Simulation analysis of the influencing factors on the wind environment around the hilly terrain

Q Chen¹, Y Liu¹

1 Wind Engineering Research Center, Xiamen University of Technology, Xiamen, Fujian, 361024, China
Email: 316994464@qq.com

Abstract. The wind environment condition of hilly terrain is closely related to wind resources utilization. In this paper, based on Fluent numerical simulation method, the wind flow characteristics around the hill topography under the influence of varied slopes, incoming wind speeds, heights and roughness are analyzed and summarized. It can be drawn that for the range from the hillside to the top on the windward side, the slope has a significant effect on the wind speed. Within the 100m height above the ground, when the hill is steeper, the wind speed is significantly enhanced. At the top of the hill, the wind speed’s maximum increment is 1.5 times of the incoming value. When the wind goes across the hilltop, the factors including the slope, height and roughness, have great influence on the wind environment on the leeward side. When the slope is greater than or equal to 0.5, the phenomenon of eddies present and the range of influence extends downstream. The wind speed weakness trend can also be found when the height and roughness increase.

1. Introduction
Wind in different topographic conditions will produce isthmus effect and slope climbing effect, directly influencing the utilization of dominant wind resources around the terrain or the avoidance of unfavorable wind conditions, i.e. the wind farm microsite or the construction surrounding structures. In China, the hilly terrain account for about 43% of the total land area[1], so the research on the wind environment around topographic affects a very-wide ranging issues.

By means of numerical simulation and wind tunnel test, many scholars simplify the complex terrain into a functional form with variables and then obtain the corresponding parameter data for analysis. First in 1975, Jackson and Hunt[2] studied small curvature hills with uniform rough surface, and obtained the analytical solution of adiabatic turbulent boundary layer of small hills through abstract simplification. They also pointed out that the maximum wind speed point was located at the top of the hills, which provided valuable reference for subsequent studies. In 1989, Gong et al.[3] carried out wind tunnel tests on the turbulence of two-dimensional and axial symmetry three-dimensional mountains, which had important reference significance for the study of mountain turbulence. Davenport et al.[4] studied the acceleration effect of wind speed on a continuous twelve mountains in two-dimensional condition. Based on the LES model, Uchida and Ohya[5] simulated the wind field in real terrain with RIAM-COMPAC editing program. Kondo et al.[6] studied the wind speed increase effect of two-dimensional hills with different slopes in wind tunnel. Yang et al.[7] the wind energy resources in complex terrain are evaluated by improving the quasi-static model of Peking University and combining numerical simulation. Chinese architectural structure load standards(GB-50009-2001)[8], the typical mountain topography is mainly considered as ridge and two-dimensional hillside, and the
effect of terrain on the increase of wind speed is taken into account so as to modify the height variation coefficient of wind pressure.

But the researches on wind environmental features around terrain conditions are still lack of systematic and comprehensive study, which needed more comprehensive discussion focusing on the basic terrain types. The method using terrain field testing can only collect limited sample points and the wind tunnel test technique may also use longer time and higher cost, so the numerical simulation has been more widely used due to high efficiency and design parameters. In this study, the computational fluid dynamics software Fluent is used to carry out simulation calculation on wind condition of typical hilly terrain, and factors affecting are comprehensively studied.

2. Calculation model

2.1 Hill terrain

In this paper, the cosine model (see Eq.1) is adopted to simulate the hilly terrain[9], and the mountain model is shown in figure 1. In the figure, \( H \) is the height of the mountain, \( L \) is the horizontal distance from the foot of the mountain to the top, \( L_1 = L / 2 \).

\[ h = H \cos^2 \left( \frac{\pi r}{4L} \right) \]  

(1)

2.2 Simulation setup

- **Size of the computational domain:** \( 17L(x) \times 5H(y) \).
- **Boundary conditions:**
  - Inflow boundary condition: Velocity inlet
  - Outflow boundary condition: Outflow
  - Surface of the hill model and the bottom: Wall
  - Surface of the top: Symmetry
- **Turbulence model:** Standard \( k-\epsilon \)
  - The quad-grid is adopted as shown in figure 2.

![Figure 1. The hilly terrain model](image)

![Figure 2. The grids near the hill](image)

2.3 Simulation cases

In this paper, the characteristics of wind environment field around the hilly terrain are discussed based on the influencing factors, such as the slope, wind speed, height and surface roughness. The research conditions are summarized in table 1~4.

| Table 1. Slope case | Table 2. Wind speed case |
|---------------------|-------------------------|
| **No.** | **Slope & height** | **Wind speed & roughness** | **No.** | **Slope & height** | **Wind speed (m/s)** | **Roughness** |
| Case 1 | S0.3H1.5 |  | Case 7 | S1H1.5 | 10 |  |
| Case 2 | S0.4H1.5 |  | Case 8 | S1H1.5 | 15 |  |
| Case 3 | S0.5H1.5 |  | Case 9 | S1H1.5 | 20 | \( \alpha =0.16 \) |
| Case 4 | S0.6H1.5 | \( U_0=10\text{m/s} \) | Case 10 | S0.3H1.5 | 10 |  |
| Case 5 | S0.7H1.5 | \( \alpha =0.16 \) | Case 11 | S0.3H1.5 | 15 |  |
| Case 6 | S1H1.5 |  | Case 12 | S0.3H1.5 | 20 |  |
Table 3. Height case

| No.  | Slope & height | Wind speed & roughness |
|------|----------------|------------------------|
| Case 13 | $0.5H1$ | $U_0=10\text{m/s}$, $\alpha=0.16$ |
| Case 14 | $0.5H1.5$ | |
| Case 15 | $0.5H2$ | |

(Slope: $S = H / L_1$, $H1=100m$, $H1.5=150m$, $H2=200m$, the roughness is presented as $\alpha$.)

The flow field at the height 200m from the surface is selected for study, as shown in figure 3, ten measuring locations along the wind direction $x$ are selected and defined as $x_1, x_2...x_{10}$.

![Figure 3. Measuring locations sketch](image)

Table 4. Roughness case

| No.  | Slope & height | Roughness | Wind speed |
|------|----------------|-----------|------------|
| Case 16 | $1H1.5$ | 0.12 | $U_0=10\text{m/s}$ |
| Case 17 | $1H1.5$ | 0.16 | |
| Case 18 | $1H1.5$ | 0.22 | |
| Case 19 | $1H1.5$ | 0.26 | |

2.4 Wind speed-up ratio

The average wind speed at the height above the horizontal ground is defined as $U_0(z)$, and the speed at the corresponding height $z$ above the mountain surface is defined as $U(z)$, and the speed acceleration ratio $\Delta S$ at the two heights is called acceleration effect and the formula is as follows:

$$\Delta S = \frac{U(z) - U_0(z)}{U_0(z)}$$

3. Results

3.1 Slope

In order to describe the changes and laws of wind speed under different slope conditions more accurately, the acceleration ratio was used, as shown in figure 4. In the figure, the horizontal axis represents the acceleration ratio and the vertical axis represents the vertical height from the surface. It can be seen from the figure that at location $x_1\&x_2$, the influence of slope on wind speed is not particularly obvious. When airflow passes the top of the hill(location $x_3$), it presents obvious acceleration effect. The larger the slope is, the more obvious the acceleration effect of wind speed near the surface will be. The maximum acceleration ratio reaches 0.7.

When the wind passes to the lee side (location $x_5\rightarrow 8$), if the slope is greater than 0.5, the wind speeds along height at each locations shows the tendency of decrease then increase first, such as at the location $x_5$, when the slope $S=1$, the wind speed starts from zero at the ground and then increased, following by reduce to the minimum when the height $h$ is 50 m. It indicates that there is obvious eddy phenomenon near the foot of the leeward. For hills with slope $S=0.5$, the vortex disappears at 2H from the foot of the mountain (location $x_7$), while for mountains with slope 1, the vortex disappears at 4H.
from the foot of the mountain (location x9). This indicates that the steeper the slope of the mountain, the farther the eddy range.

### 3.2 Wind speed

The analysis of the acceleration ratio change of the wind field on steep slope and gentle slope varying the incoming wind speed are depicted in figure 5. For both the steeper hill ($S=1$) and gentle hill ($S=0.3$), the change of the incoming wind speeds has little influence on the wind speed distribution rules at location x2&3; but at the leeward sides (location x5), the wind profile with larger incoming speed referring to the gentle hill ($S=0.3$) presents slower recovery.
The speed-up ratios around the hill with different wind speeds (left: S1H1.5, right: S0.3H1.5)

3.3 Height

The hill models with different heights (H1=100m, H2=150m, H3=200m) are adopted for research, as shown in figure 6. The change of mountain height has little influence on the wind profile on the windward surface (location x2&3). At the leeward side of the mountain, when the hill height increases, the wind lessens notably near the ground, i.e. for the case S0.5H2 at location x5, the value of speed-up ratios are close to minus one within the range of 80m above the ground, which means that the wind velocity is very small.
3.4 Roughness

Figure 7 shows the distribution laws of wind speed profile around the hill affected by roughness. The change of roughness has little influence on the wind profile on the windward side (location x2&3). But for the leeward side, the effect of roughness is reflected. The speed-up ratio at the same height with larger roughness is smaller, that is, with the increase of roughness, the acceleration ratio will decrease correspondingly.

4. Conclusions

Based on the numerical simulation of the hilly terrain, the conclusions can be drawn as follows:

The windward side of the hill: the influence of external factors on the wind speed rules from the hill foot to the hillside is small and negligible. For the range from the hillside to the top, the slope has a significant effect on the wind speed. Within the 100m height above the ground, when the hill is steeper, the wind speed is significantly enhanced.
The top of the hill: within 100m height above the ground, the wind speed’s maximum increment is 1.5 times of the incoming value. The leeward side of the hill: the factors, including the slope, height and roughness, have great influence on the wind environment. When the slope is greater than or equal to 0.5, the phenomenon of eddies present from the hillside to the foot on the leeward side. The increase of the height of the mountain weakened the wind speed on the leeward side. The wind speed weakness trend is also obvious for larger roughness.

5. References
[1] Kang Z., China debris flow research, Beijing: science press, 1989.
[2] Jackson P S , Hunt J C R . Turbulent wind flow over a low hill[J]. Quarterly Journal of the Royal Meteorological Society, 2010, 101(430):929-955.
[3] Gong W , Ibbetson A . A wind tunnel study of turbulent flow over model hills[J]. Boundary-Layer Meteorology, 1989, 49(1-2):113-148.
[4] Miller C A, Davenport A G. Guidelines for the calculation of wind speed-ups in complex terrain[J]. Journal of Wind Engineering & Industrial Aerodynamics, 1998, s 74 – 76(2):189-197.
[5] Uchida T , Ohya Y . Large-eddy simulation of turbulent airflow over complex terrain[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2003, 91(1-2):219-229.
[6] Kondo K, Tsuchiya M, Sanada S. Evaluation of effect of micro-topography on design wind velocity[J]. Journal of Wind Engineering & Industrial Aerodynamics, 2002, 90(12):1707-1718.
[7] Yang Z, Xue H, Yuan C. Evaluation of wind energy resources in complex terrain [C], Annual conference of Chinese solar energy society. 2003
[8] Load Code for the Design of Building Structures. GB50009-2001, Beijing: China Architecture & Building Press, 2002.
[9] Zhao Y, CFD simulation of wind field in complex terrain [D], North China Electric Power University (Beijing), 2011.

Acknowledgement
The authors would like to acknowledge with great gratitude for the supports of the national science foundation of China(grant No: 51778551), the science and technology plan project of Xiamen(grant No: 3502ZZ20161016), the young teachers education science research project of Fujian(grant No: JAT170410), the Natural Science Foundation of Fujian Province(grant No. 2018J01525), and the projects of Xiamen University of Technology(grant No. XPDQ18034 & XPDQ18042).