A Case Study of Wind over a Hilly Terrain

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Abstract

A case study of modification of airflow over small scale undulation of topography in a hilly terrain is shown in this paper. The target area was chosen to be the area around Mt. Takakura, Kobe City, because a small hill of about 300 m high in this area was cut down to a plateau of about 150 m high as a result of a large engineering work in the period of the field observation. Besides the field observation for about six years, airflow modification over this area was also studied by the wind tunnel and numerical experiments. The results of these three methods of study resemble each other in shape of airflow patterns but quantitative prediction by the model or numerical experiment is still incomplete. As the result of the study, it was concluded that the effect of the removed hill body was restricted in the small area just near the hill.

1. Introduction.

Wind is one of the main controlling factors of environmental condition of human activities, and knowledges of wind environments both in normal and extreme wind speed conditions are required for the purpose of town planning, design of a building and so on. While the distribution of wind is greatly affected by the surface topography and wind near the surface is especially sensitive to the surrounding small scale topography. Therefore, wind environment of a particular point or town of interest cannot be estimated from the synoptic climatological consideration without introducing some corrections for surrounding small scale topography. Because the effect of small scale topography, less than 10 km or so in horizontal scale, is normally ignorable in the free atmosphere above the planetary boundary layer, the modification is concentrated into the boundary layer near the surface. The general rule to find out the modification of wind system in the boundary layer caused by small scale topography has not been established, but is now one of the main tasks in the new field of meteorology called topo-meteorology[1].

There are three main methods of study to find out the mechanical modification of wind near the surface due to topography;

1) Field observation,
2) Wind tunnel experiment,
3) Numerical experiment.

The first one is the best way of the study provided that enough large numbers of observational points could be established, but it takes rather long time to obtain sufficient informations. The second method is the easiest way but great difficulty arises in translating the results of the experiment into the field conditions. The last one is promissing, but limitation of the computer ability in the process of computation of three dimentional flow above the irregular terrain prevents improvement of the accuracy of the results.

In the present paper, a case study of airflow over a hilly terrain made by the present authors is shown, in which all of the three methods mentioned above were applied to the same target area. A small hill in the center of the target area (292 m in height from MSL) was removed and cut down, resulting a plateau of 150 m in height during the observational period. The observation and other experiments were made for both topographies before and after removal of the hill. Comparing two kinds of the results, the effect of the removed hill body can be clearified, which is one of the main purposes of the present study.

2. The Site and Field Observation.

The area chosen for the study is the area surrounding Mt. Takakura which is near the southwestern end of the Rokko Mountains in Kobe City. The original topography of the area is shown in Fig. 1. A low mountain range of 200-300 m high runs from northeast to southwest. Mt. Takakura (292 m) is a peak on this range and is about 1.5 km from the sea coast.

In this area a big engineering work of mountain cut off was planned and started in 1964 to get soil for reclamation of the coast of Kobe City and, at the same time, to make a residential area on the remaining plateau of about 150 m high. The remaining topography at the end of the engineering work is shown in Fig. 2. As is seen from this map the mountain range is cut down, making a gap, and a plateau of about 1 km^2 is constructed. The aerial view of this area is shown in Photo. 1.

As the mountain is removed for more than 100 m in height within a few years, the effect of the removed mountain is expected to be easily found out by the continuous observation of wind around this area. Therefore, a field observation was planned in this area, and wind tunnel and numerical experiments were attempted to predict the environmental changes in the surrounding area due to mountain cut off before the engineering work.

The field observation was started in 1965 using about ten observing points shown in Fig. 1. The observation had been continued untill 1970 when the cutting off was almost over, with slite changes of observing points in the project area as shown in Fig. 2. Two of the observing points indicated as A are on the west side foot of the mountain range, four of them shown as B are on the ridge line and the rest shown as C are to the east of the mountain range. B_1 and C_1 were in the project area to be cut off and C_1 was moved a little to the east during the observation as shown in Figs. 1 and 2. B_1 was on the top of Mt. Takakura and C_1 was on the southeastern end of a small branch of the range in the beginnings, but it became to be on the top of a small hill remained. The surrounding conditions of other observing points were not changed.

The instruments used in this observation are self-recording cup anemometers with vane specially designed for the experimental observation by the present authors, by which continuous traces of mean wind speed and direction can be obtained for about a month on a roll chart. The height of the anemometer is at least 6 m from the ground and it is much higher at the point surrounded by high obstacles such as trees and houses.

The hourly mean wind speed and direction were read from the traces and analyzed. Rather long averaging time of mean wind speed (1 hr) was chosen to avoid the error caused from difference of timing at each point in the comparison processes. Fig. 3

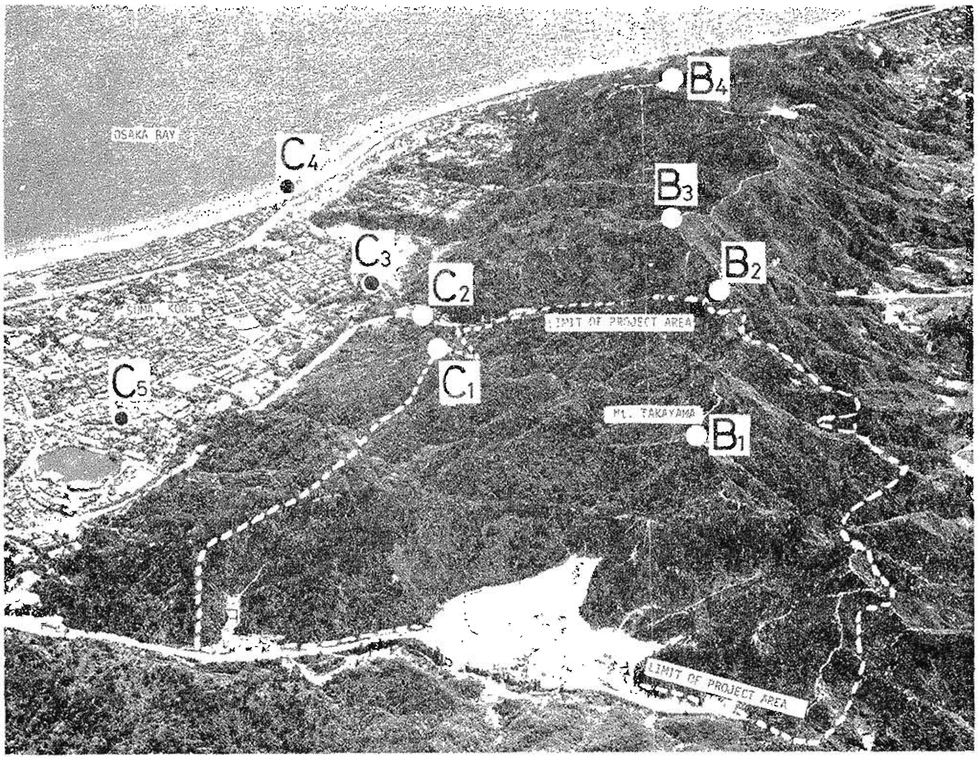

Photo. 1 Aerial view of Mt. Takakura and its vicinity of original topography from the north (See Fig. 1). The area enclosed in the dotted line is the project area of the reclamation works, and the circles show the positions of observational points.

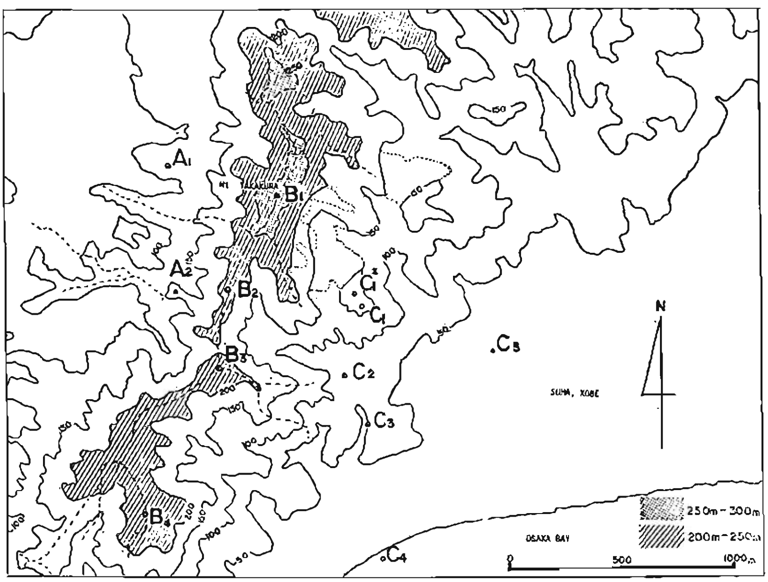

Fig. 1 Original topography before the reclamation works and the positions of observational points. Mt. Takakura is shown as B_1. (See Photo. 1)

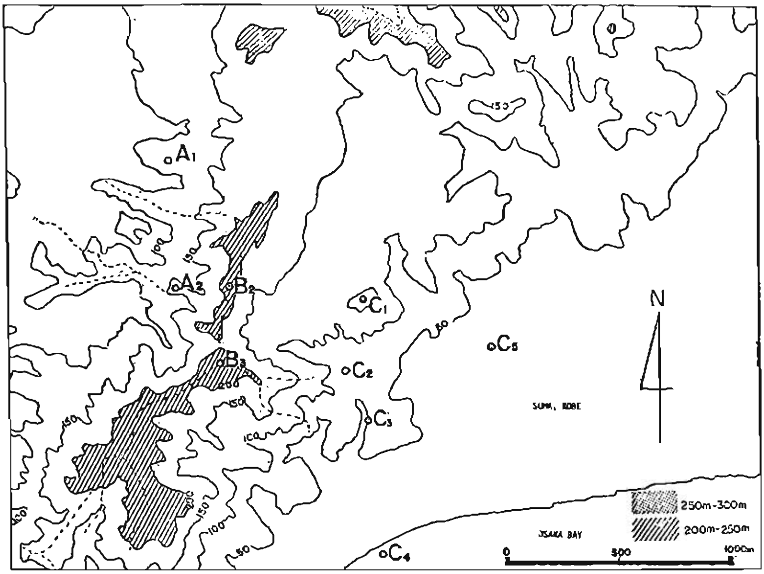

Fig. 2 Topography in the end of the reclamation works after the mountain is cut down. Mt. Takakura (B_1) of 292 m was cut down to a plateau of about 150 m high.

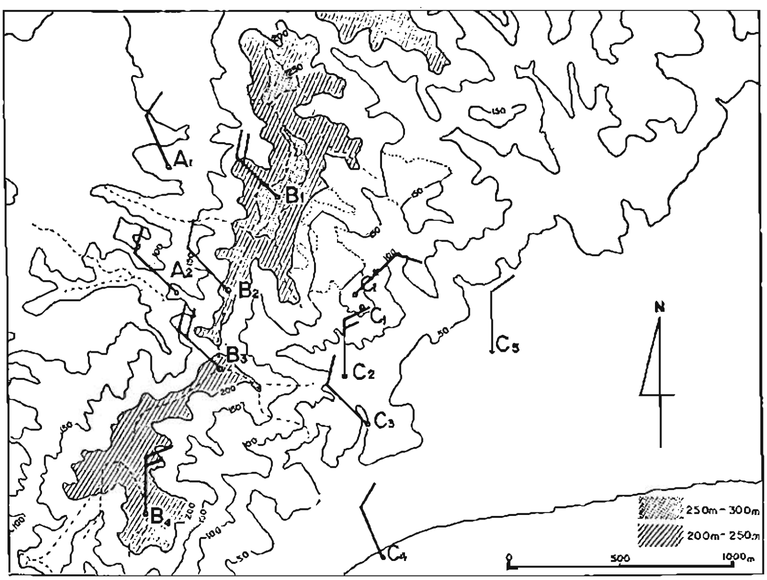

Fig. 3 A typical example of simultaneous wind distribution in the beginning of the reclamation works before the mountain was cut off (mean state from 09_h to 10_h June 28, 1966). A long blade shows 5 m/sec.

shows a typical example of simultaneous wind distribution in this area in the northwesterly wind in the early stage of works when the original topography was conserved. High winds in this area are expected to blow from this direction perpendicular to the mountain range in most cases. Wind on the ridge line is almost twice as strong as that on the foot.

To clear the wind distribution in this area, the mean relative wind speed of each point, whose reference is the wind speed at A_1 on the windward side, are shown in Figs. 4 and 5 for westerly and northwesterly wind at A_1 with topographic profile along the direction of wind passing the point B_1. In the computation of mean relative wind speed, the low wind speed cases, less than 3 m/sec at A_1, are omitted, because in low wind speed cases local circulation caused by thermal irregularity in this area might be superimposed on the general wind system and the problem becomes complicated in spite of the aim of the present study to find out the mechanical effect of the topography. The standard deviation of the individual relative wind speed at each point is also shown in the figures. The relative wind speed at each point does not change appreciably with wind speed.

As is clear from these figures the difference of relative wind speed at each point is not so clear before and after mountain cut off except at the point C_1, where fairly large increase of relative wind speed is seen in northwesterly wind after the work. In this case the barrier in the windward was revomed and in the case of westerly wind, when that point goes into the lee of the remaining hill, the increase of the relative wind speed is not seen. Moreover, in the westerly wind case shown in Fig. 4, the relative wind speeds at all points become smaller after the mountain cut off. This may be partly caused by the increase of the wind speed at the reference point A_1 after the works, which is supported by the results of wind tunnel experiment. But there

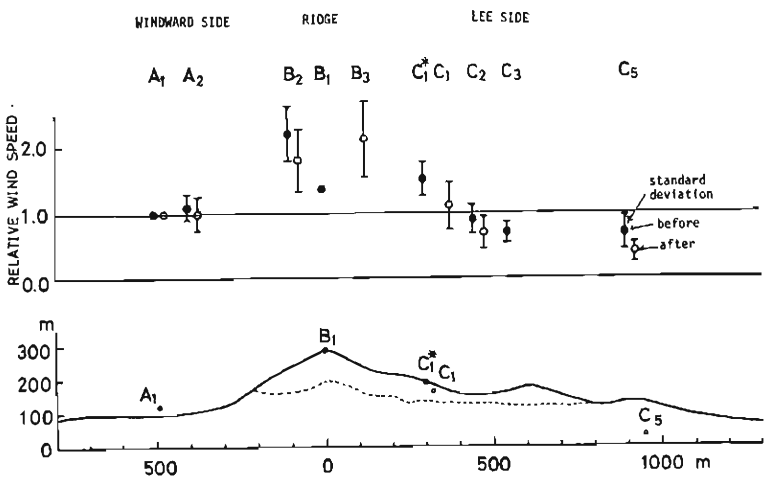

Fig. 4 The observed relative wind speed with reference to A_1 averaged for all cases when the wind direction at A_1 is from west and its wind speed being not less than 3 m/sec. Black circles show the period before the mountain was cut and white circles show the period after the mountain was cut down. The ground profile in the section parallel to wind direction crossing the point B_1 is shown in the bellow.

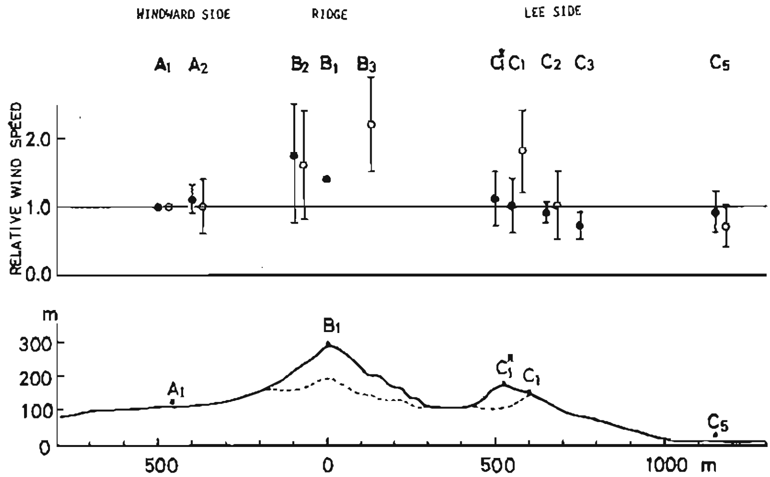

Fig. 5 The same as Fig. 4 except that wind direction is from northwest.

is another reason to decrease relative wind speed at the point on the remaining ridge, because wind becomes to flow into the gap of mountain range produced by the engineering works and wind component to cross over the range decreases causing relatively low wind speed on the remaining ridge.

3. Wind Tunnel Experiment

Model experiment of airflow above this area was made in the Göttingen type wind tunnel of the Disaster Prevention Research Institute of Kyoto University which has a working section of 1 m in diameter. The area of 4 km in diameter around Mt. Takakura was modeled in the scale ratio of 1 : 5,000 both in horizontal and vertical axes.

The boundary layer above the model surface was adjusted to simulate the boundary layer in the natural field. The wind tunnel wind speed (friction free wind speed) for testing was chosen to be 2 m/sec, which corresponds to fairly high wind speed in the field according to the similarity rule by Dr. S. Nemoto[2)]. However, this may not cause serious problem because the mechanical effect of topography on neutrally stratified flow is expected to be insensitive to wind speed.

Wind tunnel tests were made for both topographic models for original and remaining topography in several wind directions, measuring surface wind speed and direction at every mesh points in 4 cm (200 m in prototype) intervals at the height of 5 mm (25 m in prototype) from the ground surface. Wind speed was measured by a hotwire anemometer and wind direction was measured by the use of a small wind vane made of a dandelion seed proposed by Prof. J. Sakagami.

The results of the experiments in the west-by-worthwesterly wind case are shown in Figs. 6 and 7. In these figures, wind speed is plotted as a relative value to the wind tunnel wind speed in percentage. Relative wind speed at each observational point in this area is also shown in Table 1.

Wind speed is larger on the ridge and the ratio of wind speed on the ridge to that on the foot is as large as two. The lee side weak wind zone extends far down from the ridge. The relation between wind speed distribution and topography is almost the same as that expected from the field observation. And the relative wind speed at

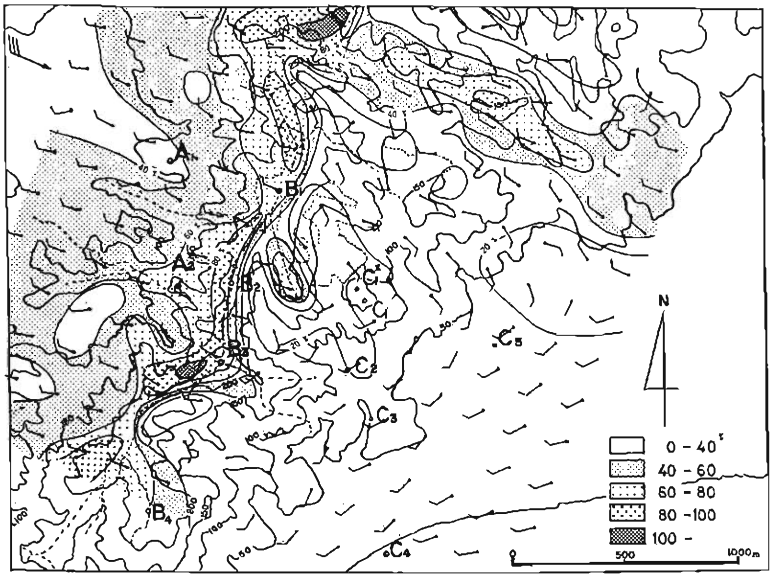

Fig. 6 Surface wind distribution before the mountain is cut down obtained by wind tunnel experiment. Wind speed is plotted as the relative wind speed to the wind tunnel wind speed in percentage. This shows the case when general wind direction is WNW.

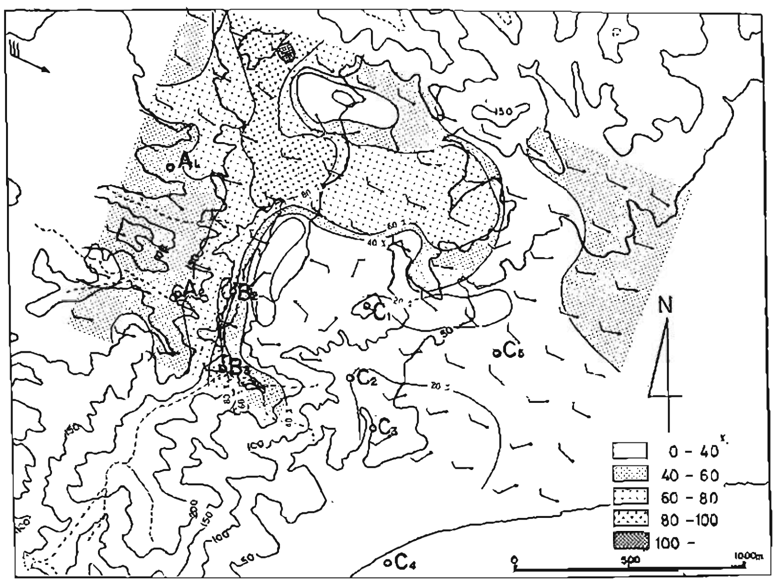

Fig. 7 Surface wind distribution after the mountain is cut down obtained by wind tunnel experiment for WNW wind. (Compare with Fig. 6.)

each observational point also agrees fairly well with the observed value.

Difference of wind before and after mountain cut off is clear in the project area and its vicinity but is not so significant over most of the town in the lee side. The newly constructed residensial area on the plateau is predicted to be very windy place. However the limitation of wind tunnel experiment is that the prediction of absolute wind speed at a particular spot is imposible only from the experiment.

4. Numerical Experiment

Modification of airflow over a irregular topography can be simulated by a numerical method. In the present study the simplest approximation of potential flow has been applied as a first trial. Therefore, the problem is transformed into the one how to solve the three dimensional Laplace's equation with a boundary condition corresponding the surface topography.

Computation has been made over the area, on which wind tunnel experiment was made, by the simplified method presented by Prof. I. Imai[3]. As the effects of surface stress and viscosity cannot be considered in the present computation, the results are not accurate enough to be compared with the previous two methods but representing some features of surface wind.

The undisturbed flow is assumed to be straight and with constant speed, and over the irregular terrain the flow is assumed to be the composition of the uniform undisturbed flow and the perturbation as follows,

$$\Phi = Ux + \phi, \qquad (1)$$

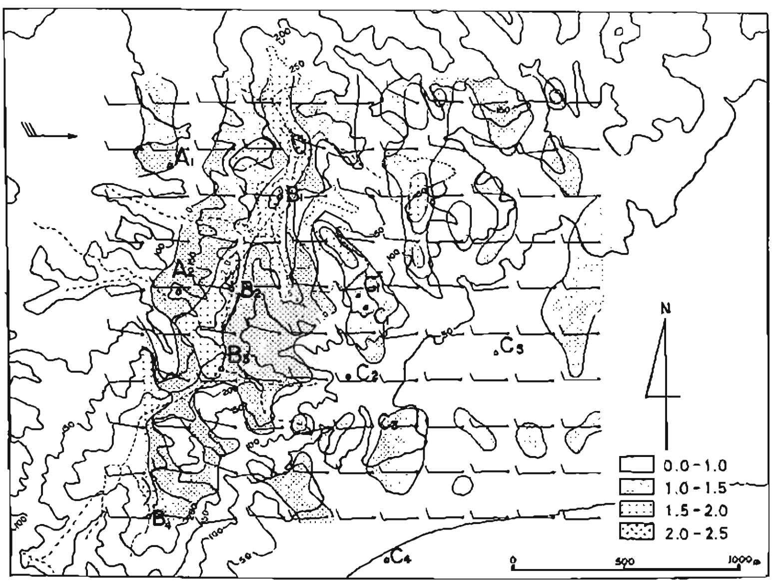

Fig. 8 Surface wind distribution before the mountain is cut down obtained by the numerical experiment for W wind. Wind speed is plotted as the relative wind speed to the undisturbed wind speed.

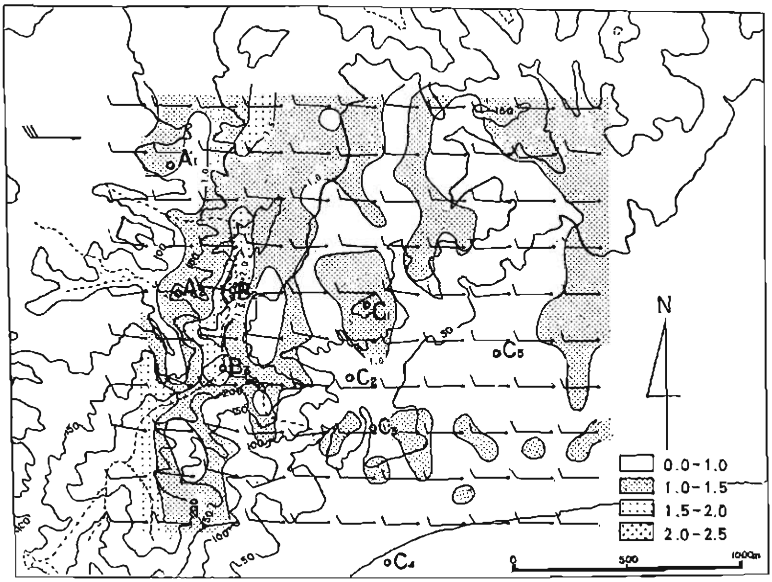

Fig. 9 Surface wind distribution after the mountain is cut down obtained by numerical experiment for W wind. (Compare with Fig. 8.)

where Φ is the velocity potential of the flow ($\Delta\Phi=0$), U speed of the undisturbed flow and ϕ being the velocity potential of the perturbation, which is also assumed to be potential flow ($\Delta\phi=0$). The co-ordinate system is taken so that the wind direction coincides with x axis and azimth with z axis.

If the amplitude of the surface undulation is small, it can be supposed to be infinitesimally small compared with the horizontal scale of the area and the boundary condition at the bottom can be written as follows,

$$\text{at } z=0, \quad \frac{\partial\phi}{\partial z}=U\frac{\partial h}{\partial x}, \tag{2}$$

where $\partial h/\partial x$ is the gradient of the ground surface, $h(x, y)$. And the upper boundary condition is

$$\text{at } z\rightarrow\infty, \qquad \phi\rightarrow 0. \tag{3}$$

By these assumptions, the problem to solve the Laplace's equation,

$$\Delta\phi=0, \tag{4}$$

can be reduced into the problem to find out the velocity potential of the perturbation, ϕ, corresponding to the source and sink distribution on the $z=0$ plane shown by Eq. (2), and the solution is written as follows,

$$\phi(x, y, z)=\frac{U}{2\pi}\iint_{-\infty}^{+\infty}h(\xi, \eta)\frac{x-\xi}{r^3}d\xi\, d\eta, \tag{5}$$

where $r=\sqrt{(x-\xi)^2+(y-\eta)^2+z^2}$. Then the surface wind distribution (u, v) is given as,

$$u=U+\phi_x(x, y, 0)$$

$$v=\phi_y(x, y, 0) \tag{6}$$

Therefore the surface wind distribution can be obtained by integrating Eq. (5) instead of solving Eq. (4). This simplification saves the computor memory and machine time.

The results of the numerical experiments are shown in Figs. 8 and 9. Owing to the simplification in the computation scheme, the absolute value of wind speed cannot be compared with the results of the field measurement or model experiment. However, the distributions of strong and weak wind regions seem to be well described even by this simplified method. The greatest discrepancy seen on the result of this numerical experiment is relatively low wind speed on the remaining plateau after cut off as shown in Fig. 10. This is caused from the approximation of neglecting the height of the undulation of topography, which shows the limitation of this assumption in the problem of this kind.

5. Conclusive Remarks

The results of three kinds of approach to find out the topo-meteorological distribu-

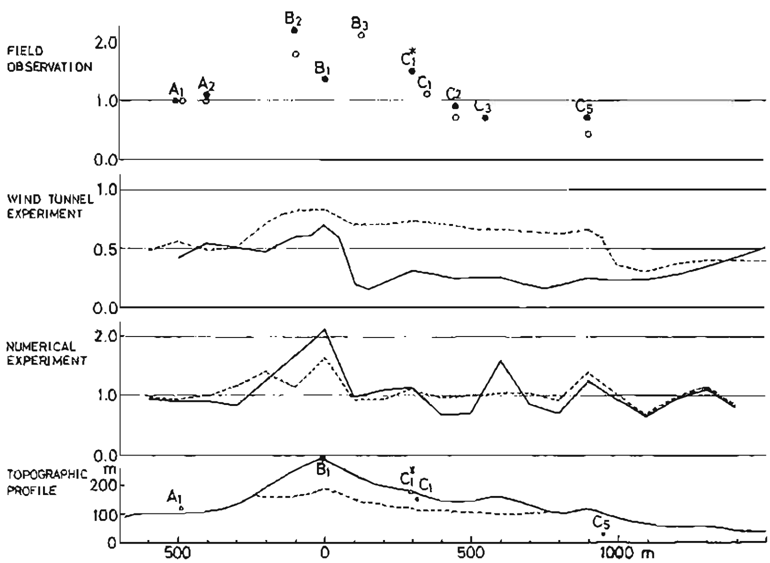

Fig. 10 Comparison of the results of the three kinds of methods for the study of the topographic effects on wind. The value shown as field observation is the relative wind speed to A_1 in W wind shown in Fig. 4. The result of wind tunnel experiment shown here is the relative wind speed shown in Figs. 6 and 7 on the line parallel to the general wind direction passing B_1 point. The result of numerical experiment is the relative wind speed shown Figs. 8 and 9 on the line parallel to the general wind direction passing B_1 point. White circles and solid lines show the states before the works and black circles show those after the hill was cut down.

Table 1 Comparison of the results of the three methods at the points of field observations.

		Genr. Wind Direction	Wind Speed	A_1	A_2	B_1	B_2	B_3	C_1	C_2	C_3	C_4	C_5
Original Topography before Mountain Cut Off	Field Observation	W	Relative to A_1	1.0 W	1.1 NW	1.4	2.2 NW		1.5 —	0.9 S		0.7 S	
		NW	Relative to A_1	1.0 NW	1.1 NW	1.4	1.8 NW		1.0 —	0.9 SW		0.9 —	
	Model Experiment	WNW	Relative to Frict. Free W.S.	0.32 WNW	0.64 WNW	0.77 WNW	0.98 WNW	0.80 WNW	0.22 —	0.20 SW	0.21 WSW	0.34 SW	0.22 SW
			Relative to A_1	1.0	2.0	2.5	2.5	3.1	0.7	0.6	0.7	1.1	0.7
		NW	Relative to Frict. Free W.S.	0.59 NW	0.60 NW	0.92 NW	0.80 NW	0.80 NW	0.31 SE	0.25 W	0.23 N	0.20 N	0.40 N
			Relative to A_1	1.0	1.0	1.6	1.4	1.4	0.5	0.4	0.4	0.3	0.7
	Numerical Experiment	W	Relative to Undist. Flow S.	1.05 W	1.05 W		1.99 W	1.57 W	1.05 W	0.75 W	0.93 W		0.96 W
			Relative to A_1	1.0	1.0		1.9	1.5	1.0	0.7	0.9		0.9
Topography after Mountain Cut Off	Field Observation	W	Relative to A_1	1.0 W	1.0 W		1.8 NW	2.1 W	1.1 NW	0.7 SE			0.4 SW
		NW	Relative to A_1	1.0 NW	1.0 NW		1.6 NW	2.2 NW	1.8 NW	1.1 NW			0.7 SE
	Model Experiment	WNW	Relative to Frict. Free W.S.	0.53 WNW	0.53 WNW		0.80 WNW	0.88 W		0.20 SW	0.20 SW		0.23 WNW
			Relative to A_1	1.0	1.0		1.5	1.7		0.4	0.4		0.4
	Numerical Experiment	W	Relative to Undist. Flow S.	1.09 W	1.07 W		2.07 W	1.56	1.34 W	0.74 W	0.92 W		0.96 W
			Relative to A_1	1.0	1.0		1.9	1.4	1.2	0.7	0.8		0.9

tion of wind near the surface shown in the previous sections are summarized in Table 1 and Fig. 10. Wind distribution is sensitive to wind direction in this hilly terrain as seen in this table. On the whole, the distribution pattern is quite similar to each other in spite of difference of the methods except on the plateau in the numerical experiment. However the detailed values of wind speed are different from method to method, and the quantitative analysis of wind distribution in the hilly terrain is still difficult by the model or numerical simulations of the present methods. Especially more accurate similitude is required for the numerical experiment than the present model for the study of topo-meteorological modification of wind.

In the present study, from the results of field measurement and by the aid of model and numerical experiments it may be concluded that the effect of the hill, which was removed by the present reclamation works, on the wind system in the vicinity is concentrated just near the hill, e.g. within 1 km, and the effect of cut off is not appreciably seen in the lee side town of about 2 km appart. This may come from the fact that the plateau of about 150 m high still remains at the higher level than the town in the windward side and there still remains several small hills which prevent the airflow to pass straightly in the newly made gap above the plateau. These mountain shape was designed in order to minimize the effects of the reclamation works in the lee side town by the wind tunnel experiment as the previous stage of the present study. However, the new residencial area on the plateau is estimated to be a windy place and some wind breaking town planning will be required.

For the establishment of the general method for the estimation of topographical modification of wind system over a hilly terrain, more detailed experiments and theoretical studies are required.

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