Research on the acceleration effect of horizontal wind in mountainous terrain

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Abstract. The utilization of mountain wind resources are important issues in the development of wind energy. However, when wind flows over mountainous terrain, its velocity and direction undergo certain changes, resulting in more complex mountain wind fields and induced structural wind effects. To study the distribution characteristics of horizontal wind in mountainous areas, in this study, wind tunnel experiments were conducted on regular mountain models with different slopes to investigate the wind field characteristics at various locations in the mountain range. The research shows that near the mountain surface, the wind speed and velocity ratio follow the order of mountain top > mountain waist > mountain foot, with a wind acceleration effect at the mountain top (wind speed ratio greater than 1) and a wind deceleration effect at the mountain foot and waist (wind speed ratio less than 1). As the height increases, the wind speed ratios gradually approach 1. Moreover, with an increase in slope ratio, the wind speed decreases at the mountain foot and increases at the mountain top. And with the increase of the slope leads to an increasing difference in wind speed ratio between the mountain top and the foot.

1 Introduction

Currently, the efficient use of wind energy and clean and environmentally friendly natural energy is of great concern, which can significantly reduce carbon dioxide and prevent global warming. The terrain in most parts of China is rugged and complicated. In recent years, the construction site of wind turbines has been transferred from coastal areas to mountainous areas. Therefore, wind energy resource assessment, especially in complex terrain areas, is one of the important topics of wind energy development. On the one hand, the abundant wind resources in mountainous areas are conducive to the collection and utilization of wind energy; on the other hand, when the natural wind passes through the complex mountain environment, a more complex wind field will be formed, which brings great difficulties to the construction of wind farms in mountainous areas. Therefore, the study of mountain wind characteristics is of great significance.

As the starting point of flow field modeling over complex terrain, the flow characteristics over simple two-dimensional hills have been extensively studied by numerous researchers. Jackson and Hunt [1] were the first to analyze the wind velocity distribution over two-dimensional smooth and low hills, which established the main parameter for mountain wind field research: wind speed-up ratio. Taylor et al. [2] made corrections to the theoretical calculation formula, simplifying the calculation of wind speed-up ratios at different heights for gentle slopes. More recently, Kamada et al. [3] conducted wind tunnel experiments to investigate the turbulent flow structure around a two-dimensional hill model in a boundary layer flow, revealing wind speed increases along the upstream slope and flow separation over the hilltop. Liu et al. [4] used large eddy simulation to study the influence of wind direction on the flow field over a two-dimensional (2D) hill, finding that the wind behind the hill is not parallel to the incoming wind direction when the wind direction is not perpendicular to the ridge line. However, these studies focused on two-dimensional hill shapes, while actual terrains are three-dimensional. Therefore, considerable research has been conducted internationally to study the wind fields near three-dimensional hills. Sun et al. [5] investigated the influence of mountain height and slope variations on the average wind speed and fluctuating wind speed of a single hill through experiments, revealing that the near-ground average wind speed at the mountain top increases with increasing slope and height. Wei et al. [6] performed numerical simulations to study the impact of different slopes, heights, and topographic features on the acceleration effect of a single hill, proposing a logarithmic calculation model that better describes the near-ground acceleration effect of mountainous terrain and applies to steep slopes. Li et al. [7] used numerical simulations to calculate the acceleration effect of a single hill and found that the maximum acceleration ratio at the

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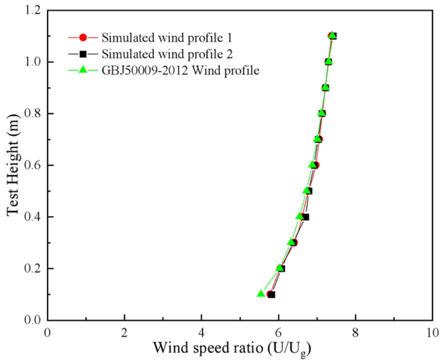
mountaintop increases with the slope and height of the hill while decreasing with the increase of the ground roughness index. Flay et al. [8] conducted numerical simulations and wind tunnel tests to measure the wind speed near Belmont Hill, providing corrections to the local code based on their study.

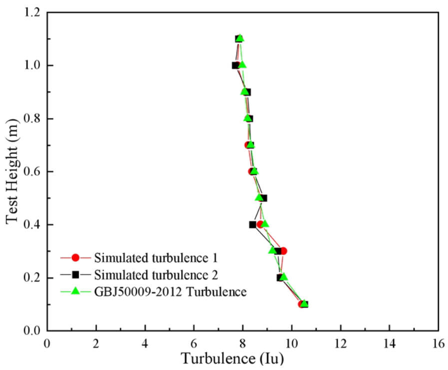
Based on the above background, this study focuses on three-dimensional mountain slopes with different slopes and conducts wind tunnel experiments to investigate the impact of slope on the wind field distribution over mountain surfaces, providing design recommendations for engineering constructions in mountainous regions.

2 Wind tunnel experiment

The wind tunnel experiments on three-dimensional mountain models were conducted in the low-speed test section of Changsha University of Science and Technology of Wind Engineering and Wind Environment Research Center. The cross-section size of the low-speed test section is 10.0 m × 3.0 m × 21.0 m, and the diameter of the turntable is 5.0 m. The wind speed can be continuously adjusted from 1.0 m/s to 18.0 m/s. According to the GB 50009-2012 standard [9], A-class turbulence in the wind field was generated using a sharp-edged and rough-surface element. The wind speeds at each measurement point and the incoming wind speed were measured using the Cobra probe and dedicated software from the TFI company in Australia. Fig. 1 shows the results of the wind field calibration, which are found to be very close to the required conditions, meeting the experimental requirements.



(a) Average wind speed profile



(b) Turbulence intensity profile

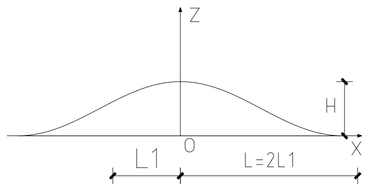
Fig. 1. Wind field debugging results

2.1. Model fabrication and measurement point distribution

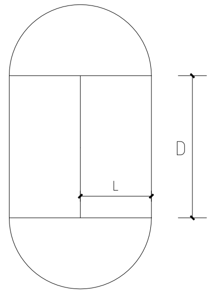
The experiment used a cosine function to model the cross-section of the mountain and considered the influence factors of the mountain length D. Fig. 2 illustrates the cosine mountain model. The model satisfies the following equations:

$$Z = H\cos^2(\pi r / 2L) \tag{1}$$

Where: r is x, and the distance from the point to the original position o is calculated; H is the height of the mountain, and the distance from the bottom of the mountain to the top of the mountain at the origin o; L is the width of half the mountain, and the horizontal distance from the foot of the mountain to the origin o; z is the coordinate, and the vertical distance from the point to the bottom of the mountain is calculated.



(a) Cross-sectional view of the mountain



(b) Top view of the mountain

Fig. 2. Cosine mountain model diagram

To analyze the wind speed distribution at various locations near the mountain terrain and its variation with height, a 1:500 scale model was used in the experiment. The model was made of polyvinyl chloride foam, and measurement points were arranged at three locations: mountain foot, mountain waist, and mountain top. Wind speeds at different heights from 0 to 900 m above the mountain surface were measured using the cobra probes. Fig. 3 shows the experimental setup and measurement point distribution.

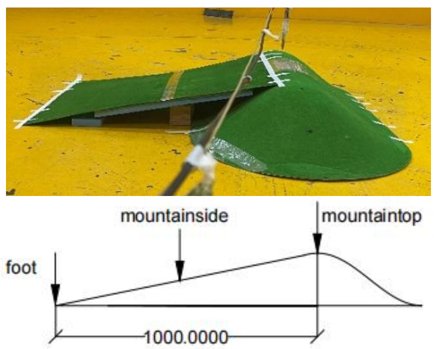
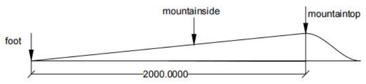
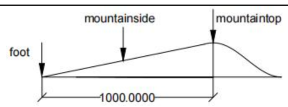
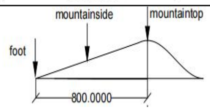
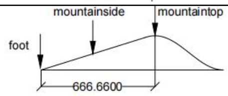
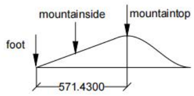
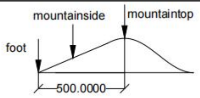


Fig. 3. Photos of the installation of the regular mountain model in the wind tunnel

2.2. Experimental conditions

In this study, a 1:500 scale regular sine mountain range was constructed, and different slopes were set to investigate the influence of the slope and length on the wind profile. The slope conditions are shown in the following table, and measurement points were set at the mountain top, waist, and foot to obtain wind speed data at distances of 5 m, 10 m, 45 m, 60 m, 90 m, 120 m, 150 m, 180 m, 210 m, 240 m, 270 m, 300 m, 360 m, 420 m, 480 m, 540 m, 600 m, 700 m, 800 m, and 900 m downwind.

Table 1. Different slope mountain model working condition setting (Mountain height 200mm)

Condition	slope	Mountain length	
1	0.1	2000mm	
2	0.2	1000mm	
3	0.25	800mm	
4	0.3	666.66mm	
5	0.35	571.43mm	
6	0.4	500mm	

a.Mountain height 200mm

3 Experimental results and analysis

3.1. Definition of wind speed ratio

The acceleration effect refers to the phenomenon where the average wind speed at a certain height in the mountainous terrain is higher than that in the flat terrain at the corresponding height, and it is most pronounced near the ground on the mountaintop [10]. To quantitatively characterize the size of the acceleration effect, the wind speed ratio S is defined as follows:

$$S(Z) = U(Z) / U_0(Z) \quad (2)$$

Where U(Z) is the average wind speed at the height of z from the mountain surface, and U0(Z) is the average wind speed at the corresponding height of the incoming flow. Fig. 4 illustrates the relationship between U(Z), U0(Z), and the acceleration effect.

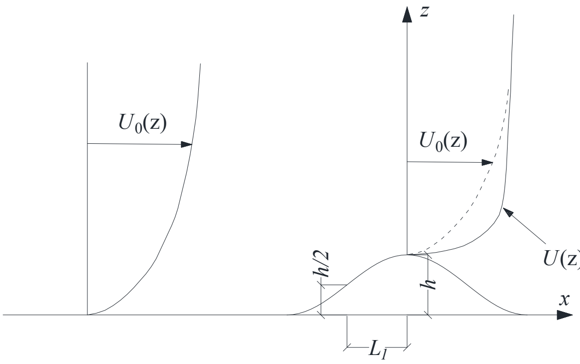
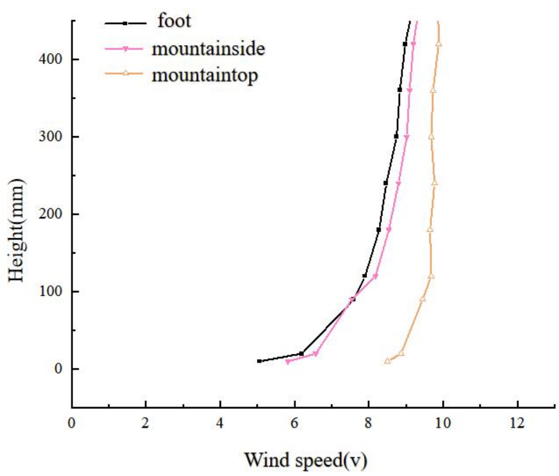


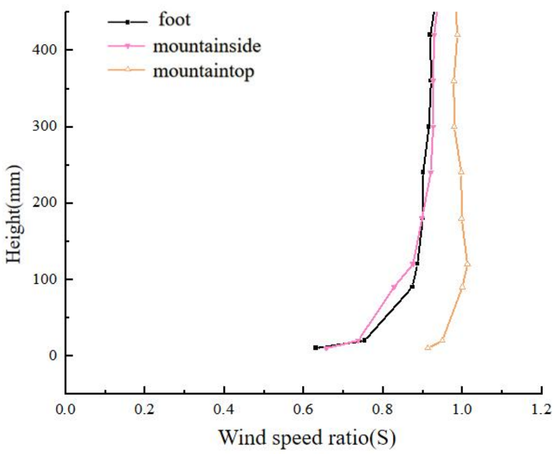
Fig. 4. Horizontal wind speed ratio definition

3.2. Analysis of wind characteristics at different locations near the mountain

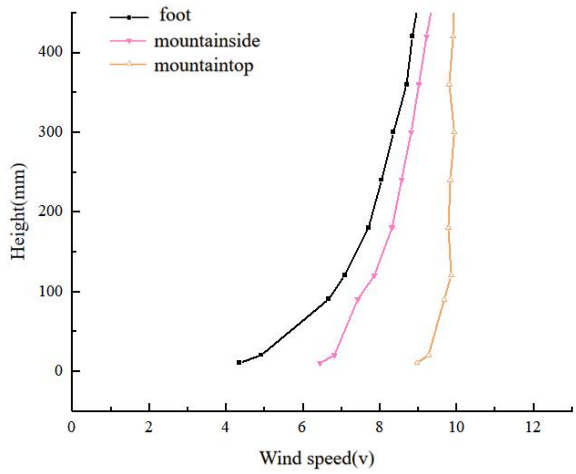
To analyze the wind speed distribution of the entire terrain, Fig. 5 compares the changes in wind speed along height at various measurement points in different slopes. It can be seen from Fig. 5 that: near the mountain surface, the wind speed ratio at the top of the mountain is the largest, greater than 1, and it shows a wind acceleration effect here. There is a wind deceleration effect at the foot and side of the mountain, and the wind speed ratio is less than 1. With the increase in height, the wind speed ratio and wind speed ratio gradually get closer. The wind speed ratio is the smallest at the foot of the mountain, which is less than 1, and gradually approaches 1 with the increase in height. Near the top of the mountain, the wind speed ratio is 1~1.15 and gradually decreases to 1 as the height rises. With the increase in slope ratio, the wind speed at the foot of the mountain becomes smaller, and the wind speed at the top of the mountain becomes larger: the wind speed ratio at the foot of the mountain decreases from 0.6 to 0.4; The wind speed ratio at the mountainside is about 0.6; Wind speed increased from 0.9 to 1.15 at the peak. As the slope ratio increases, the difference between the wind speed at the top and the foot of the mountain widens.



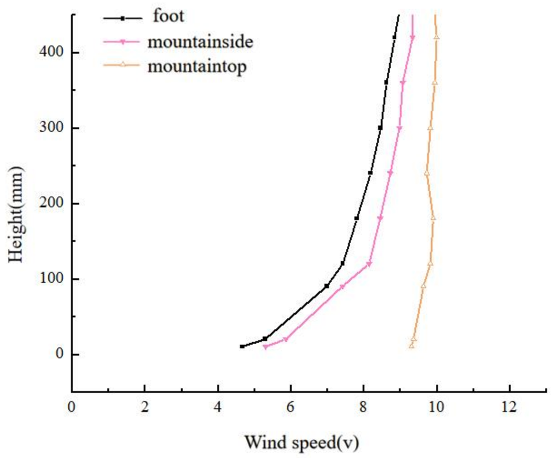
(a) Mountain wind speed (slope 0.1)



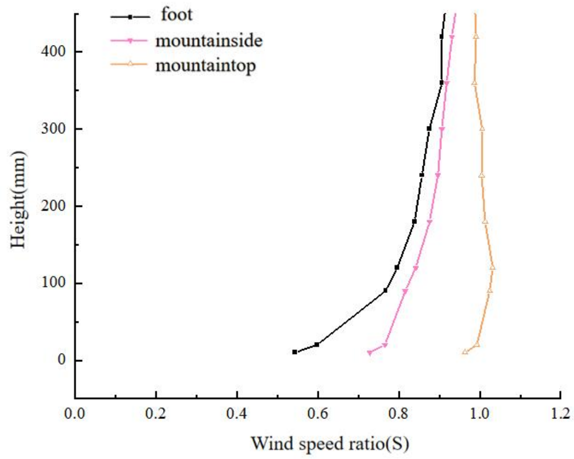
(b) Mountain wind speed ratio (slope 0.1)



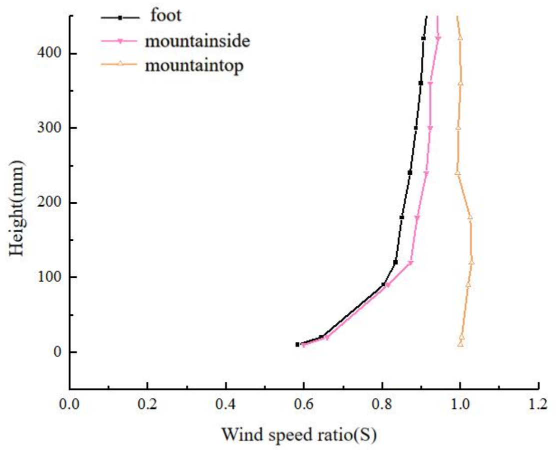
(e) Mountain wind speed (slope 0.25)



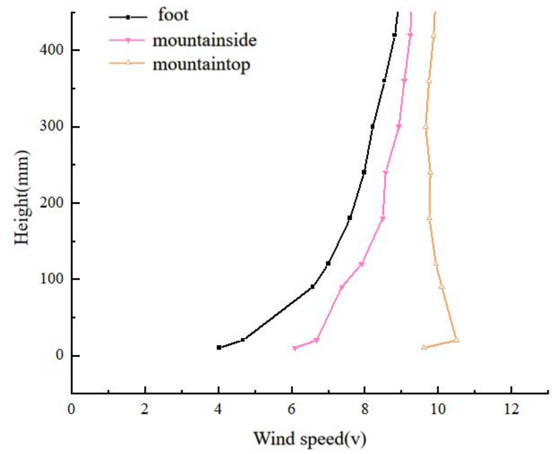
(c) Mountain wind speed (slope 0.2)



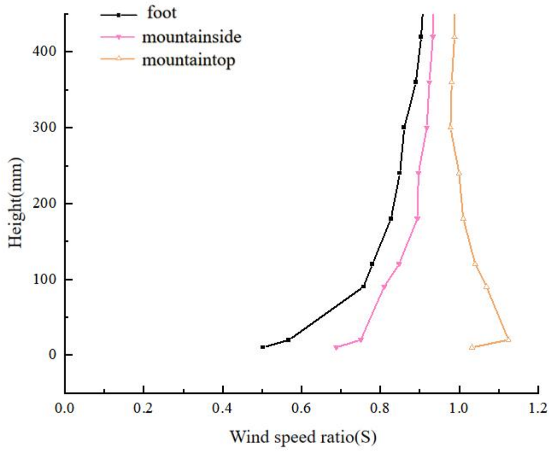
(f) Mountain wind speed ratio (slope 0.25)



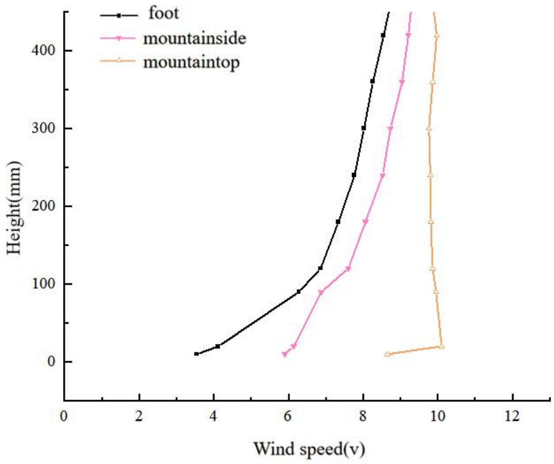
(d) Mountain wind speed ratio (slope 0.2)



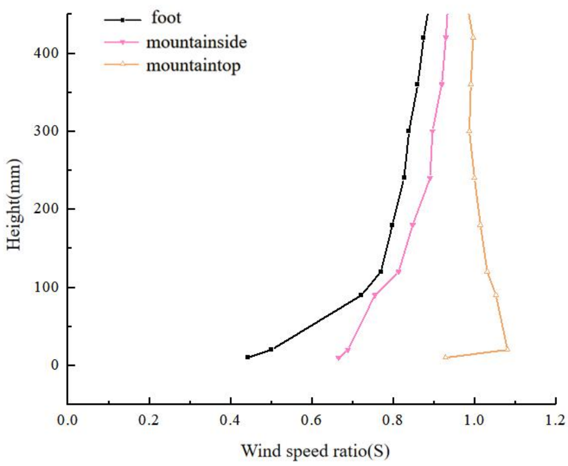
(g) Mountain wind speed (slope 0.3)



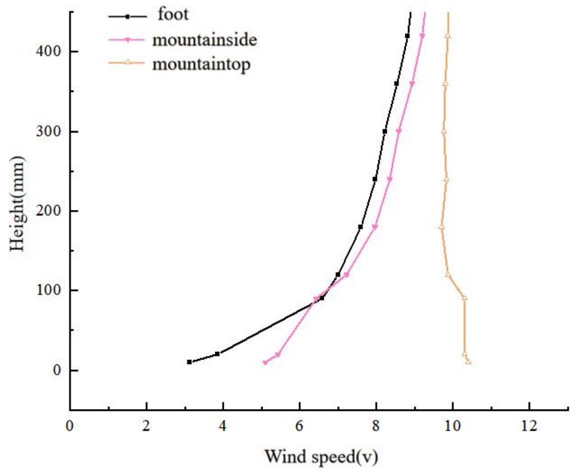
(h) Mountain wind speed ratio (slope 0.3)



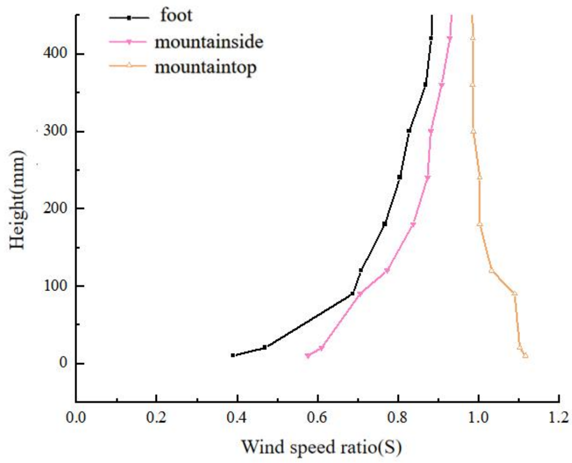
(i) Mountain wind speed (slope 0.35)



(j) Mountain wind speed ratio (slope 0.35)



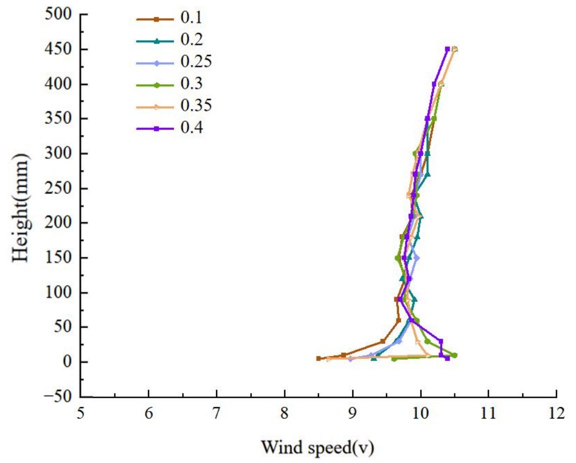
(k) Mountain wind speed (slope 0.4)



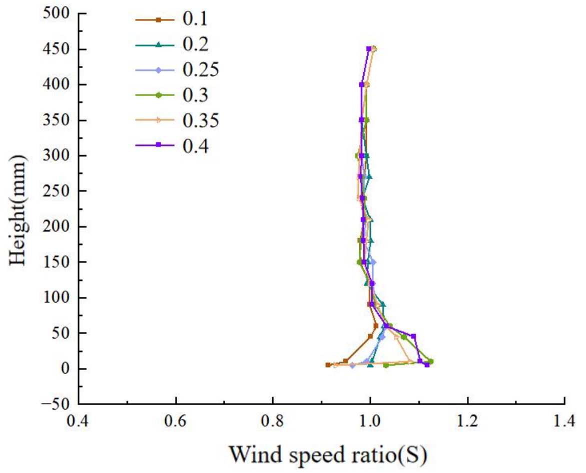
(l) Mountain wind speed ratio (slope 0.4)

Fig. 5. Wind speed and wind speed ratio at the foot, mountainside, and mountaintop of mountains with different slopes

To provide a more detailed analysis of the influence of slope on the wind speed distribution over the mountain surface, Figure 6 presents the wind speeds and velocity ratios at the mountain top for different slope ratios. From the figures, it can be observed that near the mountain surface, the wind speed and velocity ratio are relatively large at the mountain top, and this effect gradually decreases with increasing height. This phenomenon becomes more pronounced with increasing slope ratio. For slopes ranging from 0.1 to 0.25, the wind speed ratio near the ground is approximately 0.9 to 1.0, and the decrease in the velocity ratio with increasing height is not very significant. When the slope reaches 0.3 to 0.35, the wind speed ratio near the ground increases to 1.08 to 1.15, and the decrease in the velocity ratio with increasing height becomes more evident. When the slope reaches 0.4, the wind speed ratio near the ground is 1.15, and the decrease with height becomes more pronounced.



(a) Wind speed at the mountaintop



(b) Wind speed ratio at the mountaintop

Fig. 6. Comparison of wind speed and wind speed ratio at mountaintop with different slopes

4 Conclusions

This study conducted wind tunnel experiments to simulate the wind field distribution over regular continuous mountain ranges in A-class wind fields. By comparing and analyzing the experimental results, the following conclusions can be drawn:

1)Near the mountain surface, the wind speed and velocity ratio follow the order of mountaintop > mountainside > mountain foot. The mountain top exhibits a wind acceleration effect with a velocity ratio greater than 1, the maximum is 1.12, while the mountain foot and waist experience a wind deceleration effect with a velocity ratio less than 1, and the minimum is only 0.4. As the height increases, the wind speed ratios gradually approach 1.

2)With an increase in the slope ratio, the wind speed decreases at the mountain foot and increases at the mountain top: The wind speed ratio at the foot of the mountain decreased from 0.6 to 0.4; The wind speed at the top of the mountain increased from 0.9 to 1.6. The difference in wind speed ratio between the mountain top and foot increases with increasing slope, requiring careful consideration in engineering applications.

3)Near the mountain surface, the wind speed and velocity ratio are relatively large at the mountain top, and this effect gradually decreases with increasing height. This phenomenon becomes more pronounced with increasing slope ratio.

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