APPLICABILITY OF LINEAR AND NONLINEAR WINND PREDICTION MODELS TO WIND FLOW IN COMPLEX TERRAIN

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ABSTRACT: The applicability of the conventional linear model and the developed nonlinear model to the flow in steep and complex terrain were investigated. For flows over two-dimensional ridges, the linear model considerably overestimates the wind speed when the slope angle exceeds 20 degree due to the inability of predicting flow separation. For the flow over complex terrain, the nonlinear model can predict the flow separation or rapid change in wind direction, while the linear model cannot. This results the overestimation of wind speed by linear model. The annual mean wind speeds in Tappi Wind Park at ten wind turbines were predicted by both models and compared with measurements. The prediction error in the linear model is 14.2%, while that in the nonlinear model is only 4.9%.
Keywords: Wind Prediction, Wind Farm, Numerical Methods

1 INTRODUCTION

Numerical model is widely used for the wind resource estimation recently. One of the most popular models used in this field is the linear model which was first proposed by Jackson and Hunt [1]. The linear model has been implemented in WAsP [2], a standard program widely used for wind resource prediction. However it is known that the linear model loses prediction accuracy when the slope angle of terrain becomes large. Xu and Taylor [3] compared the results predicted by linear and nonlinear models. They concluded that the linear model overestimates the wind speed at hill top and that this overestimation becomes large with the increase of the slope angle. Hewer [4] examined the flow over an isolated hill of moderate slope and pointed out that the linear model overestimates the mean wind speed at the lee side of the hill. Matsuzaka et al. [5] applied WAsP to predict the annual mean wind speed in Tappi Wind Park, Japan, and noticed that the prediction error is quite large.

Bowen and Mortensen [6] proposed a ruggedness index and criterion for judgement of prediction accuracy of the linear model. Since Japan is a mountainous country, where slope angles are large, the ruggedness index suggests that the large error may be included in the prediction by the linear model. For the wind resource estimation in Japan, the authors developed a nonlinear model, MASCOT, and examined the performance of the model in detail by a wind tunnel test [7].

In this study, we applied linear and nonlinear models, to the flow prediction over two-dimensional ridges and complex terrain, and revealed the applicability of these models.

2 NUMERICAL MODELS

A linear model, WAsP was used in this study, which is one of the most widely used wind prediction models in the world and is based on the linear model proposed by Jackson and Hunt [1]. The detail of WAsP is described in user's manual [2].

As a nonlinear model, MASCOT was used, which is based on Reynolds averaged Navier-Stokes equations with turbulence models. Finite volume method and SIMPLE algorithm with a collocated grid were adopted. To improve the numerical efficiency, the Residual Cutting Method was used for solving linear equation systems. As a result, analysis of wind flow with one million grids covering an area of $10\text{km}\times10\text{km}$ with 50m resolution can be performed by a PC within one hour. The detail of this model is described in Ishihara et al. [7].

3 NUMERICAL RESULTS AND DISCUSSION

3.1 Two dimensional ridges

Since the slope angle is a dominant factor to judge the applicability of the numerical model, the flows over two-dimensional ridges with different slope angles were simulated by the linear and the nonlinear models.

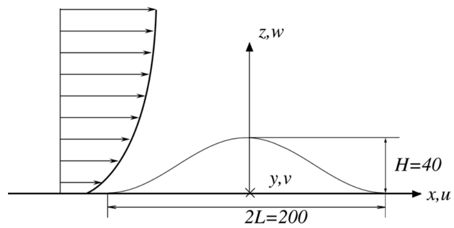

Figure 1: Coordinate system and notations

The model ridge has a cosine squared cross section and is described as:

$$z_s = \begin{cases} H\cos^2\left(\pi\dfrac{x}{2L}\right), & |x| < L \\ 0, & |x| > L \end{cases}$$

where H is the height of the ridge, L is the horizontal distance between the hilltop and hill foot. Fig. 1 shows the coordinate system used in this study, where x, y and z are the streamwise, spanwise and vertical directions. A second vertical coordinate $z'=z-z_s$ is also used to denote height above the surface. Five ridges with different slope angles were tested and the dimensions of each ridge are summarized in Table I. A mean slope angle is defined as:

$$\theta = \tan^{-1}(H/L).$$

The ridge is covered with artificial grass and has a roughness length of 0.3mm. The vertical profile of mean speed and the turbulent kinetic energy measured in an undisturbed boundary layer was used in the inlet boundary condition. The detail of the configuration of the flow is described in Ishihara et al.[7].

Table I: The dimensions of the ridges

case	H (mm)	L (mm)	θ (degree)	H/z_0
1	40	800	2.9	133
2	40	400	5.7	133
3	40	200	11.3	133
4	40	100	21.8	133
5	40	50	38.7	133

Fig.2 demonstrates the flow patterns over the ridges with typical slope angles simulated by the nonlinear model. In the case with the slope angle of 5.7 degree, the flow attaches the terrain surface and the flow pattern is almost symmetric (Fig.2a). When the slope angle exceeds 10 degree, a slight flow separation can be observed at the downwind hill foot and the reverse flow is limited near the terrain surface as shown in Fig.2b. In the case with the slope angle of 21.8 degree, the flow separates behind the hilltop and a circulation zone is formed at the lee side of the ridge. The flow pattern at the lee side differs remarkably from the upwind side of the ridge.

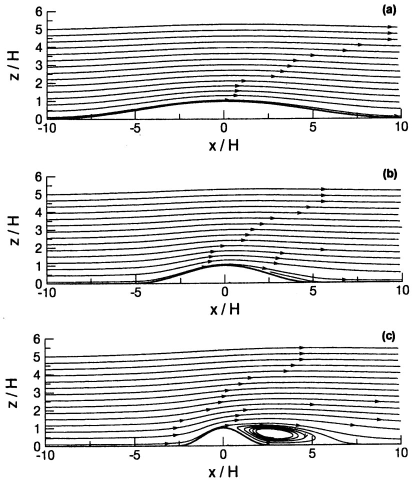

Figure 2: Sreamlines over two-dimensional ridges with: (a)θ=5.7; (b)θ=11.3; (c)θ=21.8.

When the flow separates, the mean wind speed predicted by the linear model becomes inaccurate. Fig. 3 shows the variation of topographic multiplier for wind speed with the streamwise distance at z'/H=0.25. The topographic multiplier for the wind speed is defined as U/U_0 , where U stands for the wind speed above the terrain and U_0 for that of undisturbed flow. x/H=0 corresponds to the top of the ridge and x/H=-2.5 and +2.5 correspond to the foots of the ridge. The linear model overestimates the wind speed for all regions, especially behind the ridge, where the topographic multiplier for the wind speed calculated by the linear model is about one while experimental result and the prediction by the nonlinear model show negative value corresponding to reverse flow.

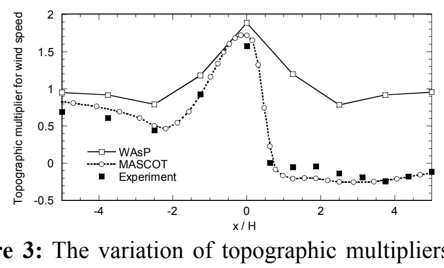

Figure 3: The variation of topographic multipliers with the streamwise distance

Fig. 4 shows the variation of the topographic multipliers for the wind speed with the slope angle predicted by the linear and the nonlinear model at the top of the ridge at z'/H=0.25. The topographic multiplier predicted by the linear model increases monotonically with the slope angle, while that by the nonlinear model has a peak around 15 degree. When the slope angle exceeds 15 degree, the flow separation becomes remarkable, which forms the recirculation zone behind the ridge and changes the shape of the hill apparently. This is the reason why the nonlinear model shows a peak value at 15 degree. The linear model overestimates the wind speed when the slope angle exceeds 20 degree and underestimates in the region between 5 degree and 15 degree. It is only when the slope angle is less than 5 degree, that the topographic multiplier predicted by the linear model agrees with that by the nonlinear model. This indicates that the linear model can only be used when the slope angle is less than 5 degree, which coincides with the limitation of the linear model.

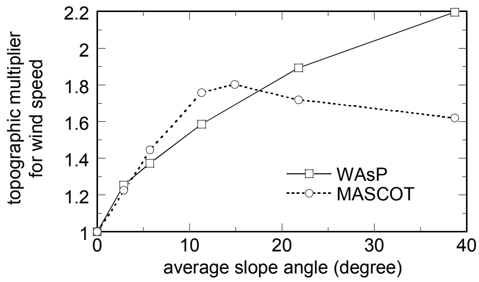

Figure 4: The variation of topographic multiplier for wind speed with the slope angle at the z'/H=0.25 at the hilltop

3.2 Complex terrain

Since the real terrain is usually much more complex, the flow field over complex terrain measured in a wind tunnel test was used to examine the applicability of the linear and nonlinear models.

Fig.5 shows the terrain model used in the wind tunnel test, which is 1:2000 scale with a diameter of 4m. The experiment was carried out in a circuit wind tunnel in the Wind Engineering Laboratory, the University of Tokyo.

Figure 5: The terrain model

The measurement locations and the elevation contours of the terrain model are shown in Fig.6. The measurements were performed at seven sites for eight wind directions using a split-fiber probe, designed for measuring flows with high turbulence and separation. The detail of the wind tunnel test is described in Yamaguchi et al. [8].

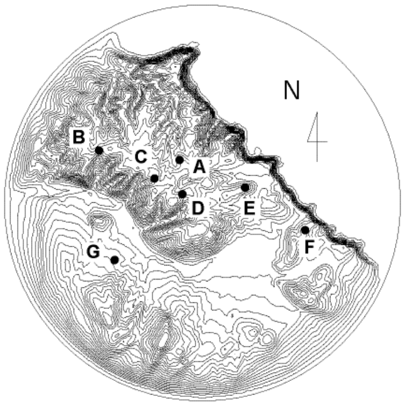

Figure 6: The elevation contours and the locations of measurement sites

Although all the sites are located on a plateau, the surrounding terrains are quite different. The terrain around the site B is very complex and the wind speed changes considerably with the wind direction. The site F is located near a steep cliff and flow separation may occur. Fig.7 shows the variation of the topographic multiplier with the wind direction at the height of 40m at the site B. Flow is strongly influenced by the surrounding terrain and the topographic multiplier varies considerably with the wind direction. The nonlinear model catches this feature and gives fairly good agreement with the experiment, while the linear model overestimates the wind speed with the southwesterly wind (225 degree). The mean wind velocity vector with this wind direction is shown in Fig.8. The wind direction is forced to change to southerly by the local valley. This feature cannot be predicted by the linear model. This is the reason why the linear model overestimates the wind speed with the southwesterly wind.

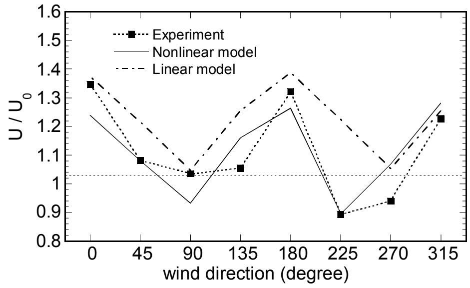

Figure 7: Measured and predicted topographic multipliers for the mean wind speed at the site B

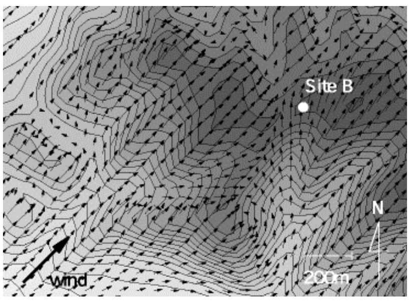

Figure 8: Mean wind velocity vectors around the site B with the southwesterly wind predicted by MASCOT

The site F is characterized by the flow separation at the edge of the cliff. When the wind is northeasterly, remarkable decrease in the mean wind speed can be seen in Fig.9. The nonlinear model demonstrates this wind speed decrease with the northeasterly wind, while the linear model overestimates the mean wind speed. This is because the linear model cannot predict the flow separation. Fig.10 shows the mean wind velocity vectors in the vertical cross section around the site F. It is clear that the flow separates near the edge of the cliff.

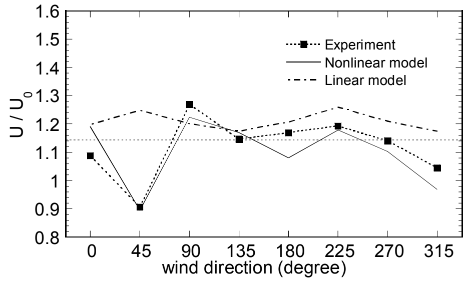

Figure 9: Measured and predicted topographic multipliers for the mean wind speed at the site F

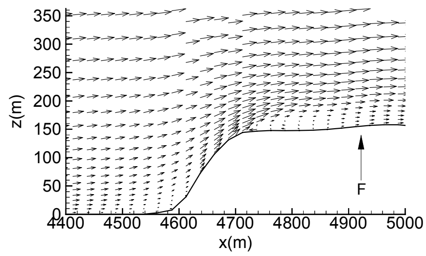

Figure 10: Mean wind velocity vectors in the vertical cross section around the site F predicted by MASCOT

3.3 Application to Tappi Wind Park

Tappi Wind Park, the first wind farm in Japan, owned by Tohoku Electric Power Co. The wind farm consists of eleven wind turbines, all of which are located on complex terrain. Fig.11 shows the overview of the wind farm.

Ten minutes mean wind speed and wind direction are measured by an anemometer installed at the top of the nacelle of each wind turbine. In this study, wind data measured at the lighthouse in 1997 were used as a reference data, which is available from Japan Coast Guard.

Figure 11: The overview of Tappi Wind Park

Measured and predicted annual mean wind speeds are shown in Fig.13. The nonlinear model, MASCOT, shows good agreement with measurements for all the wind turbines. Although the linear model, WAsP, shows fair agreements with the measurements for the turbines No.1 and No.6 to 10, it overestimates the annual mean wind speeds for the turbines No.2 to 5. The averaged error in the linear model is 14.2%, while that in MASCOT is only 4.9%.

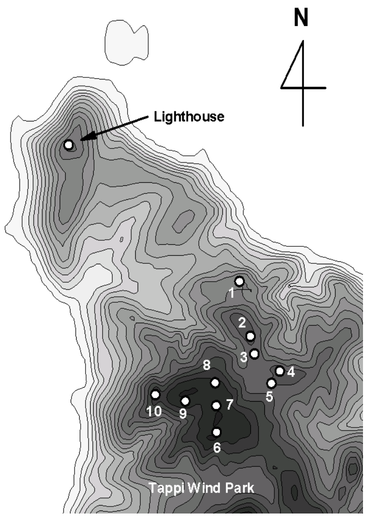

Figure 12: Elevation contours and the wind turbine locations in Tappi Wind Park

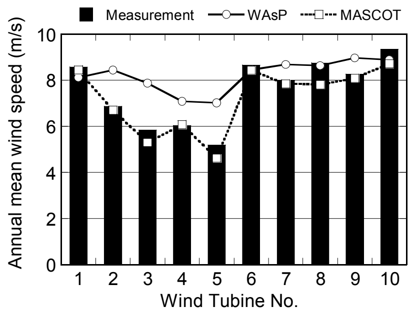

Figure 12: Measured and predicted annual mean wind speeds at ten wind turbines in Tappi Wind Park

Wind turbines No. 2 to 5, at which the linear model overestimates the wind speeds, are located at relatively low elevations and are behind the summit in the wind farm with the prevailing wind. Fig. 14 shows the mean wind velocity vectors in the vertical cross section predicted by the nonlinear model around the turbine No. 5. It can be seen that the wind speed decreases behind the summit. As the result, the annual mean wind speed at the turbine No.5 shows a low value. This is the reason why the linear model overestimates the wind speed at these turbines.

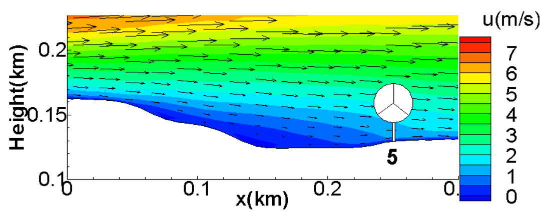

Figure 14: Mean wind velocity vectors in the vertical cross section at the turbine No.5

The annual mean wind speed measured at the turbine No.10 gives the maximum value. This is because the turbine No.10 is located at the windward side of the summit with the prevailing wind. Fig. 15 shows the mean wind velocity vectors in the vertical cross section predicted by MASCOT. It can be seen that the turbine catches increased wind. As the result, the highest annual mean speed was recoded at this turbine.

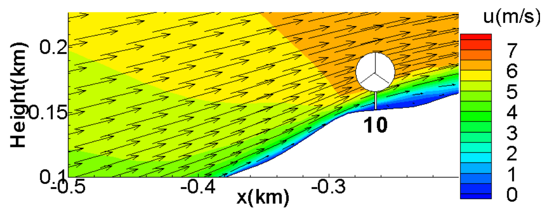

Figure 14: Mean wind velocity vectors in the vertical cross section at the turbine No.10

4 Conclusions

The applicability of conventional linear model and the nonlinear model to the flow in steep and complex terrain were investigated. The limitation and the accuracy of the linear model were made clear. The following summarizes the major conclusions of this study.

1) The linear model considerably overestimates the wind speed over a terrain when the slope angle exceeds 20 degree, and gives an accurate wind speed only when the slope angle is less than 5 degree.
2) The nonlinear model developed by the authors accurately predicts the wind speed over any type of terrain. The flow separation and rapid change in the wind direction in the complex terrain can be simulated by the nonlinear model.
3) In Tappi Wind Park, the annual mean wind speeds at the ten wind turbines are accurately predicted by the nonlinear model, while the linear model overestimates the annual mean wind at some sites. The mean prediction error in the nonlinear model is 4.9% and that in the linear model is 14.2%.

Acknowledgement

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