Numerical modeling of local wind focusing on computational domain setting and boundary treatments

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ABSTRACT: Computational domain size required for the numerical prediction of flow over a two-dimensional ridge and a three-dimensional hill was investigated by changing the computational domain heights and widths and the distances between the terrain and the inlet boundary. It was found that the computational domain heights should be decided so that the blockage is less than 5%, the width of the computational domain should be wider than the length ten times as long as the hill height and inlet boundary should be set so that the distances between the inlet boundary and the terrain center is longer than the length twenty times as long as the terrain height for the two dimensional ridge and ten times for the three dimensional hill. For the analysis of flow over continuous terrain, new boundary treatments were proposed in which the volume of the terrain is maintained. This method shows better result than the conventional one. An additional domain was also introduced at the windward of the analytical domain so that the effect of the upwind terrain was taken into account.

KEYWORDS: local wind prediction, non-linear model, computational domain setting, boundary treatment

1 INTRODUCTION

Prediction of the turbulent flow over complex terrain plays a dominant role in engineering applications such as the efficient extraction of wind energy and the safety of structures. Numerical models based on CFD are widely used for the prediction of the flow over complex terrain recently. However, some there are several problems to apply numerical simulation to the flow over real terrain.

One of the problems is that numerical simulation is strongly dependent on the effect of the boundary. If the computational domain size is not enough, the flow will be affected by the boundary. This is known as a blockage problem. In wind tunnel test, the blockage should be less than 5 %. The location of inlet boundary is also an important problem. However, few study have been done on how to set the computational domain. The other important problem is the treatment of the terrain at the boundary. Although several methods have been proposed, the volume of the terrain is not maintained in those conventional methods, making the flow near the boundary different from the real one.

In this study, first by changing the size of the computational domain, the effect of the boundary is investigated. Then, a new method is proposed for the treatment of the terrain near the boundary. As a numerical model, finite volume method with standard k-e model[1)] was used.

2 COMPUTATIONAL DOMAIN SETTING

Computational domain setting is an important factor for the numerical prediction of flow over terrain. When larger computational domain size is used, the prediction accuracy increases but the computational cost increases, too. To clarify the influence of the computational domain settings, two type of terrain was used as example in this study. One is a two-dimensional ridge with the cross section of cosine curve and the other is a three-dimensional hill with the same cross section. Figure 1 shows the cross section of the terrain at the center of the computational domain. The height of the hill or the ridge (H) is set to 40m and the distance between the center of the hill or the ridge and the hill foot (*L*) is set to 100m. The distance between the center of the hill or the ridge, the computational domain height and the span wise computational domain width are defined as respectively.

In this study, various computational domain size were tested for the two dimensional ridge and the three dimensional hill. All the cases tested in this study are summarized in table 1.

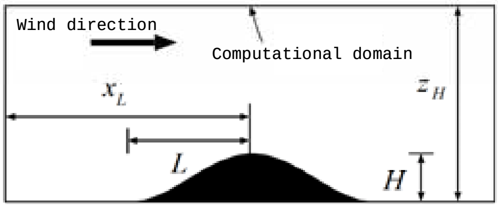

Figure 1. The definition of the computational domain

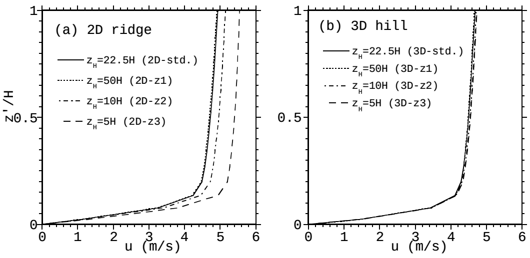

Figure 2. The effect of the computational domain height

Table 1. The computational domain of each case

	x_L	z_H	y_W	E^H_{top}	Block-age
2D-std.	30*H*	22.5*H*	-	-	4.4%
2D-*z*1	30*H*	50*H*	-	0.6%	2.0%
2D-*z*2	30*H*	10*H*	-	4.4%	10.0%
2D-*z*3	30*H*	5*H*	-	12.4%	20.0%
2D-*x*1	20*H*	22.5*H*	-	0.8%	4.4%
2D-*x*2	10*H*	22.5*H*	-	3.5%	4.4%
2D-*x*3	5*H*	22.5*H*	-	9.5%	4.4%
3D-std.	30*H*	22.5*H*	20*H*	-	0.6%
3D-*z*1	30*H*	50*H*	20*H*	0.4%	0.3%
3D-*z*2	30*H*	10*H*	20*H*	0.8%	1.3%
3D-*z*3	30*H*	5*H*	20*H*	1.2%	2.5%
3D-*y*1	30*H*	22.5*H*	10*H*	0.4%	1.1%
3D-*y*2	30*H*	22.5*H*	5*H*	2.1%	2.2%
3D-*x*1	20*H*	22.5*H*	20*H*	0.1%	0.6%
3D-*x*2	10*H*	22.5*H*	20*H*	0.3%	0.6%
3D-*x*3	5*H*	22.5*H*	20*H*	1.5%	0.6%

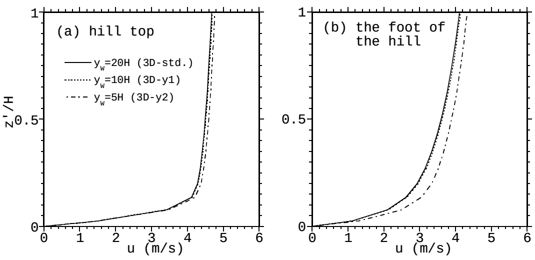

Figure 3. The effect of the computational domain width

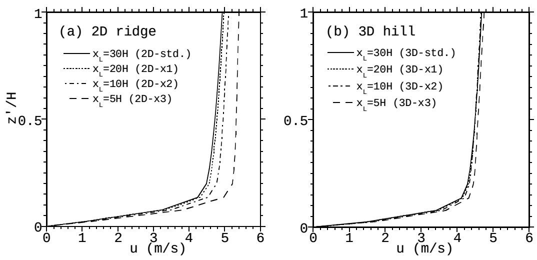

Figure 4. The effect of the position of the inlet boundary

2.1 *The effect of the computational domain height*

The height of the computational domain has to be set so that the top boundary does not affect the flow over the terrain. In wind tunnel experiment, it is said that when the blockage is less than 5%, the flow over terrain is not affected by the top boundary. In this study, the case with the domain height of 22.5H was taken as a standard case, the blockage of which is 4.4% for the two-dimensional ridge implying that the effect of the top boundary is little. To make this clear, the standard case was compared with the case which has the computational domain height of 50H(case 2D-z1). In addition, when the cases with lower domain height ()

2.2 *The effect of the computational domain width*

The width of the computational domain also has a significant effect to the three dimensional hill. In this study, the case with the computational domain width of 20*H* was taken as a standard case and the simulated flow field was compared with the flow field by narrower domain (10*H* and 5*H*). In the last case, the width of the domain is equal to the width of the hill.

Figure 3 shows the vertical wind profile at the top (a) and the foot (b) of the hill for various computational domain widths. Little difference can be seen between the case with the width of 20*H* and 10*H*. However, when the width was 5*H*, overestimation of wind speed can be observed. This is more significant at the foot of the hill. Although the blockage of this case is only 2.2%, the flow is strongly affected by the side boundary. This implies that when predicting the wind speed over three-dimensional hill, the width of the computational domain have to be taken wide enough regardless of the blockage.

2.3 *The effect of the inlet boundary*

In order to save the computational cost, inlet boundary is often located near the terrain. However, when the distance between the inlet boundary and the terrain is close, the reflection of the pressure at the inlet boundary affects the flow over terrain. In this study, the case where the distance between the inlet boundary and the terrain is 30H, was considered as the standard case. Two cases were compared with the standard case. In one case the distance between the inlet boundary and the terrain is 20H and the other 10H.

Figure 4 (a) shows the vertical wind speed profile at the top of the two-dimensional ridge. When the distance to the inlet boundary is 30H and 20H, little difference can be seen. On the other hand, when the distance to the inlet boundary is less than 10H, the wind field is strongly affected by the boundary. In the case where the distance to the inlet boundary is 5H, the prediction error of the wind speed reaches 9.3%. Thus, for the simulation of the flow over a two-dimensional ridge, the distance between the inlet boundary and the terrain should be at least 20times larger than the hill height.

Figure 4 (b) is the figure for the flow over three-dimensional hill. Compared to the flow over two-dimensional ridge, the effect of the inlet boundary is small and no significant difference is found among the three cases. It is concluded that for a three-dimensional hill, the distance between the inlet boundary and the terrain should be at least 10 times larger than the hill height.

3 BOUNDARY TREATMENT FOR COMPLEX TERRAIN

3.1 *A new boundary treatment method*

Figure 5 shows the proposed computational domain to simulate the flow over complex terrain. The domain of interest is named analytical domain. The additional domain is added to the upstream of the analytical domain to take the effect of the upstream terrain into account. The importance of this domain is shown later. Around the analytical and additional domains, buffer zones, where terrain is modified, are added to minimize the effect of the boundary.

For the modification of terrain in the buffer zones, two conventional methods have been proposed. Maurizi et al. [2] proposed a method in which the elevation of the terrain at the boundary is extended. On the other hand, in wind tunnel tests, the elevation of the terrain is set to zero at the outer edge of the model. In these conventional methods, the cross section area of the modified terrain differs from the original one, resulting the over or underestimation of wind speed in the analytical domain.

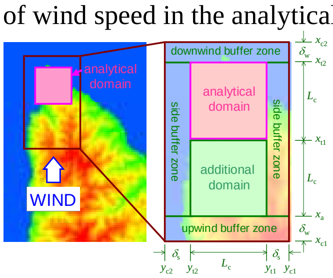

Figure 5. The computational domain for MASCOT

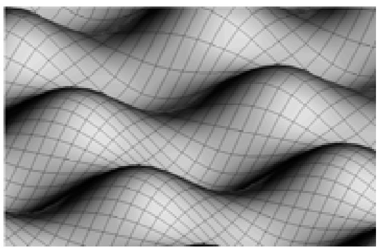
Figure 6. Model terrain with sin curve

We propose a new method in which the cross section area is conserved to avoid this problem. Let $h(x, y)$ be the original terrain. In proposed method, the modified terrain, $\hat{h}(x,y)$ is defined as:

$$\hat{h}(x,y)=\begin{cases} H_{sb} & (y_{c1}\le y<y_{m1})\\ H_{sb}(x)+\dfrac{2(y-y_{m1})}{\delta_s}\left[h(x,y_{t1})-H_{sb}(x)\right] & (y_{m1}\le y<y_{t1})\end{cases} \qquad (1)$$

where, H_{sb} is given by

$$H_{sb}(x) = \frac{1}{3}\left[\frac{4}{\delta_s}\int_{y_{c1}}^{y_{t1}} h(x,y)\,dy - h(x,y_{t1})\right] \tag{2}$$

3.2 *Verification*

To verify the boundary treatment, a model terrain with sine curve is considered (Fig. 6) and vertical profile of mean wind speed is compared for three different boundary treatment methods.

Figure 7 shows the cross section of the model terrain. The original terrain (solid line), modified terrains by proposed method (dotted line) and the conventional methods (dashed-dotted line and dashed line) are shown.

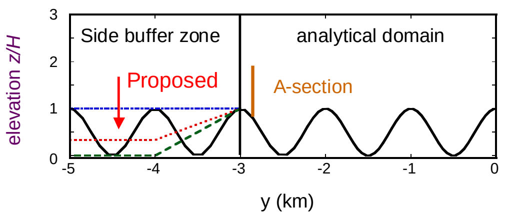

Figure 7. The treatment methods of side buffer zone

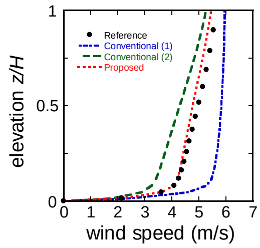

Figure 8. Vertical profile of mean wind speed at A-section

Vertical wind profiles for each case at the A-section (Fig. 7) are shown in figure 8. The filled circles show the reference value, the dashed and dashed-dotted lines show the conventional methods and the dotted line show the proposed method. The proposed method improves the overestimation or the underestimation of the wind speed by conventional ones.

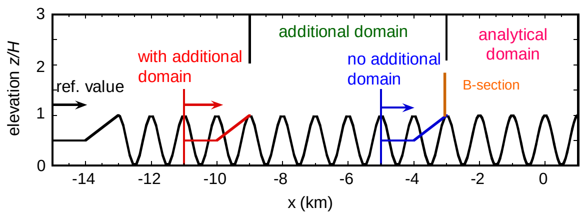

Figure 9. Cross section of the terrain in flow direction

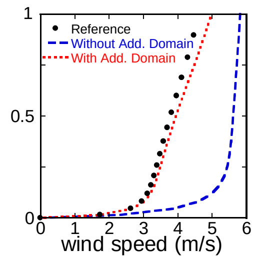

Figure 10. Vertical profile of mean wind speed at B-section

To examine the effect of the upwind terrain, simulations of the flow with and without additional domain were carried out (Fig. 9) and the vertical profiles of the wind speed at B-section were compared. The results are shown in figure 10. The case with additional domain (dotted line) shows favorable agreement with the reference value (filled circles), while the case without additional domain (dashed line) largely overestimates the wind speed.

4 CONCLUSION

Computational domain size and the treatment of the terrain at the boundary were investigated. Following results were obtained. 1) Computational domain heights should be decided so that the blockage is less than 5%. 2) The width of the computational domain should be wider than the length ten times as long as the hill height 3) Inlet boundary should be set so that the distances between the inlet boundary and the terrain center is longer than the length twenty times as long as the terrain height for the two dimensional ridge and ten times for the three dimensional hill. 4) Proposed method for the treatment of the terrain at the boundary shows better result than the conventional one.

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