An experimental study on the turbulent flow over two-dimensional plateaus

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Abstract

Turbulent wind flow over complex terrain is very important for wind energy exploitation. In the present study, the flow characteristics over two-dimensional plateaus were studied in atmospheric boundary layer (ABL) wind tunnel through PIV measurements. The effects of windward and leeward slopes on turbulent flow characteristics were studied. The results indicates that the flow velocity decreases upstream of the windward side compared with the undisturbed flow, as the block effect of plateau. A flow separation takes place as the slope is steep, and the effect is far downstream of the plateau. The effects of slopes and steps are not evident, with the main difference occurring near the ground.

Keyword: complex terrain; plateau; wind flow

I. Introduction

Wind energy is one of the most important alternatives to traditional fossil energy. Since suitable sites in flat terrain have been exploited a lot, and due to the mountainous terrain features in certain places, the sites on complex terrain is becoming more important in onshore wind energy development than before. Thus the study of atmospheric turbulent flow over complex terrain, including separation and reattachment of boundary layer, is becoming important for wind turbine siting.

The former researchers have done a lot on the flow over complex terrain, including experimental and numerical investigations, especially for isolated hills [1]. Beritter et al [2] studied the streamwise mean and turbulent velocities over a rough, bell-shaped, two-dimensional hill, with maximum slope 0.26 in a wind tunnel. The results were compared with Taylor’s computational model and Jackson and Hunt’s analytical linearized model [3], and close agreement was found. Detailed wind tunnel measurements of mean flow and turbulence were done by Gong and Ibbetson [4]. The flow passed over a two-dimensional ridge and a circular hill, both having cosine-squared cross-section and maximum slope about 15°. The measurement over a three-dimensional hill was also done. The results were broadly similar to those over the two-dimensional ridge, but with perturbation amplitudes reducing. The turbulent flow over single two-dimensional hills with different shapes was also measured by Ferreira et al [5] and Kim et al [6] in wind tunnels, which was compared with numerical simulation simultaneously, respectively. The turbulent boundary layer over three-dimensional steep hills was investigated by Ishihara et al [7], which was compared with the numerical results by Ishihara [8]. Two-dimensional multiple hills were investigated by Carpenter and Locke [9], Kim et al [6], Lee et al [10]. The effects of slopes and relative size of neighboring hills were discussed. Cao and Tamura [11] studied the effects of surface roughness on the turbulent flow over a two-dimensional steep hill, accompanied with a large separation. The roughness was found to be beneficial for improving the speed-up ratio, while the separation bubble extended further downstream.

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The flow over escarpments was studied less compared with that over hills. Bowen and Lindley [12] measured the turbulent flow field over two-dimensional forward-facing escarpments in a wind tunnel with a hot-wire anemometer. Four shape-edge escarpments with their slopes between a cliff and a 4:1 gradient were investigated. The flow over gentle escarpments were also obtained by Bowen and Jackson. These studies considered upslope flow, not including the downslope flow. Stefan et al [13] analyzed the downslope flow characteristics. But as scarcity of data for downslopes, the comparison with upslope-wind was not done.

As described above, the former researches mainly focus on the two-dimensional or three-dimensional hilly terrain, and other terrains are lack of data. The study of flow over escarpments is mainly for the upslope and the data for downslope is in need. The method of former experimental researches is mainly single point measurements, such as hot wire, and the detail of flow field is limited for understanding the mechanisms of the flow phenomenon. In this paper, based on the PIV method, the flow field over isolated plateaus with different escarpment shapes in the wind tunnel, is investigated to get a better understanding the physics of the flow field around the upslope and downslope.

II. Experimental Setup

The experiments were conducted in a large-scale Aerodynamic/ Atmospheric Boundary Layer (AABL) Wind Tunnel at Shanghai Jiao Tong University as shown in Fig.1. The wind tunnel is closed-circuit and the test section is 8 m long, 1.2 m wide and 0.9 m high. The triangular spires were sited at the beginning of the test section and the wooden blocks were covered on the wind tunnel floor to simulate the neutral atmospheric boundary layer. Figure 2 shows the mean velocity profiles of the simulated atmospheric boundary layer. The measured data can fit well with a logarithmic function as

$$u = u^* \log \left( \frac{z}{z_0} \right)$$

with $u^* = 0.50$ m/s, $z_0 = 0.1$ mm, and the von Karman constant $k = 0.41$.

![Figure 1. The test section of the AABL wind tunnel](image)

![Figure 2. The mean velocity profiles of simulated atmospheric boundary layer (□: experimental data, - - - : logarithmic law fit)](image)

As shown in Fig. 3, three typical two-dimensional plateau models with different slope shapes were made by wooden frame and covered by a thin film piece. The slope shape is Gaussian curve, which is defined as

$$z = h e^{-\left(\frac{y}{h}\right)^2} \ln 2$$

(1)
where the value of $h$ and $l$ are shown as Table 1 for different models. The Model I and Model II only have one step and while the Model III has two steps. The shapes of windward and leeward slopes are same for a single model, and these models are symmetry. As reported in [14], the speed-up effects is sensitive to the length of the level top, thus the length of each model is same. The height $H$ is 110 mm, and the length $L$ is 220 mm for Model I, as well as for Model II and Model III.

![Figure 3. Schematic diagram of the plateau models](image)

<table>
<thead>
<tr>
<th>Model</th>
<th>$h$ (mm)</th>
<th>$L$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td>110</td>
<td>55</td>
</tr>
<tr>
<td>Model II</td>
<td>110</td>
<td>27.5</td>
</tr>
<tr>
<td>Model III</td>
<td>55</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Table 1. The value of $h$ and $L$

During the experiments, the detailed flow field measurements around the plateau models were achieved by using a high resolution digital Particle Image Velocimetry (PIV) system as shown in Figure 4. For the PIV measurements, the oncoming airflow was seeded with ~1 μm oil droplets through a seeding generator. A double-pulsed Nd:YAG laser provided the illumination, adjusted on the second harmonic and emitting two pulses at the wavelength of 532 nm. A high-resolution 14-bit CCD camera was mounted with its axis normal to the laser sheet. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation via a digital delay generator, which controlled the timing of the laser illumination and the image acquisition.

![Figure 4. Experimental setup of PIV measurements](image)
III. Results and Discussion

3.1 The flow characteristics over plateaus with different slope shapes

As the laser reflection from the solid surfaces, the flow field near the wall could not be measured by the PIV used in this experiment. Although many methods have been tried, such as using a fluorescent paint, the results were not satisfied. The region near the surfaces which couldn’t be measured was blank in the following figures.

In this section, the effect of plateau of velocity and turbulent kinetic energy distribution are discussed. As an important feature of flow over complex terrain, the flow accelerates along with the increasing height and reaches a maximum value at the crest. The fractional speed-up ratio is usually used to quantify the speed-up effect, which is defined as

$$\Delta S = \frac{U(z) - U_0(z)}{U_0(z)}$$  \hspace{1cm} (2)

where $U_0(z)$ and $U(z)$ are the undisturbed velocity the velocity over complex terrain at height $z$, respectively.

Turbulent kinetic energy is an important parameter for wind flow. In order to describe the effect of plateau on the turbulent kinetic energy, $\Delta k$ is defined as

$$\Delta k = \frac{k(z) - k_0(z)}{k_0(z)}$$  \hspace{1cm} (3)

where $k_0(z)$ and $k(z)$ are the undisturbed turbulent kinetic energy and the turbulent kinetic energy affected by the plateau.

The flow characteristics over plateaus can be gotten from the case of Model I. As displayed in Figure 5, the flow field is affected by the plateau before the leading edge and the velocity near the ground decreases upstream of the leading edge. Correspondingly, when $x/H$ is less or equal to 1.5, the fractional speed-up ratio near the ground is below zero as shown in Figure 6. The flow accelerates with the increasing up-slope height and reach a maximum immediately downstream of the crest. Thus, the fractional speed-up ratio is above zero and reaches a maximum value of 0.7. After that, a region with low mean velocity grows over the level top. This also can be confirmed from the fractional speed-up ratio profiles. The fractional speed-up ratio decreases with the increasing stream-wise length, which is obvious under the height of $H$ above the local ground, as presented in Figure 6. These characteristics are similar with that of the flow over escarpment described in Ref.[12]. As the leeside slope is steep, a flow separation take place, and the fractional speed-up ratio is under zero near the ground. The main effect region is under the height of 1.2$H$ above the local ground, and the effect is still strong at $x/H=6$.

![Flow characteristics over plateaus](image-url)
As shown in Figure 5, the velocity distributions of flow fields over Model I and Model II with different slopes are similar over each upslope. The small difference occurs near the ground just downstream of each crest. The flow field downstream of the crest are similar for Model I and Model II. The evident difference can be found near the ground immediately before the leeward slope. As the slope is steep for each model, the flow separation takes place. The separation region becomes larger as the slope increases, as shown in Figure 5. The high turbulent kinetic energy region, which means the flow mixing is strong, is larger for Model I compared with that for Model II as shown in Figure 7. All in all, the flow structures are similar for Model I and Model II, with the main difference occurring near the ground and the flow separation region. For Model I and Model II, the fractional speed-up ratio profiles are almost the same and the main difference occurs near the ground as shown in Figure 6. The difference is most evident as $x/H = 1.5H$ and $-1.5H$, because the local heights of the two models are different.
Figure 6. Fractional speed-up ratio profiles for plateaus with different slopes (○: model I, △: model II)

Figure 7. Ensemble-average turbulent kinetic energy distributions for plateaus with different slopes
(a) Model I
(b) Model II

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As presented in Figure 8, the effect of plateau on the turbulent kinetic energy is obvious near the ground. The turbulent kinetic energy becomes larger compared with the undisturbed one. This effect is more evident in the wake flow after the plateau compared with other regions, which can also be seen in Figure 7. This is because of the flow separation, which increases the velocity gradient. As the flow passed over the level top, the kinetic energy decreases with increasing streamwise distance. This is because that boundary layer develops over the level top and the velocity gradient becomes smaller compared with that over the crest. As the wake flow after the plateau expands, the height where the $\Delta k$ reaches a maximum value decreases. For different slopes, the discrepancy is not great except $x/H = 1.5$ and -1.5.

![Figure 8. Turbulent kinetic energy profiles for plateaus with different slopes (○: model I, ▲: model II)](image-url)

3.2 The flow characteristics over plateau with two steps

As shown in Figure 9, the velocity reaches a maximum just behind the crest for Model III, which is similar with that for Model I. The flow separation region over leeside slope is almost same with that for Model I. The flow velocity distributions for Model III are almost same with that for Model I. As presented in Figure 10, the turbulent kinetic energy is almost same with that for Model I. Thus, the step have no evident effect on the flow characteristic over plateaus as the slope is steep.

This also can confirmed from the fractional speed-up ratio profiles. As shown in Figure 11, the fractional speed-up ratio for Model III is almost same with that for Model I. The main difference occurs near the ground as $x/H = 3$ and 6. This indicates that the step affects the flow field over leeward slope. But the effect is not very evident for the plateau models studied in this experiment.

The turbulent kinetic energy profiles for Model III are similar with that for Model I, as shown in Figure 12. The plateau makes the turbulent kinetic energy increase near the ground evidently over windward side and the level top. As the flow separation takes place, a high TKE region appears in the wake over leeward slope. The discrepancy in the $\Delta k$ is not very evident, with the main difference occurring near the ground and in the wake flow over leeward slope.
Figure 9. Ensemble-averaged velocity distributions for plateaus with different slopes

Figure 10. Ensemble-averaged velocity distributions for plateaus with different slopes
Figure 11. Fractional speed-up ratio profiles for plateaus with different slopes (○: model I, △: model III)

Figure 12. Turbulent kinetic energy profiles for plateaus with different steps (○: model I, △: model III)

Conclusion

The flow characteristic over two-dimensional plateaus were investigated by measuring the flow field over three plateau models in the ABL wind tunnel through PIV. The effects of slope and step were studied. As the limited of the
PIV used, the flow field very close to the ground couldn’t be measured. The wind speed decreases near the ground upstream of the windward side because of the block effect. Immediately downstream of the crest, the flow accelerates and the fractional speed-up ratio reaches a maximum value. A region with lower velocity is found over the level top. A flow separation takes places as the steep leeward slope and a higher turbulence kinetic energy region can be found. The effect of plateau is still strong as $x/H=6$.

The effects of windward and leeward slopes are not evident as the slopes are too steep. The main difference is near the ground and the wake flow downstream of the plateaus. The effect of the step is also not evident with the slope studied in this experiment, and main difference occurs near the ground.

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