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Measurements and Predictions of Local Wind Field in Complex Terrain

Takeshi ISHIHARA

Department of Civil Engineering, the University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan

1. INTRODUCTION

For the efficient use of wind energy in mountainous areas in Japan, it is very important to accurately predict local wind field in complex terrain. Operational experience in Tappi Wind Park, owned by Tohoku Electric Power Co., has indicated that the capacity factor of individual wind turbine varies from 14.8% to 38.8% depending on its location [1], although the site has an excellent annual mean wind speed up to 9m/s. Tappi Wind Park is located at the tip of Tsugaru peninsula of the main island of Japan, where terrain is very complex and steep. The estimations of annual mean wind speed at the wind turbine locations using WAsP [2], a standard program widely used for wind resource prediction, show significant differences from the observations due to the limitation of linear model. This suggests that it is necessary to develop non-linear models that are available for complex terrain in Japan.

This paper aims to describe techniques recently developed for measuring and predicting local wind field in complex terrain. The results of split-fiber measurements of separated flow over steep topographies are first illustrated to provide details of mean wind speed and turbulence statistics of separated flow and to shed some light on the structure of the turbulent flow in the near-wake region [3][4][7]. Then, a non-linear model developed for prediction of mean wind speed and turbulence in mountainous areas is discussed, which has made it possible to accurately estimate wind resource in complex terrain [5][6][7].

2. FLOW MEASUREMENTS

As numerical models become more sophisticated and accurate, the need for high-quality flow measurements becomes more and more apparent.

Conventional X-wire probe anemometers have been widely used for turbulence measurement. However, this probe cannot give reasonably accurate flow measurements in the regions of highly turbulent and reversing flow. X-wire probe overestimates longitudinal velocity components and underestimates lateral and vertical turbulence in the near-wake region, because it is unable to differentiate between positive and negative quantities and underestimates lateral and vertical velocity components when longitudinal velocity components are small [3].

The pulsed-wire has been developed for turbulence measurement in highly turbulent and recirculating flows. Unfortunately, the pulsed-wire measurements show the erratic probabilities near zero velocity due to the limited yaw response and cannot give a reasonable accuracy when turbulent intensity is less than about 0.1. For this shortcoming, the pulsed-wire has never been used for turbulence measurement in complex terrain where the turbulence intensity varies in a wide range.

In this study, a split-fiber probe was designed for measuring flows with a high turbulence and separation. In this method, output voltages from the anemometers connected to the two films were compared with each other, and since the output from one anemometer is greater than that of the other, the instantaneous flow direction can be determined. The detailed information on the calibration procedures have been described by Ishihara et al. [3].

2.1 Flow measurements for single hills

The first example shows turbulent flows over single hills, aiming to provide details of mean velocity and turbulence statistics of separated flow over a two-dimensional ridge and a circular hill and shed some light on the structure of the turbulent flow in the near-wake region. The experimental emphases are on the three-dimensionality of the separated flow and surface roughness effect.

The model hills have a cross-section of $z_s(r)=H \cos^2(\pi r/2L)$ with H =40 mm and L =100 mm. The maximum slope is thus about 32°. Table 1 summarizes the main aerodynamic parameters in the experiment. Two ridges labelled as 2dr and 2ds have different surface roughness. For the rough case, the ridge surface was covered with an artificial grass, while in the smooth case no any roughness element was used. The ridge spanned the entire tunnel width. The two corresponding circular hills were also covered with and without the grass, and are marked as 3dr and 3ds. For each case, the roughness of the hill surface was identical to that of the surrounding terrain.

Table 1 Main aerodynamic parameters in the experiment

Case	δ/H	z_r/H	H/z_0	Re_H	R_*
2ds	9.0	0	4000	1.2×10^4	0.14
2dr	9.0	0.125	133	1.0×10^4	6.4
3ds	9.0	0	4000	1.2×10^4	0.14
3dr	9.0	0.125	133	1.0×10^4	6.4

Fig. 1 shows vertical profiles of mean velocity components of U for each case. The profile in the undisturbed (no-hill) boundary layer (dashed line) is superimposed on the local profiles. The dashed-dot line in the figures is the locus of zero streamwise velocity. It can be seen that streamwise mean velocity U are the increase in velocity near the surface on the hilltop, the slight deceleration at the upwind hill foot, and the flow separation behind the hill. Some features are worthy of particular comment. First, a strong shear layer forms immediately downstream of the top of the hill. This layer is identified by a point of inflection in $U(z)$, high values of the mean shear $\partial U/\partial z$, and also by high values of the Reynolds stress. The second notable feature is that the reversed flow region behind the two smooth cases (2ds and 3ds) is much smaller than those behind the corresponding rough cases (2dr and 3dr). The third feature is that the downstream extents of the recirculating region of the two-dimensional ridges are longer than those of the three-dimensional hills.

It is of interest to know how turbulence might be modified as the flow goes over the hill (see Figs. 6,7,8 of [4]). It is clear that highly turbulent energies are generated by the flow separated on the lee slope of the ridges and hills and far in excess of those that occur in the undisturbed boundary layer. In the near-wake region beyond the separation bubble, the profiles of σ_u and σ_w are substantially rounded and the peak values decay with the downstream distance. The most striking behaviour in the three-dimensional wake is that σ_v profiles show second local maxima in the so-called wall layer, which could not be observed in the two-dimensional wake. In this layer, the σ_u profiles show a roughly constant value. It should be noted that for the rough hill the second peaks in the σ_v profiles are weak, indicating that increase of surface roughness will reduce turbulent motion in the spanwise direction.

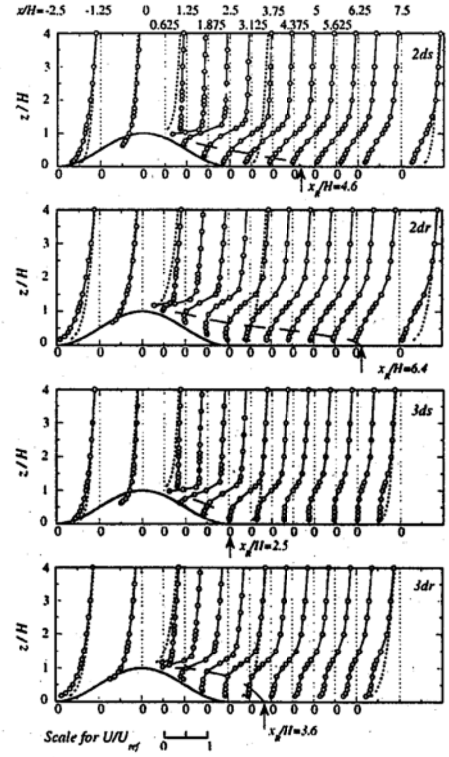

Fig. 1 Vertical profiles of the streamwise velocity components normalized by the reference velocity.

2.2 Flow measurements for a real terrain

The second example shows flow measurements on Shakotan Peninsula area, north of Japan. The terrain model used in this experiment is shown in Fig. 2. The topographic feature of this area is very complex and there are steep cliffs along the north-east coast.


Fig. 2 Terrain model used in this study.

The measurement locations shown in Fig. 3 correspond to the wind observation masts. These sites are all located on a plateau except for G, but the surrounding terrain is different. Around the mast A is relatively flat and less complex. Around the mast B, C and D is a very complex terrain. For the masts E and F, there is a steep cliff with the height of 150m from the sea in northeast side. Mast G is located at a relatively low elevation and surrounded by mountains.

As expected, the wind speed ratio at point B varies remarkably with the wind direction. The wind speed ratio at z=20m reaches almost 1.5 with the southerly wind while it is only around 0.9 with the southwesterly wind. The most striking characteristic of point F is that the wind speed ratio decreases to 0.8 with the northeasterly wind while it stays around 1.2 with the other wind directions. This is because of the cliff located about 200m away from the point F. When the wind blows from the northeast, the flow separation at the cliff causes low wind speed. The detailed information on the measurement has been described in [7].

Fig. 3 Measurement locations

3. NUMERICAL SIMULATIONS

Prediction of the turbulent flows over steep terrains plays a dominant role in wind energy exploitation in mountainous areas. However, comparatively fewer investigations of turbulent wake flows behind steep terrain have been made. Prediction accuracy of numerical solutions for mean velocity as well as turbulence in the separated region has not been made fully clear. In this study, three-dimensional non-linear model is developed and used to simulate flow over single hills and a real terrain

The Reynolds averaged Navier-Stokes equations and k-ε turbulence model are used in the present study. Since the expression of the Reynolds stress is an important factor for successful simulations of the turbulent wake flows, a nonlinear expression proposed by Shih et al [8] is used to approximate the Reynolds stress. This expression has several advantages compared to the standard k-ε eddy viscosity model. First, this model is fully realizable. It will not produce negative energy components and will not violate the Schwarz's inequality between turbulent velocities. Second, the effective eddy viscosity is anisotropic as it should be.

To suit the computation of complex flow, the arbitrary non-orthogonal collocated grid system is used. The governing equations are rewritten in the curvilinear coordinate system and are solved using a common discrete method. In this study, finite volume method and the SIMPLE algorithm are adopted. The QUICK scheme is employed for the convection terms in the Navier-Stokes equations, the first order upwind difference for the convection terms in the equations of k and ε, and the second-order central difference for the other terms. The Rhie and Chow's PWIM (pressure weighted interpolation method) is used to avoid pressure-velocity decoupling.

3.1 Numerical simulations for the single hills

To evaluate the performance of the turbulence model, data shown in the previous section are used. The measured mean velocity and the turbulence kinetic energy profile are used as an undisturbed upstream condition for numerical simulations.

Predicted profiles of streamwise and vertical velocity at different stations in the central plane of the hill are given in Fig. 4. Standard k-ε model and Shih's nonlinear model yield virtually identical results on the upstream side of the hill. Relatively large differences were obtained inside the separated region, where the predicted streamwise velocity by standard k-ε was higher than the experimental value. The main reason is presumed to be due to the overestimation of the turbulence kinetic energy in the separated region.

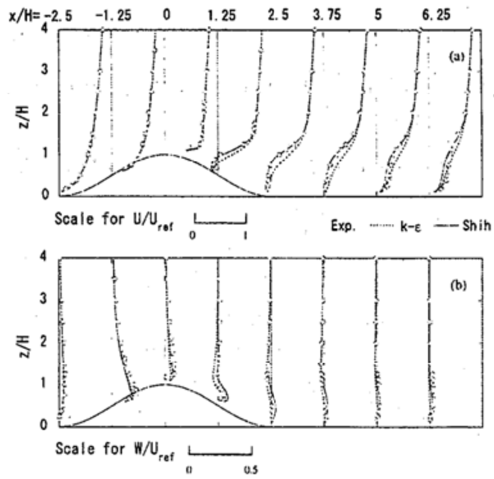

Fig. 4 Vertical profiles of mean velocities in the central plane of the hill

Fig. 5 shows that eleven particles start from the upstream foot of the hill. The particles near the central plane pass around behind the hill and enter the separated region. These particles are lifted toward the hilltop by the upward flow on the lee slope of the hill and then escape downstream. This flow pattern is considerably different from that behind the two-dimensional ridge [5]. The reason why the flow pattern changes can be interpreted by using the continuity equation [6].

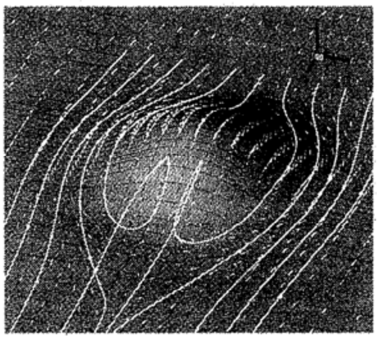

Fig. 5 Surfaces velocity vectors and particle traces over the hill

Fig. 6 shows vertical profiles of turbulent kinetic energy in the central plane of the hill. Prediction by Shih's nonlinear model favorably agrees with the experimental value better than the standard k-ε model. Especially, in the separated region, the overestimation of the turbulent energy from the standard k-ε model is evidently improved by Shih's nonlinear model. The results on the upstream side of the hill and hilltop are also slightly improved by Shih's model.

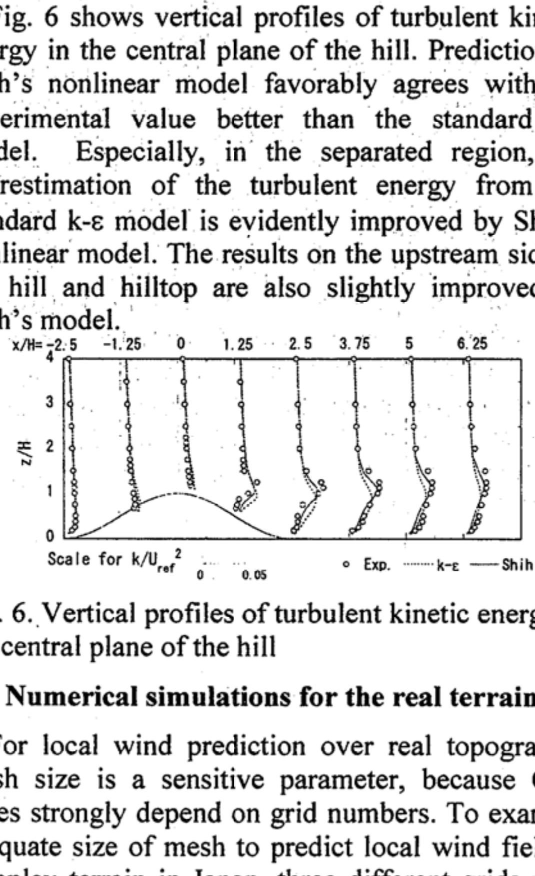

Fig. 6. Vertical profiles of turbulent kinetic energy in the central plane of the hill

3.2 Numerical simulations for the real terrain

For local wind prediction over real topography, mesh size is a sensitive parameter, because CPU times strongly depend on grid numbers. To examine adequate size of mesh to predict local wind field in complex terrain in Japan, three different grids were used. The mesh interval of each grid is 100m, 50m and 25m. Fig.7 shows the mean velocity vectors of flow field in each case. It is clear that 100m grid cannot simulate the flow separation behind the cliff, while 25m and 50m mesh results can predict the flow separation and show favourably good agreement with the experiment.

4. CONCLUSION

The techniques recently developed for measuring and predicting local wind field in complex terrain are presented. Local wind field with a high turbulence and reversing flow have been measured by split-fiber probe, to investigate features of turbulent wake flows and to provide a high-quality data set for evaluating the performance of various numerical models. A three-dimensional non-linear model has been developed and used to simulate flow over single hills and a real terrain. The results show good agreement with measurements. It is now possible to simulate turbulent flow over a single hill within a few minutes on a PC and local wind field in a real terrain with 10km wides under several hours on a workstation.

References

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Key words: complex terrain, split-fiber measurements, nonlinear model, prediction of highly turbulent and separated flow.

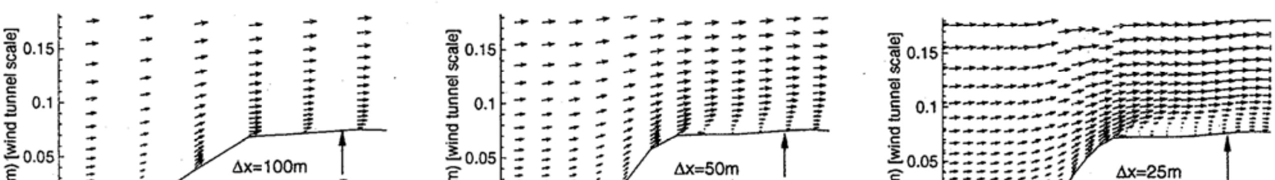

Fig. 7 Mean velocity vectors at point F calculated with different mesh sizes .