Experimental researches on wind characteristics around typical simplified forms of hills

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ABSTRACT

The reasonable determination of wind parameters in mountainous area plays an important role in wind resistant design of long-span bridges. The wind fields around eight typical simple hills are experimentally investigated by using wind tunnel tests. For different testing cases and measuring locations, the longitudinal, translational, and vertical time-varying fluctuating wind speeds are recorded by Cobra Probe, and the mean wind speed, standard deviations, angle of incidence are comprehensively investigated. The speed-up and shielding phenomena can be observed for all sections. Notable attack angle (>10°) can be detected for some locations. For different type obstacles, the wind fields those close to the models are distinct, and the difference decreases with the increasing distance from the obstacles. For the influence of wind field in front and behind of the hill, the triangle and trapezoid hill are more significant than those of the semicircle hill. The larger slope ratio generates the more obvious influence. Some conclusions are drawn to serve as a building block to understand the complex wind fields.

1. INTRODUCTION

In recent years, numerous of long-span bridges have been built in mountainous areas. The wind loading is very important and even control the structural design of light-weighted flexible bridges. The accurate determination of the design parameters of wind fields in mountainous area plays an important role in wind-resistant design of long-span bridges for both construction and operation stages. For the wind field characteristics in mountainous areas, the main research methods include wind tunnel test, numerical simulation, and in-situ measurement. The mean wind speed profiles, turbulence intensity, power spectra of fluctuating components, non-Gaussian and nonstationary behaviors, attack angle are the most concerning topics. Currently, the perfect theoretical framework has not been established. Previous experimental and numerical researches have mainly focused on the simplified regular mountainous terrain and the actual complex mountainous terrain. For the simplified cases, the measured and
simulated results are relatively reliable, and some rules can be summarized. However, the configuration is very different with the actual surroundings, and some details cannot be considered, and therefore, the results cannot directly be used for the wind-resistant design of bridges. The on-site testing method is the most direct and efficient. However, it is also the most difficult and expensive. A large amount of papers have been published concerning wind tunnel tests (e.g. Ishihara et al. 1999; Takahashi et al. 2005; Yamaguchi et al. 2003), numerical simulations (e.g. Cao and Tamura, 2006; Tamura et al. 2007; Zhou et al. 2010), and in-situ measurements (e.g. Li et al. 2002; Pang et al. 2010; Zhu et al. 2011), and many interesting and insightful conclusions were drawn.

In this study, the wind field velocities around eight typical sections are measured in wind tunnel tests, and the characteristics of average and fluctuating wind speeds and attack angles are investigated. For all sections and different yaw angles, the speed-up and shielding features of wind velocities at different locations are quantified, and comprehensive comparisons are made and analyzed.

2. EXPERIMENTAL MODELS AND SETUPS

In order to study the wind field characteristics around different shapes and slopes of the mountains, three kinds of cross sections are included: semicircle section, triangle section, and trapezoid section. Detailed sections and sizes are shown in Fig. 1, and they are sequentially called Cases 1-8, respectively. The height \( H_0 \) of all models was 10 cm. The semicircle hill models were made by PVC, plexiglass, or aluminium materials.

![Fig.1 Cross sections of the test models (unit: cm)](image)

The experiments were conducted in the wind tunnel of Dalian University of Technology (DUT-1). The test section is 3m wide, 2.5m high, and 18m long. The turbulence intensity is about 0.8% or less, and the airflow angle is less than 0.5°. The Cobra probe (Australia), which has 4 pressure holes, was used to measure the vertical, lateral, and horizontal wind velocity. Considering the wind fields at different heights and longitudinal distances are needed to be measured, the data acquisition instrument, i.e., the Cobra probe, should be adjustable and can be conveniently removed. Therefore, a
mobile slippery course was designed with a highly adjustable bracket. In the experiment, the two Cobra probes are placed on the bracket, and the height adjustment range was 1cm~35cm; and the bracket placed on the mobile slippery course, moving back and forth in the range of 0~2.5m. The test apparatus were shown in Fig. 2.

The test wind speed is 10 m/s, the sampling frequency is 200 Hz, sampling time is 40.96s, sampling points is 8192. The measuring point location: height(H): 6.25cm, 6.25cm, 7.5cm, 8.75cm, 10cm, 15cm, 20cm, 25cm, 30cm. The longitudinal distance(D) (relative distance to leeward mountain foothills as a starting point): -60cm, -50cm, -40cm, -30cm, -20cm, -10cm, 0, 10cm, 20cm, 30cm, 40cm, 50cm, 60cm, 80cm, 100cm, 120cm, 140cm, 160cm, 180cm, 200cm. The wind tunnel test pictures of the working conditions were shown in Fig. 3. For all eight kinds of models, the wind longitudinal direction is perpendicular to their axes, respectively. The yaw angle (β) can be considered as 0°, i.e., β=0°. In addition, for Case 1, the conditions of β=15°, 30°, 45° were also tested to investigate the influence of wind directions. For different cases, the time-varying wind speed along three directions were recorded, by which the longitudinal average wind speed profiles, standard deviations, attack angles can be analyzed.

3. RESULTS AND ANALYSES

3.1 Longitudinal Average Wind Speed
For $\beta=0^\circ$, the longitudinal average wind speed profiles for different locations of eight sections are shown in Fig. 4. In the figure, the black solid line represents the experimentally measured results, and the red dotted line represents the average wind speed profiles in the empty wind tunnel. And the measured wind speed is non-dimensionalized with respect to the testing wind speed ($U_0$) without any interference.
In Fig. 4, the abscissa and ordinate are also nondimensionalized for convenience of comparisons. Along the vertical direction, the region covers 3 times of the model height. Along the longitudinal direction, in front of and behind the models, the regions cover 6 and 20 times of the model height, respectively. The following conclusions can be drawn:

1. For the influence of the wind speed in front of the hill, the triangle section is more remarkable than that of the semicircle hill. For the triangle hills, the obvious influence is incurred by the larger slope. For the wind speed at the top of the hill, the speed-up effect can be obviously found for the semicircle hill, and this effect is almost negligible for the triangle hills. For Case 2, the wind speed on the tip of the hill is lower than $U_0$, and it tends to close $U_0$ when the height increases.

2. For the wind speed behind of the hill, the wind barrier effect of the triangle hills is more significant than that of the semicircle hill. Behind and above the semicircle hill, the wind speed is close to $U_0$. As comparisons, behind the triangle hill, within the $2H_0$ height, the average wind speed is less than $U_0$. Therefore, the triangle hills have more barrier effect than that of the semicircle hill. The affected region is much wider. The reasons for the above phenomena can be explained as: when the wind approaches the hill, the horizontal air flow is blocked and lifted, the vertical air flow is speeded up, and the horizontal component is decreased. More steep hills result in more remarkable blockage effect, and the lower speed of the horizontal air flow at the top and behind of the hills.

3. For the influence of the wind speed around the hill, the trapezoid hill is bigger than that of the semicircle hill. For the right-angled trapezoid hill, when the right-angled surface is facing the oncoming flow, the influential effect is the biggest. The speed-up effect at the top of the hills does not appear for the trapezoid hills. In the behind of the trapezoid hill, when the height is below $2H_0$, the mean wind speed is less than $U_0$.

4. Compare Case 3 with Case 7, the windward side slopes of the triangle and trapezoid hills are same, the average wind speed profiles are almost the same in addition to at the top of the hill. So the same of the windward side slope, the relatively consistent influence on the wind speed for two sections.

In conclusion, for different shapes of the hills, the effect trend of the wind speed is roughly same, but the influential size and the area are different, especially for the regions close to the hills.
In order to further compare the interference effects of different hill sections on the longitudinal average wind speeds, they are intuitively and quantitatively shown in Fig.5. For the sake of convenient comparisons, the results of semicircle and triangle hills, i.e., Cases 1-4 are put together, and other trapezoid hills, i.e., Cases 5-8 are put together.
From Fig. 5, the following conclusions can be drawn:

(1) Within a certain interval in front of the hill, the triangle hill with shortest bottom side (Case 2) has the most remarkable influence. The longer length of the bottom side has the smaller influence on the wind speed. In other words, the steeper the windward side slope, the greater of the impact on the wind speed located in front of the hill. The semicircle hill has the least influence.

(2) For the wind speed on the bottom of the windward side and the top of the hill, the semicircle hill is bigger than those of the triangle hills. When $H=1.5H_0$, the mean wind speed of the semicircle hill reaches $1.22U_0$. When $3H_0 \geq H > 1.5H_0$, the mean speed
of the semicircle hill is higher than \( U_0 \). But the speed-up effect is not obvious at the top of the triangle hills.

(3) In the leeside of the hill, the wind shielding effects of the triangle hills are obviously stronger than that of the semicircle hill. For the semicircle hill, it mainly affect the area of \( D<6H_0 \), \( H<H_0 \). With the increase of distance, the interference effect decreases. The wind speed is close to \( U_0 \) when \( H>1.5H_0 \). For the triangle hills, the wind speed is close to 0 when \( D<6H_0 \), \( H<H_0 \). When \( D>6H_0 \), the wind speed increases with the increasing of distance. The semicircle hill shielding effect is weaker than those of triangle section hills.

(4) In front of the hill, the right-angled trapezoid (Case 8) has the most significant influence on the wind speed. In the leeside of the hill, the effects are roughly same for all trapezoid cases. The influence on the wind speed is roughly same for the triangle and trapezoid hills.

### 3.2 Standard Deviation of Longitudinal Wind Speed

For the 8 cases, the standard deviations of longitudinal wind speed at different locations are shown in Fig. 6. Some conclusions can be drawn.

(1) The results of Case 1 are very different with other seven cases. For the wind fields located in front of the hills, the semicircle section has relative weak influence. For Case 1, when \( 0<D/H_0<5 \), \( \sigma_U \) are relatively higher. For other cases, except for \( H/H_0=1.5 \), when \( 8<D/H_0<12 \), \( \sigma_U \) are relatively higher. When \( H/H_0=1.5 \) and \( D=0 \), \( \sigma_U \) are relatively higher for Cases 2-8. For Case 1, when \( D/H_0>5 \), \( H>H_0 \), \( \sigma_U \) are insensitive to height. However, for other cases, when \( H>H_0 \), \( \sigma_U \) varies a lot with height. It can be concluded that the generated vortices behind the triangle and trapezoid sections are much larger than that of the semicircle section.

(2) For the triangle sections, some characteristics can be summarized.

(a) When \( D<0 \) and \( H<H_0 \), \( \sigma_U \) increases with the decrease of \(|D|\). The larger slope has more significant influence. When \( H=1.5H_0 \), from the hill windward foot to the leeward foot, \( \sigma_U \) increases monotonically. When \( D=0 \), \( \sigma_U \) increase firstly, and then decrease. For Cases 2,3,4, \( \sigma_U \) reach the maximums at \( D=10H_0,8H_0,6H_0 \), respectively.

(b) When \( D>0 \), and \( H<H_0 \), with the increase of \( D \), \( \sigma_U \) increase firstly, and then decrease. For Cases 2,3,4, \( \sigma_U \) reach the maximums at \( D=12H_0,12H_0,10H_0 \), respectively.

(c) When \( D>0 \), and \( H>H_0 \), with the increase of \( D \), \( \sigma_U \) increase firstly, and then decrease. For Cases 2,3,4, \( \sigma_U \) reach the maximums at \( D=8H_0,8H_0,6H_0 \), respectively.

(d) Generally, the larger slope exert more remarkable and wide influence. Correspondingly, the generated vortex is larger, and the reattachment point if farther.
3.3 Influence of Yaw Angle

Fig. 6 Standard deviations for different cases
In order to investigate the influence of yaw angle on the wind fields behind the hills, the wind tunnel tests on the semicircle section were carried out, and the yaw angles are 15°, 30°, and 45°, respectively. The longitudinal average wind speeds at four yaw angles are comparatively shown in Fig. 7. It can be seen that:

At the location close to foot of the hill, the wind speed for the yaw angle oncoming flows is slightly lower than the orthogonal wind case. When $D<4H_0$ and $H>1.5 H_0$, the wind speeds are higher than the oncoming wind speed of $U_0$. The speed-up effect is noticeable, and this effect increases with decrease of yaw angle. When $D>4H_0$ and $H>1.5 H_0$, the wind speed is close to $U_0$. As a comparison, when $H<1.5H_0$, the average wind speed increase with the increasing of distance, and the shielding effect decays.
The standard deviations of longitudinal wind speeds, i.e., $\sigma_U$ at four yaw angles ($\beta=0^\circ, 15^\circ, 30^\circ, 45^\circ$) are shown in Fig. 8. It can be seen that:

For the cases of $\beta=0^\circ, 15^\circ$, their results are fairly close, and $\beta$ has negligible influence. For the cases of $\beta=30^\circ, 45^\circ$, the results are fairly close. When $H=0.875H_0$ or $H_0$, $\sigma_U$ decreases with the increase of distance, which are very different with $\beta=0^\circ, 15^\circ$. When $H<H_0$, $\sigma_U$ are relatively higher, especially for the cases of $D/H_0<5$. On these locations, the turbulence intensities are higher than 20%, and some extreme cases are higher than 40%. When $H>H_0$, most $\sigma_U$ are lower than 1.0 for all yaw angles. In the measured regions of $0<D<20H_0$, $\sigma_U$ increases with the increase of distance.
3.4 Added Wind Attack Angle $\alpha$

Due to the blockage and interference effect of hills, the wind flow directions will be altered, and large attack angle may be incurred. The wind-induced responses may be distinct, especially for long-span flexible bridges. In traditional wind-resistant specifications for bridges, the wind attack angle ranges from $-3^\circ$ to $+3^\circ$. In the mountainous areas, the wind attack angle may be far exceeding this region. So, it is of great significance to study the characteristics of attack angle influenced by various kinds of hills. For the semicircle section, under four yaw angle ($\beta=0^\circ$, $15^\circ$, $30^\circ$, $45^\circ$) conditions, the attack angles at different locations are measured and shown in Fig.9.
Fig. 9 Wind attack angle of different positions under different yaw angles

It can be observed that:

1. When \( D \leq 4H_0 \) and \( \beta = 45^\circ \), the influence of yaw angle is comparatively lower than other three cases. For the case of \( \beta = 45^\circ \), when \( D=0, H_0 \), \( \alpha \) ranges from \(-3^\circ\) to \(+3^\circ\). With the increase of \( D/H_0 \), the attack angle slightly increases. When \( D=4H_0, H=H_0 \), \( \alpha = -8^\circ \). When \( D=0, H=H_0, \beta = 15^\circ \), the added attack angle \( \alpha = -13^\circ \). With the increase of \( D/H_0 \), the attack angle decreases when the height is lower than \( 1.5H_0 \). For the case of \( H < 1.5H_0 \), \( \alpha < -5^\circ \); and when \( H > 2H_0 \), \( \alpha \) ranges from \(-5^\circ\) to \(0^\circ\).

2. For any yaw angle, the attack angle induced by the hill decreases with the increase of \( D/H_0 \). When \( D > 6H_0 \), the influence by different yaw angle tend to be close. When \( D \geq 10H_0 \), \( \alpha \) is distributed in \((-3^\circ, +3^\circ)\), and the hill influence is negligible.

CONCLUSIONS

The wind field velocities around one semicircle section, three triangle sections, four trapezoid sections are measured by using wind tunnel tests, and the characteristics of the time-varying fluctuating wind speeds and attack angles are investigated. For all sections and different yaw angles, the speed-up and shielding features of wind velocities at different locations are quantified, and comprehensive comparisons are made and analyzed. Some significant conclusions are drawn to help understanding the complex wind fields interfered by different simplified configurations of typical hills.

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REFERENCES


