”. The direction of approaching flow changes dramatically below 150 mm and both average yaw angles are approximately -60°, which means local approaching flow is basically parallel to the direction of valley 3. Site 1 is located at the right base of Mountain D and the approaching flow directly descends from the previous high hill and result in a big wind velocity and a small overall turbulence intensity in the corresponding heights.
Fig. 9 Yaw angle profiles in three typical approaching wind directions

Fig. 10 Wind attack angle profiles in three typical approaching wind directions

Horizontal mean wind profiles and overall turbulence intensity profiles at deck upper surface are given in Figures 11. The difference at the same height cannot be neglected, especially in the third approaching wind direction. The wind velocity and the overall turbulence intensity follow the opposite trend, which means the local topography has no significant effect on the standard deviation of the turbulence.

Fig. 11 Horizontal wind mean profiles and overall turbulence intensity profiles at deck upper surface in three typical approaching wind directions

3.2 Design standard wind speed and minimum critical wind speed for flutter

Without the field measurement data of bridge site, the Gradient Wind Velocity $V_G$ in the atmosphere was suggested by JTG/T D60-01 (2004). The basic wind velocity at Nyingchi,
southeast Tibet, namely, the characteristic 10 minutes mean wind velocity at 10 m above
ground level in open country terrain (terrain category B) corresponding to 100-year return
period, is 29.7 m/s. The exponent $\alpha$ of mean wind profile is about 0.16, the height of Gradient
Wind is 350 m. Thus, the Gradient Wind Velocity $V_G$ in the atmosphere for the service state is as follows:

$$V_G = V_{10} \left( \frac{z_G}{z_{10}} \right)^\alpha = 29.7 \times \left( \frac{350}{10} \right)^{0.16} = 52.5\text{ m/s}$$ (1)

The reference wind velocity in the wind tunnel tests $U_{\text{ref}}$ was measured
simultaneously and the design standard wind speed at different levels $V_d$ can be obtained as follows:

$$V_d = \left( \frac{U_d}{U_{\text{ref}}} \right) \times V_G$$ (2)

For construction state, the return period is taken as 20 years, and the corresponding
design reference wind speed $V_{d}^{*}$ is determined as

$$V_{d}^{*} = 0.88 \times V_d$$ (3)

According to the Specification [JTG/T D60-01 (2004)], When examining the flutter
instability for bridges, wind tunnel tests should take into account the interval of wind attack
angle between -3° and +3°. The Specification is applicable to the flat topography (coastal area
or plain area), where large wind attack angles do not likely to happen at a certain long return
period. As for the complex terrain, wind attack angles may be larger than the above proposed
interval. Wind Resistant Design Standard-(A) (1976) suggested that when surrounding
topographies are complex, wind tunnel tests should take into account the interval of wind
attack angle between -7° and +7°.

According to the Specification [JTG/T D60-01 (2004)], the minimum critical wind
speed for flutter is as follows:

$$\left[ V_{cr} \right] = K \cdot \mu_f \cdot V_{d0}$$ (4)

where, $V_{d0}$ is the standard design wind speed at the deck level; $\mu_f$ is a synthetic coefficient
considering the influence of turbulence on wind speed and the incomplete correlation of
winds along the bridge span. It depends on the local terrain condition and the length of bridge
span, and is set to 1.394 here. $K$ is a comprehensive safety factor, considering the
uncertainties in wind tunnel tests, design and construction of bridge, and is set to 1.2.

Table 2: The process of determining the design minimum critical wind speed for flutter at the
interval of wind attack angle between +5° and +10°

<table>
<thead>
<tr>
<th>Wind direction(*)</th>
<th>$U$</th>
<th>$U_{\text{ref}}$</th>
<th>$U / U_{\text{ref}}$</th>
<th>Site number</th>
<th>Wind attack angle(*)</th>
<th>$V_{d0}$</th>
<th>$\left[ V_{cr} \right]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>6.37</td>
<td>10.7</td>
<td>0.595</td>
<td>5</td>
<td>13.3</td>
<td>31.2</td>
<td>52.2</td>
</tr>
<tr>
<td>165</td>
<td>6.72</td>
<td>10.5</td>
<td>0.640</td>
<td>4</td>
<td>10.1</td>
<td>33.6</td>
<td>56.2</td>
</tr>
<tr>
<td>165</td>
<td>6.39</td>
<td>10.6</td>
<td>0.603</td>
<td>5</td>
<td>13.1</td>
<td>31.7</td>
<td>53.0</td>
</tr>
<tr>
<td>180</td>
<td>5.54</td>
<td>10.8</td>
<td>0.512</td>
<td>4</td>
<td>12.9</td>
<td>26.9</td>
<td>45.0</td>
</tr>
<tr>
<td>210</td>
<td>6.35</td>
<td>10.4</td>
<td>0.610</td>
<td>5</td>
<td>13.8</td>
<td>32.0</td>
<td>53.5</td>
</tr>
<tr>
<td>240</td>
<td>4.28</td>
<td>10.9</td>
<td>0.393</td>
<td>5</td>
<td>13.3</td>
<td>20.6</td>
<td>34.5</td>
</tr>
</tbody>
</table>

The wind attack angle at the deck level in the study dramatically fluctuated between
-16° and +18° according to Guo, ZS. (2013). The values of the design standard wind speed at
the deck level were determined at 5 intervals of wind attack angle between -20° and +20° in
consideration of the measurement error by choosing the maximum value for safety at the 5
key sites in the 26 different wind directions. If assuming that equation 4 is valid between -20°
and +20°, the minimum critical wind speed for flutter can then be calculated and wind tunnel tests should take into account these different intervals of wind attack angle. The process of determining the design minimum critical wind speed for flutter at the interval of wind attack angle between +5° and +10° is shown in Table 2.

The mean wind velocity to the reference wind is small when the wind attack angle is large, especially at positive wind attack angles. The values of the minimum critical wind speed for flutter at different intervals of wind attack angle are shown in Figure 12.

4 Conclusions

Profiles of wind characteristics at each pylon site in a mountainous terrain vary significantly depending on the approaching wind direction.

(a) The majority of mean wind profiles cannot be presented by the normal profile in a mountainous terrain. The Power Law presumably suitably represent the mean wind profile when the approaching flow passes along the valley or descend from a relatively high summit with the varying height barriers on the route. The wind velocity speeds up dramatically at low levels and the profile resembles an “S” shape when the flow directly descends from an extremely high summit.

(b) The local topography has no significant effect on the standard deviation of the turbulence, and the overall turbulence intensity profile follows the opposite trend of the corresponding mean wind profile.

(c) The direction of flow include yaw angle and wind attack angle, which is sensitive to the approaching wind direction in a mountainous terrain.

The wind attack angle presumably significantly fluctuates in a mountainous terrain, and the mean wind velocity to the reference wind is small when the wind attack angle is large, especially at positive wind attack angles. The design standard wind speed and the minimum critical wind speed for flutter rely on the wind attack angle and should be determined at different intervals of wind attack angle and wind tunnel tests should take into account these different intervals.

Acknowledgements

The work described in this paper was supported by the National Natural Science Foundation of China (Grant 91215302). Any opinions and concluding remarks presented in this paper are entirely those of the writers.
References


Guo, ZS. (2013). Analysis on wind-resistant performance of the Polonggou Bridge—part I: wind-tunnel tests of terrain model, Research Reports, No.SLDRCE WT201307A, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China, 2013.


