An Experimental Investigation of Streamwise and Vertical Wind Fields on a Typical Three-Dimensional Hill

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Abstract: To study the streamwise and vertical wind fields on a typical three-dimensional hill, wind tunnel tests were performed. The mean values and turbulence intensities of the streamwise and vertical wind speeds of the typical positions above the hill were measured, and they are presented in the form of contour maps for design. Furthermore, the speed-up of the mean wind speeds in the streamwise direction was compared with codes. Finally, the windage yaw of a jumper cable was examined as an example of how to take into account the streamwise and vertical wind field influence on the wind load in the analysis of wind-induced responses. The results show that the most significant speed-up effect in the streamwise direction occurs on the hill crest, and the wind speed-up decreases with the increase of the height. Overall, the wind speed-up along the crosswind center line is larger than that along the along-wind center line of the hill. In the codes, the speed-up effect specified for the structure at half the height of the upstream side of the hill is relatively conservative. With regard to the mean wind speed in the vertical direction, the wind climbing effect located at half the height of the upstream side of the hill is the most significant. The area with the stronger turbulence intensity appears at the foot of the upstream and downstream sides of the hill. The influence of the vertical wind on the jumper cable is remarkable where the wind climbing effect is the most significant, which is worthy of attention in the design of the structure immersed in a hilly terrain-disturbed wind field.

Keywords: wind tunnel test; hilly terrain; speed-up; vertical wind; wind field calculation

1. Introduction

Due to the surface changes of the earth, such as the gorges and hills [1], the wind field within the atmospheric boundary layer (ABL) changes. This significantly affects the wind forces on structures, the dispersion of pollutants, the utilization of the wind power, and other wind-related research fields. Hilly terrain enables a significant increase of the near-surface wind speed, which results in a larger wind load on the structure. Furthermore, the hills may affect the local wind direction, which leads to a distorted directional variation of the wind [2]. In light of this, it deserves efforts made to gain insight into the wind field of the airflow over the hilly terrain.

Extensive studies related to the wind field over the hilly terrain have been conducted, using the field measuring, wind-tunnel test, and computational fluid dynamics (CFD) method. Field measuring is recognized as a most direct and effective means, such as that for Kettles Mountain in Canada [3], for Sirhowy Canyon in Wales [4], and for Askervein Mountain in Scotland [5]. The main advantage...
of the field measuring is that the wind field information can be intuitively and accurately observed. However, due to the various adverse external conditions, this method is hard to be performed without strong financial support.

Wind tunnel testing is an important and cost-effective method, and widely adopted in current wind engineering field. DeBray [6] studied the wind flow of the slopes through a wind tunnel test, and presented a wind speed model for the upstream and downstream sides of the hill. Jackson and Hunt [7] proposed a wind speed profile model of a symmetrical hill with a two-dimensional (2-D) flow, and mean wind velocities were used in their work. Jackson [8] proposed a law of wind profile for the flow over steep slopes, and suggested that the law is merely suitable for the steep slopes less than 10 km in length and 20° in slope. Taylor and Lee [9] proposed a simplified method to consider the speed-up at different heights by using the maximum speed-up, which is called the original guideline. Finnigan [10] reviewed the results of the field measurements and wind tunnel tests, and compared the mathematical models proposed in the literature. Finnigan found that the maximum speed-up error of the algorithm by Jackson [8] in the calculation of flow separation is less than 15% to 18%. Carpenter and Locke [11] conducted substantial wind tunnel tests to study the wind fields of the flow over different hill geometries, such as the shallow sinusoidal hill, the steep sinusoidal hills, the consecutive hill, and other irregularly shaped hills. They compared the wind-tunnel test results with that obtained by using CFD in association with a $k-\varepsilon$ turbulence model, and found that the greatest mean speed-up ratio appears at the height of 5.0 m above the hill crest. For the single shallow hill the speed-up ratio is 2.13, whereas for the steep hill it is slightly less than 2.08. Ishihara et al. [12] conducted a wind tunnel test on a circular hill with a cosine-squared cross section. They compared the results with those in the undisturbed ABL, and found that the maximum perturbations in both streamwise and vertical wind speed variances could be observed at the height of the hill and on the lee slope of the hill. The maximum speed-up ratio is 1.5, and appears at the hill crest. Pirooz and Flay [13] utilized the wind-tunnel measurements and CFD simulations to study the speed-up of the airflow over bell-shaped hills, and compared the results with that in wind-loading codes. They found that the maximum speed-up ratio obtained from the CFD simulation is 2.15, and none of the codes provides a satisfactory result for speed-up.

With regard to CFD-based analysis, Kim et al. [14] studied two series of two-dimensional hills, and found that the turbulence energy is dissipated due to the influence of the front hill, which results in a reduction of the wake area behind the rear hill. Ishihara and Hibi [15] compared the results obtained by using Shih’s non-linear $k-\varepsilon$ model and the standard $k-\varepsilon$ model [16], respectively. They found that the non-linear Shih’s $k-\varepsilon$ model provides a better prediction, and shows a good agreement with the experimental results. Iizuka and Kondo [17] investigated the performance of four different subgrid-scale (SGS) models to predict a turbulent flow over two-dimensional (2-D) steep ridges, using two kinds of surface roughness. By comparing the results with that by Ishihara et al. [18], they found that the results attained via hybrid SGS model match well with the experimental data in case of 2-D rough ridge, but cannot predict the flow well in the wake of a 2-D smooth ridge. Breuer et al. [19] studied the wind field around a 2-D periodical hill, with consideration of different Reynolds numbers over a wide range, through wind tunnel tests and numerical simulations. Ishihara and Qi [20] studied the turbulent flow over a 2-D steep ridge and a three-dimensional (3-D) steep hill having rough and smooth surfaces, in which a delayed detached-eddy simulation (DDES) method was used. Liu et al. [21] studied the mean and turbulent quantities on the surfaces on an isolated hill by large-eddy simulations (LES), and found a spiral-shaped structure in both the lateral and vertical directions. Liu et al. [22] also studied the turbulent flow over a 2-D hill and a 3-D ridge with a smooth ground by using LES. In the wake it was found that the spectra of fluid are very sensitive to the oncoming turbulence in case of 2-D ridge.

Most of the above studies focused on the streamwise mean wind speed; however, few studies have been conducted on the vertical wind and the wind fluctuations. To date, the relevant terms in the codes
used to determine the characteristics of the hilly terrain wind field are not sufficient for wind engineering. It is worth noting that the formulae in these codes are mainly for two-dimensional situations.

In this paper, a wind tunnel test was conducted to study the wind fields of streamwise wind and vertical wind for the flow over a typical 3-D hill possessing a cosine-squared cross section. The mean wind speed, along with the turbulence intensity at the typical positions on the surface of the hill, was measured. Furthermore, the speed-up along the streamwise direction was compared with that specified in the codes. The contour maps of the mean wind speed, as well as the turbulence intensity in the directions of streamwise and vertical, are presented, which provides a reference for the wind resistant design of the structures under the hilly terrain wind field, and also enriches the database of experimental study on speed-up ratio. Finally, an example of the windage yaw of the jumper cable that is frequently utilized in the transmission lines is given to show the usage of the presented hilly terrain wind field in the analysis of wind-induced response of a structure stationed on top of a hill.

2. Setup of the Wind Tunnel Test

The wind tunnel testing method was utilized to study the characteristics of the wind field involved with a hilly terrain, and the tests were completed in ZJU-1 wind tunnel in Zhejiang University, China. The wind tunnel has a testing section of 4.0 m wide and 3.0 m high, and the testing wind speed ranges from 0.0 to 50.0 m/s.

However, the shapes of the hills in nature are diverse and the profiles of the corresponding wind fields are different. For design, it is necessary to survey the wind characteristics information by using a generalized hill shape and a standard flow field. Therefore, a cosine-squared cross-section (Figure 1) is adopted herein for the wind tunnel test, and can be expressed as:

\[
zs(x,y) = \begin{cases} 
H \cos^2\left(\pi \frac{\sqrt{x^2+y^2}}{2L}\right), & \sqrt{x^2+y^2} < L \\
0, & \sqrt{x^2+y^2} \geq L 
\end{cases}
\]  

(1)

![Coordinate system and notations.](image.png)

Figure 1. Coordinate system and notations.

In Equation (1), the hill height \( H \) is 100 m and the base radius \( L \) is 350 m. The streamwise, spanwise and vertical directions are denoted by \( x, y, \) and \( z \), respectively, as shown in Figure 1. The origin is set at the center of the bottom of the hill. A local vertical coordinate \( Z_i = z - z_s \) is employed to describe the height above the surface of the hill, where \( z_s \) is the height of the points on the hill surface.

The scale of the model is 1:1000. Thus, the base radius of the model for test is 0.35 m, and the height of the model is 0.1 m. The model of the hill is shown in Figure 2.
Remarkable effects of the surface roughness on the characteristics of the wind fields over the hilly terrain have been emphasized by previous studies [23–25]. With consideration of that the vegetation on the surface of the real hill may create a certain surface roughness, the average height of the vegetation is assumed to be 2.0 m. To simulate this vegetation-induced surface roughness, plastic fibers with a height of 2.0 mm were distributed over the surface of the hill model.

The Cobra Probe [26] was used to measure the wind speeds in the hilly terrain-disturbed ABL wind. The sampling frequency is 1250 Hz, and the duration is approximately 60 s for each measuring. The oncoming wind field belongs to Type A (a reference to offshore seas and islands, coasts, lake shores and desert areas) according to GB 50009-2012 [27]. The oncoming neutral ABL wind is physically simulated by using a passive method with a scale ratio of 1:1000, namely, spires in association with floor roughness arrays are employed for the simulation. The simulated wind speed $V$ normalized by $V_{H}$ (the wind speed at a height of gradient wind) at the reference height, along with the streamwise turbulence intensity $I_{u}$ is shown in Figure 3, as depicted in the full scale dimension. The wind speed and turbulence intensity for Type A [27] can be expressed as:

$$V = V_{10}(z/10)^{0.12}$$

$$I_{u} = I_{10}(z/10)^{-0.12}$$

where $V_{10}$ and $I_{10}$ are the mean wind speed and turbulence intensity, respectively, at the height of 10 m. The measured profiles of mean wind speed and turbulence intensity are close to the requirements in GB 50009-2012. The streamwise wind power spectra attained at the height of 0.09 m and 0.15 m in the wind tunnel test are generally close to the von Karman spectrum [28], as shown in Figure 4a,b, in which $n$, $S$, and $\sigma$ are the frequency, spectrum and standard deviation of the fluctuating wind speed, respectively. Overall, the simulated oncoming wind fields are generally in accordance with the requirement of the code [27].
The wind speeds at five heights of every measured point were measured, and the surface, as shown in Figure 5. Thus, for analysis, the experimental results measured are mirrored with respect to x-z plane. The wind speeds at five heights of every measured point were measured, and the heights are 0.03 m, 0.06 m, 0.09 m, 0.12 m, and 0.15 m, respectively.

Figure 3. Mean wind speed and turbulent intensity.

Figure 4. Tested wind power spectra and von Karman spectrum.

Twenty one test points with a sequential number assigned were merely placed at the half of the hill, due to the symmetry. Furthermore, the test points are arranged along the five lines above the hill surface, as show in Figure 5. Thus, for analysis, the experimental results measured are mirrored with respect to x-z plane. The wind speeds at five heights of every measured point were measured, and the heights are 0.03 m, 0.06 m, 0.09 m, 0.12 m, and 0.15 m, respectively.

Figure 5. Layout of the test points.
3. Results and Discussion

3.1. Wind Field Characteristics in the Streamwise Direction

To quantifiably describe the wind speed-up effect, the speed-up was defined by [7]

\[ S_u(Z_i) = \frac{V_u(Z_i)}{V_0(z)} \]  

(4)

where \( S_u \) is the streamwise wind speed-up at the height of \( Z_i \) above the hill, \( V_u \) is the wind speed at the height of \( Z_i \), and \( V_0 \) is the wind speed at the height of \( z \) in the undisturbed ABL. If \( S_u \) is greater than 1.0, the wind speeds up, otherwise the wind slows down, in comparison with the wind speed in the undisturbed ABL.

3.1.1. Speed-Up

Figure 6 shows the profiles of the mean wind speed-up in the streamwise direction measured on the along-wind center line of the hill \((y = 0)\). The most remarkable features of the streamwise mean speed are the increase in the wind speed near the surface on the hill crest, the slight deceleration at the foot of upstream side of the hill, and the flow separation behind the hill. Whether it is in the wind speed-up or deceleration area, the near-surface wind speed is greatly affected by the hill. As the height increases, the wind speed is gradually weakened due to the decreasing influence of the hill. The wind speed-up phenomenon near the hill crest is more significant than that at other positions. The greatest speed-up occurs on the hill crest and its value is 1.34. In the deceleration zone of the upstream side of the hill, the most obvious deceleration effect occurs at \( x/L = -0.75 \), where the minimum value of the speed-up is 0.69. At \( x/L = 0.75 \) and \( x/L = 1.00 \), due to the generation of the flow separation, the wind speed profiles at these positions are significantly different from the profiles in the undisturbed ABL.

![Figure 6. The streamwise mean wind speed-up \( S_u \) on the along-wind center line of the hill \((y = 0)\).](image)

Figure 7 shows the profiles of the streamwise mean wind speed-up measured on the crosswind center line of the hill \((x = 0)\). Compared to the case of \( y = 0 \), the flow has different speed-up effects, for the positions along the crosswind direction. Similarly, the closer the location is to the hill crest, the more significant the speed-up effect of the flow can be found. At the same position, as the height increases, the speed-up effect decreases. Compared to the wind speed-up found on the along-wind center line of the hill \((y = 0)\), the wind speed-up observed on the crosswind center line \((x = 0)\) is more significant.
The area in which the values of the speed-up are greater than 1.1 becomes smaller with increasing significant. However, as the $Z_{i}$ the downstream side of the hill. Relatively, the lower half of the downstream side of the hill is more height increases. The wind deceleration effect appears on the lower halves of the upstream side and the downstream side of the hill. Relatively, the lower half of the downstream side of the hill is more significant. However, as the $Z_{i}$ increases, the deceleration effect weakens.

According to the data acquired at the measuring points at different heights, contour maps of the speed-up are achieved and shown in Figure 8. The maps are for the heights above the hill surface $Z_{i}$ of 30 m, 60 m, 90 m, 120 m, and 150 m. It can be seen that the speed-up in the area near the hill crest is the most significant for each subplot. It reaches its maximum value at the height of $Z_{i} = 30$ m. The area in which the values of the speed-up are greater than 1.1 becomes smaller with increasing $Z_{i}$. However, at the foot of downstream and upstream side of the hill, the speed-up increases as the height increases. The wind deceleration effect appears on the lower halves of the upstream side and the downstream side of the hill. Relatively, the lower half of the downstream side of the hill is more significant. However, as the $Z_{i}$ increases, the deceleration effect weakens.

Figure 7. The streamwise mean wind speed-up $S_{u}$ on the crosswind center line of the hill ($x = 0$).

Figure 8. The wind speed-up $S_{u}$ at different heights.
3.1.2. Turbulence Intensity

Turbulence intensity, as a measure of the pulsation of the wind, is generally equal to the ratio of the standard deviation of the time-varying wind speed to the time-averaged wind speed. Figure 9 shows the contours of the streamwise turbulence intensity at different heights above the surface of the hill. The same color of the area where the turbulence intensity is greater than 0.5 is used in the contour maps. The maximum turbulence intensity appears at the foot of the downstream side of the hill. When $Z_i = 30$ m, there is an area with strong turbulence on the upstream side of the hill, which is smaller than the area where a strong turbulence exists on the downstream side. The turbulence intensity on the upstream side is not as strong as that on the downstream side of the hill. In general, with increasing height, the area with strong turbulence intensity on the upstream side disappears. This sounds reasonable, because the farther the location is, the less the disturbance of the hill is.

3.2. Wind Field Characteristics of the Vertical Direction

3.2.1. Mean Wind Speed

The vertical wind component ratio (VWCR) $S_w$ is used to represent the vertical mean wind speed, which can be defined as

$$S_w(Z_i) = \frac{V_w(Z_i)}{V_0(z)}$$

where $V_w$ is the vertical wind speed at the height of $Z_i$, and $V_0$ is the wind speed at the height of $z$ in the undisturbed ABL. Its definition is similar to the streamwise speed-up $S_u$.

Figure 10 shows the VWCRs measured on the along-wind center line of the hill ($y = 0$). In the upstream side of the hill, the VWCR is positive, which indicates that the wind blows up. In contrast, on the downstream side of the hill, the VWCR is negative, which indicates that the wind blows down. There is almost no vertical wind at $x/L = -1.00$ (the foot of the upstream side of the hill) and $x/L = 0$ (the
The largest positive VWCR appears at the height of 30 m above the surface of the hill where \( x/L = -0.5 \), and the largest negative vertical wind component ratio appears at the height of 150 m above the surface of the hill where \( x/L = 0.75 \). These findings are mainly attributed to the separation and attachment of the flow on the lee side. Although a large VWCR appears at a higher position with \( x/L = 0.75 \), the VWCR is close to 0.0 provided \( Z_i \) is less than 60 m. The VWCRs measured at different heights are almost the same, in case of \( x/L = -0.75 \).

Figure 11 shows the VWCR measured on the crosswind center line of the hill (\( x = 0 \)). The VWCR at each measuring point is very small, which indicates that the vertical wind speed predominately functions for the structure near the along-wind center line. Moreover, at the same location, there is no significant difference between the VWCRs along the height.

![Figure 10](image1.png)

**Figure 10.** The vertical wind component ratio \( S_v \) on the along-wind center line of the hill (\( y = 0 \)).

![Figure 11](image2.png)

**Figure 11.** The vertical wind component ratio \( S_v \) on the crosswind center line of the hill (\( x = 0 \)).

Figure 12 shows the contour plots of the VWCR in case of \( Z_i = 30 \) m, 60 m, 90 m, 120 m, and 150 m, respectively. The maximum positive VWCR at all heights occurs on the upstream side of the hill and the maximum positive value is 0.28, which indicates that the climbing effect is significant at this location. Meanwhile, the maximum negative VWCR among those measured at all heights occurs at the mid of the downstream side of the hill, and the maximum negative value is –0.26. It implicates that this position has a significant downhill effect. As the \( Z_i \) increases, the absolute values of the upward and downward VWCR decrease. It means that the hill-climbing effect and the downhill effect decrease as the height increases, due to the decrease of the disturbance caused by the hill. The area where the VWCR is close to zero is mainly located on the upstream side of the hill near the center line of the hill (\( x = 0 \)).
The area with strong turbulence appears at the upstream side of the hill and the foot of the downstream side of the hill, because the vertical mean wind speed is small in these areas. In the area where the absolute value of VWCR is small. Accordingly, the turbulence intensity and the VWCR are inversely related. The area with strong turbulence appears at the upstream side of the hill and the foot of the downstream side of the hill, because the vertical mean wind speed is small in these areas. In the area where the absolute value of VWCR is small. Accordingly, the turbulence intensity and the VWCR are inversely related.

Figure 12. The vertical wind component ratio $S_{w}$ at different heights.

3.2.2. Turbulence Intensity

Figure 13 shows the contour plots of the turbulence intensity of the vertical wind speed, for $Z_{i} = 30$ m, 60 m, 90 m, 120 m, and 150 m, respectively. The same color is used for the area where the turbulence intensity is greater than 1.0. The turbulence intensity is small where the absolute value of VWCR is large. Moreover, the turbulence intensity is large in the region where the absolute value of VWCR is small. Accordingly, the turbulence intensity and the VWCR are inversely related. The area with strong turbulence appears at the upstream side of the hill and the foot of the downstream side of the hill, because the vertical mean wind speed is small in these areas. In the area where the vertical wind turbulence intensity is relatively small, the streamwise turbulence intensity is much larger, as well as the VWCR. Therefore, it is necessary to pay attention to these locations.

Figure 13. Cont.
profiles at the hill crest for a hill of 3-D is smaller than that for a 2-D hill. In comparison with a 2-D flow. In addition, it is found that the present results (tunnel test and field testing. This may be attributed to the characteristics of the 3-D flow, that is to say the 3-D vortex and separation of the flow lead to a more diffusion/dissipation of the wind energy, in comparison with a 2-D flow. In addition, it is found that the present results (H/L = 0.286) are close to those obtained in the field measuring (H/L = 0.26) [5]. Generally, at the hill foot on the upstream side, the profiles resulting from the 3-D study are greater than those obtained in the 2-D study, whereas the profiles at the hill crest for a hill of 3-D is smaller than that for a 2-D hill.

Figure 13. The vertical turbulence intensity at different heights.

3.3. Comparison of Speed-ups for Horizontal Wind

Figure 14 shows the results of speed-up in the previous studies, along with the present results. Except for the field test results presented by Walmsley et al. [5], the curves provided in different studies are for the hill with a shape function of sine/cosine type. It is found that the present results are close to those obtained by Cao et al. [25], for the vertical profile at the hill foot on the upstream side of the hill. However, the greater amounts found in the present study may be attributed to the greater slope used in their work, which slows down the oncoming flow. On the hill crest, the speed-up usually reaches its maximum values. The comparison of the CFD results obtained by Carpenter and Locke [11] and Girma et al. [29] shows that the speed-up ratio at the same non-dimensional height increases with the increasing H/L. It is found that the CFD results are generally greater than those obtained from the wind tunnel test and field testing. This may be attributed to the characteristics of the 3-D flow, that is to say the 3-D vortex and separation of the flow lead to a more diffusion/dissipation of the wind energy, in comparison with a 2-D flow. In addition, it is found that the present results (H/L = 0.286) are close to those obtained in the field measuring (H/L = 0.26) [5]. Generally, at the hill foot on the upstream side, the profiles resulting from the 3-D study are greater than those obtained in the 2-D study, whereas the profiles at the hill crest for a hill of 3-D is smaller than that for a 2-D hill.

Figure 14. Comparison of speed-up $S_u$ between tests and other studies.
In the following, the present speed-up results are compared with those used in the design codes to further enrich the database of the study on speed-up. The height variation coefficient of wind pressure is defined in GB 50009-2012 [27] to account for the influence of hilly terrain, which is called the terrain correction coefficient \( \eta \). The expression of the correction coefficient \( \eta_B \) at the hill crest is

\[
\eta_B = [1 + \kappa \cdot \tan \alpha (1 - \frac{z}{2.5H})]^2
\]

(6)

where the term of \( \tan \alpha \) is the slope of the upstream side of a hill/slope, and it is no more than 0.3; \( \kappa \) is a constant (2.2 for a hill and 1.4 for a slope); \( H \) is the height of the hill or the slope; and \( z \) is the height from the hill surface. Furthermore, the wind speed-up caused by hilly terrain is equal to \( \eta_B^{0.5} \).

In ASCE 7-10 [30], the multiplier, \( K_{zt} \), is used to take into account the effects of topography, and is defined as [30]

\[
K_{zt} = \left(1 + \frac{K_1}{K_2} \frac{K_3}{K_4}\right)^2
\]

(7)

where \( K_1, K_2, \) and \( K_3 \) are the factors to consider the reductions in speed-up with horizontal distance downstream and upstream of the crest, and the reduction caused by the height above the local terrain, respectively. Then, the basic wind speed should be multiplied by \( K_{zt}^{0.5} \). The values of \( K_1 \) for different topographies, such as 2-D hills, and 3-D axis-symmetrical hills, are given by ASCE 7-10. The factors, \( K_2 \) and \( K_3 \), can be computed by [30]

\[
K_2 = (1 - |x|/\mu L_u)
\]

(8a)

\[
K_3 = \exp(-\gamma z/\mu L_u)
\]

(8b)

where \( \mu \) and \( \gamma \) are the factors for horizontal and height attenuation, respectively. \( L_u \) is the horizontal distance from the hill crest to the upstream slope at 1/2 of the hill height.

In the European standard, EN 2004-1-4 [31], the orographic factor \( C_0 \) is used to account for isolated hills and cliffs, but not for the undulating and mountainous regions, and indicates the increase in mean wind speed. It can be computed by [31]

\[
C_0 = 1 \quad \text{for} \quad \phi < 0.05 \quad \text{(9a)}
\]

\[
C_0 = 1 + 2s \phi \quad \text{for} \quad 0.05 < \phi < 0.3 \quad \text{(9b)}
\]

\[
C_0 = 1 + 0.6s \phi \quad \text{for} \quad \phi > 0.3 \quad \text{(9c)}
\]

where \( \phi \) is the upstream slope, and \( s \) is the orographic location factor.

In AS/NZS 1170.2 [32], it is recognized that the speed-up effect is independent of the slope for \( H/(2 L_u)>0.45 \). The speed-up multiplier (\( M_h \)) can be calculated by [32]

\[
M_h = 1.0 \quad \frac{H}{L_u} < 0.05 \quad \text{(10a)}
\]

\[
M_h = 1 + \left(\frac{H}{3.5(z + L_1)}\right)\left(1 - \frac{|x|}{L_2}\right) \quad 0.05 < \frac{H}{2L_u} \leq 0.45 \quad \text{(10b)}
\]

within the separation zone,

\[
M_h = 1 + 0.71\left(1 - \frac{|x|}{L_2}\right) \quad \frac{H}{2L_u} > 0.45 \quad \text{(10c)}
\]

elsewhere,

\[
M_h = 1 + \left(\frac{H}{3.5(z + L_1)}\right)\left(1 - \frac{|x|}{L_2}\right) \quad \frac{H}{2L_u} > 0.45 \quad \text{(10d)}
\]

where \( z \) is the height above the local ground, and \( x \) is the distance from the hill center. \( L_1 \) is the greater of 0.36 \( L_u \) and 0.4\( H \). \( L_u \) is the horizontal distance from the hill crest to the upstream slope at 1/2 of the hill height, and \( L_2 \) is 4 \( L_1 \) at upstream slope and the ridge and 10 \( L_1 \) at the downstream side.
In AIJ 2004 [33], the wind speed-based correction factor \( E_g \) is used to take into account the hilly terrain

\[
E_g = (C_1 - 1)[C_2\left(\frac{Z}{H_s} - C_3\right) + 1] \exp[-C_2\left(\frac{Z}{H_s} - C_3\right)] + 1
\]

where \( H_s \) is the hill height, and \( C_1, C_2, \) and \( C_3 \) are coefficients.

Because the speed-up multiplier specified by the aforementioned codes is in regard to the speed-up effect on the upstream side of the hill on the along-wind center line of the hill \( (y = 0) \), the amounts of the speed up for the typical positions on the upstream side of the hill are compared with those in the codes, as shown in Figure 15. At \( x/L = -1 \) (the foot of upstream side of the hill), the speed-up values obtained from the wind tunnel tests are smaller than those from the standards. The speed-up values in ASCE 7-10 and AS/NZS 1170.2 are less than 1.0, whereas those in GB 50009-2012 and AIJ 2004 are greater than 1.0, and those in EN 2004-1-4 are greater than 1.0. Furthermore, at \( x/L = -0.5 \) (the half height of the upstream side of the hill), the speed-up value obtained from the wind tunnel test is smaller than those in the codes. In this case, the speed-up value in AIJ 2004 is 1.0, and the values in the codes of other countries are all greater than 1.0. The speed-up values calculated via GB 50009-2012 are the largest and linearly changeable. The comparison indicates that for the upstream side of the hill foot and half height of the upstream side of the hill, the wind speed-up calculated by the codes are much bigger than the results obtained in the wind tunnel test. At \( x/L = 0 \) (hill crest), the speed-up obtained from the wind tunnel test is basically between that from AS/NZS 1170.2 and that from AIJ 2004, and is much smaller than those from GB 50009-2012 and EN 2004-1-4. The speed-up values obtained by ASCE 7–10 are the smallest among all. Generally, the divergence of the speed-up in the specifications of the codes is significant. Moreover, with respect to the speed-up that occurs at the hill foot, the codes underestimate the reduction of the wind speed.

![Figure 15. Cont.](image-url)
4. Application: Windage Yaw of the Jumper Cable over Hilly Terrain

A jumper cable is a conductive device connecting the tensile clamps on both sides of a tension tower in a transmission line. It is used to maintain a sufficient electrical clearance distance between the live conductor and the conductive portion of the tower (Figure 16). Many accidents in power transmission lines are attributed to the excessive windage yaw of jumper cables, which results in a reduction of the electrical apparatus clearance distance. As the windage yaw of the jumper cable is very sensitive to the wind loadings, the cable is employed herein as an example to clarify the using of the presented contour plots resulting from the hilly terrain-disturbed wind field.

The translational displacement responses of the cable subjected to wind loads can be computed via finite element (FE) approach, and the commercial software ANSYS was then utilized. In the FE analysis, the displacement responses can be computed by

$$ F = KD $$  \hspace{1cm} (12)$$

where \( K \) is the elastic stiffness matrix, and \( D \) is the vector of the translational displacement. The \( F \) in Equation (13) is the vector of the external wind loading, and it has a form of

$$ F = \{F_1, \ldots, F_i, \ldots, F_N\}^T, \text{ and } F_i = \{F_{x_i}, F_{y_i}, F_{z_i}\}^T $$  \hspace{1cm} (13)
where $N$ is the number of the nodes. $F_i$ is the nodal force sub-vector for the $i$th node, and in a form of

$F_{xi} = 0.5\rho V_0^2 S^2 g_0 \mu_{sx} A_{xi}$ \hspace{1cm} (14a)

$F_{yi} = 0$ \hspace{1cm} (14b)

$F_{zi} = 0.5\rho V_0^2 S^2 g_0 \mu_{sz} A_{zi}$ \hspace{1cm} (14c)

in which $\rho$ is the density of the air, $\mu_{sx}$ and $\mu_{sz}$ are the drag coefficients of the cable in the $x$ and $z$ direction, $A_{xi}$ and $A_{zi}$ are the projected areas in the $x$ and $z$ direction, and $V_0$ is the wind velocity at height of $z$ in the undisturbed ABL.

Thus, the windage yaw angle $\alpha$ induced by the wind loads can be computed by

$$\alpha = \text{atan}[D_x/(D_s - D_z)]$$ \hspace{1cm} (15)

where $D_x$ and $D_z$ are the streamwise displacement and vertical displacement of the cable, respectively, and $D_s$ is the sag of the cable.

Figure 16. A picture of the jumper cable.

In the FE modelling of the cable, the two-node truss element is employed, and each node of the element has three translational degrees-of-freedom (DOFs). As the cable takes a shape of catenary curve due to its self-weight, the initial coordinates of each node are in accordance with the classic catenary equation [34]. The ends of the jumper cable are hinged. The internal initial tensile force of the cable caused by the self-weight is simulated by prescribing an initial tensile stress for each element. The wind loadings on the structure are simplified as concentrated forces acting on the nodes. The FE model of the jumper cable with boundary conditions and nodal wind loads is illustrated in Figure 17, and the relevant parameters are listed in Table 1. Figure 18 depicts the locations of the jumper cable, along with the wind direction of the oncoming flow, for the following study.

A sensitivity analysis was performed in advance to determine an appropriate mesh that would balance the calculation accuracy and the computational cost. Five FE meshes, namely, the cable is divided into 20, 40, 80, 160, and 320 elements, respectively, were thus employed for the sensitivity analysis. Based on these meshes, the streamwise displacement, vertical displacement, and the windage yaw angle of the cable on the hill crest were obtained and listed in Table 2. It is found that the number of the elements affects the wind-induced response of the jumper cable slightly, provided that it is greater than 20. Generally, a denser mesh may result in a better solution, but requires a higher computational
cost. A compromise should be made between the calculation accuracy and the cost. The mesh with 160 elements was therefore adopted in the following FE analysis.

![Figure 17. FE model of the jumper cable.](image)

**Table 1.** Calculating parameters of the jumper cable.

| Parameters                              | Value        |
|-----------------------------------------|--------------|
| Diameter of the cable                   | 21.6 mm      |
| Span of the cable                       | 12 m         |
| Sag of the cable (Dₛ)                   | 3.33 m       |
| Height of the lowest point of the cable  | 30 m         |
| Density of the cable                    | 3176 kg/m³   |
| Density of the air                      | 1.25 kg/m³   |
| μsx and μsz                             | 1.1          |
| Wind speed at the lowest point (V₀)     | 22.82 m/s    |

![Figure 18. Positions of the jumper cable on the hill.](image)

**Table 2.** The wind-induced response with different number of elements.

| Number of Elements | 20   | 40   | 80   | 160  | 320  |
|--------------------|------|------|------|------|------|
| streamwise displacement (m) | 2.6357 | 2.6360 | 2.6353 | 2.6352 | 2.6351 |
| vertical displacement (m)    | 1.2955 | 1.2960 | 1.2954 | 1.2952 | 1.2952 |
| windage yaw angle (°)        | 52.746 | 52.756 | 52.741 | 52.737 | 52.736 |

With consideration of the disturbance of the hilly terrain to the ABL wind, the corresponding wind-induced structural responses can be obtained through Equations (13)–(16), and denoted as R. Note that the structural response herein can be the translational displacement, windage yaw angle,
internal force, and so on. For convenience, the wind response accounting for the hilly terrain is normalized by
\[
\overline{R} = \frac{R}{R_0}
\]  
where \(\overline{R}\) is the normalized wind-induced response, and \(R_0\) is the corresponding response resulting from the undisturbed ABL wind. In this study, the streamwise displacement, vertical displacement, and the windage yaw angle of the cable immersed in the undisturbed ABL wind are 1.22 m, 0.23 m, and 11.69°, respectively, given that the wind speed at 30 m height is 22.82 m/s.

The normalized wind-induced responses are shown in Figure 19, where only streamwise wind speed is considered. Compared to the wind-induced responses in the undisturbed ABL wind field, at the foot of the upstream and downstream sides of the hill, the wind-induced response of the jumper cable weakens, and the response then increases near the crest. The vertical displacement has a largest increase, which is 90% larger than that in the undisturbed ABL wind field at the hill crest. Because the wind slows down at the foot of the upstream and downstream sides of the hill, as a result the wind loads suffered on the jumper cable reduce. Thus, the streamwise and vertical displacements of the cable decrease, and so does the corresponding windage yaw. Furthermore, the wind speeds up near the hill crest and the phenomenon of wind speed-up is very significant, which leads to the increase of the wind loads imposed on the jumper cable. Consequently, it will cause the increase of the streamwise and vertical displacements, as well as the corresponding windage yaw angle.

![Figure 19. Normalized wind-induced responses of the jumper cable (only streamwise wind speed is considered).](image)

To study the effects of the vertical wind speed on the wind-induced response of the jumper cable, the wind-induced responses of the jumper cable located on the along-wind center line of the hill \((y = 0)\) are compared. The streamwise displacement, vertical displacement, and windage yaw angle of the lowest point of the jumper cable under different conditions, i.e., considering the vertical wind speed or not, are shown in Table 3. On the upstream side of the hill, the wind-induced responses decrease with \(x/L\) and then increase, and reach their maximum at the crest \((x/L = 0)\). After considering the vertical wind speed, the increase of these three wind-induced responses of the jumper cable are remarkable at \(x/L = -0.5\) and \(x/L = -0.25\), and the maximum increase of vertical displacement is 9.30%. The vertical displacement of the lowest point of the jumper cable at \(x/L = 0.25\) decreases by 1.73%. These findings are mainly attributed to the vertical wind. On the upstream side, the upward flow resulting in positive vertical wind may provide a lift force, and the effect of it is equivalent to reducing the weight of the cable, and consequently increases the windage yaw angle. Nevertheless, the effect of the downward flow occurs on the downstream side is equivalent to increasing the cable weight, which results in a reduction of windage yaw angle.
Table 3. The wind-induced response of the lowest point of the jumper cable.

| x/L = −1, y = 0 | x/L = −0.75, y = 0 |
|-----------------|-------------------|
|                  | Streamwise         | Vertical           | Windage Yaw Angle | Streamwise | Vertical | Windage Yaw Angle |
| Only considering the streamwise wind speed | 1.215 | 0.231 | 21.594 | 1.068 | 0.177 | 18.885 |
| Considering both the streamwise and vertical wind speed | 1.215 | 0.231 | 21.604 | 1.078 | 0.181 | 19.056 |
| Increase | 0.04% | 0.10% | 0.04% | 0.86% | 1.99% | 0.90% |

| x/L = −0.5, y=0 | x/L = −0.25, y = 0 |
|-----------------|-------------------|
|                  | Streamwise         | Vertical           | Windage Yaw Angle | Streamwise | Vertical | Windage Yaw Angle |
| Only considering the streamwise wind speed | 1.657 | 0.442 | 30.102 | 2.468 | 1.096 | 48.239 |
| Considering both the streamwise and vertical wind speed | 1.723 | 0.484 | 31.456 | 2.513 | 1.147 | 49.412 |
| Increase | 4.00% | 9.30% | 4.50% | 1.80% | 4.67% | 2.43% |

| x/L = 0, y = 0 | x/L = 0.25, y = 0 |
|----------------|-------------------|
|                  | Streamwise         | Vertical           | Windage Yaw Angle | Streamwise | Vertical | Windage Yaw Angle |
| Only considering the streamwise wind speed | 2.637 | 1.297 | 52.775 | 2.023 | 0.686 | 37.742 |
| Considering both the streamwise and vertical wind speed | 2.635 | 1.295 | 52.737 | 2.009 | 0.674 | 37.415 |
| Increase | −0.05% | −0.14% | −0.07% | −0.73% | −1.73% | −0.87% |

5. Conclusions

This paper presents the contour plots of mean wind speed (speed-up), and turbulence intensity at various heights for a flow over a typical three-dimensional hill, contour plots of the vertical mean wind speed (vertical wind component ratio) and the corresponding turbulence intensity, for design reference. The experimental results presented herein would enrich the database of the study on speed-up. The gathering, separation, diffusion, and attachment of the flow are the main factors accounting for the follows, leading to a speed-up on the upstream side, and a deceleration on the downstream side.

The speed-up at the hill crest is the largest and the maximum speed-up is 1.34, which appears at the hill crest, and is located at a height of 30 m above the hill surface. A wind deceleration effect appears on the lower halves of the upstream and downstream side of the hill. The results, measured at the foot of the hill and the mid-height of the upstream side of the hill, are less than that specified in the codes. The test results at the hill crest are between those in AS/NZS 1170.2 and AIJ 2004, less than the results in GB 50009-2012 and EN 2004-1-4, and greater than that in ASCE 7-10.

For vertical mean wind speed, the wind climbing effect at the half height of the hill on the along-wind center line of the hill (x/L = −0.5, y = 0, Z = 30 m) is the most significant when the vertical wind component ratio is 0.28, and the downhill effect near the half height of the downstream side of the hill (x/L = 0.43, y/L = 0.43 or −0.43, Z = 30 m) is the most significant when the vertical wind component ratio is −0.26. For the turbulence intensity of the streamwise wind speed, there is an area of strong turbulence intensity at the foot of downstream side of the hill. With an increase of height, the turbulence intensity of the vertical wind speed tends to be consistent.

Due to the presence of the hill, the wind-induced response of the structure in the hilly terrain will increase or decrease. For the jumper cable, the wind-induced response of the jumper cable near the hill crest will be greater than that in the undisturbed ABL, and the rest of the area will be the opposite.
After considering the effect of vertical wind speed, the increase of the wind-induced response of the jumper cable is remarkable in some positions where the wind climbing effect is significant.

Overall, the comparison of the present results and those obtained from the codes shows the divergence among the codes, also the overestimations at the upstream and downstream foots of the hill, with regard to horizontal wind. The finding that the speed-up profile is strongly related to the $H/L$ and the shape of the hill implies a need of a careful modification of current codes. Actually, it is worth noting that among the presented codes, only the code of AS/NZS 1170.2 [32], from which the results are close to present results, takes into account the factor of $H/L$. Furthermore, the presence of the vertical wind probably leads to an adverse effect on the structure, which is not well considered in the current codes, and not well investigated in the previous studies. It is necessary to achieve a simplified design equation for the estimation of the vertical wind speed in further studies.

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