CHARACTERISTICS OF AIRFLOW OVER THE BARRIERS IN THE STORM

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SUMMARY

Recently, various kind of structures, such as observatories, radio antennae and electric power lines, are becomming to be constructed on the sites with complex topography. For the design of these structures, knowledges of wind characteristics over irregular terrain are especially important. The results of storm wind observations over the small barriers of about a few kilometers with typical topographic features are presented and the characteristics of airflow over a complex topography are discussed in contrast with wind characteristics over the flat uniform land.

1. INTRODUCTION

Recent increase of social needs requires to construct various kinds of structures, such as observatories, radio antennae, transport facilities and electric power lines, on the site with complex topography. And the recent development of engineering technics has made it possible to construct them. However, the environmental conditions of such a site with complex topography, such as the top of a hill or the mountain gap, are not clear in most cases. Especially, the wind characteristic, which is one of the most important informations for the design purpose, is hardly available. Therefore, the design conditions for use over the flat uniform land are often used, even on the top of the hill with a slite modification of the mean wind speed.

The aim of the present paper is to clear the characteristics of airflow over a complex topography in contrast with those over a flat uniform land.

2. TOPO-METEOROLOGICAL STUDIES OF AIRFLOW

The height domain which is occupied by the man-made structures is normally less than a few hundreds meters from the ground and its horizontal dimension is also about the same size. Thus the knowledge of wind structure in this space volume at the site of interest is required for the design purpose.

The wind structure in such a small scale domain is affected remarkably by the surrounding topographic irregularity with horizontal scale larger than the size comparable to the scale of the space domain under consideration. While the wind above the friction layer, represented by the gradient wind, would not be affected by the small scale topographic features. Therefore there exists a scale domain which is too small to be conceived from the results of observa-

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tions with the existing network of weather stations but is large enough to deform the flow patterns near the surface. In this scale domain, the phenomena are restricted in the friction layer of the atmosphere and the external condition of wind above the friction layer, represented by the gradient wind, is not modified. The new branch of meteorology which deals with the modification of airflow by surface topography in this scale, may be called topometeorology after Schroeder[1].

In the following sections typical examples of topo-meteorological modification of airflow characteristics over the small scale barriers are shown from the results of a series of storm wind observations at various site made by the present author and his collaborators.

3. WIND OBSERVATIONS OVER THE NARUTO STRAITS

The first example is the results of wind observations over the Naruto Straits at the southeastern opening of the Seto Inland Sea of Japan. The general topography of the strait is shown in Fig. 1. Two narrow but bluff capes are streching from the both sides of the channel of about 5 km in width forming a narrow gap of about 1.2 km. The barriers streching from the both coasts are about 60 to 100 m in height from the sea surface. A intensive wind study was made to establish the design criteria for the electric power line crossing this strait where strong wind is expected in the case of typhoon.

Measurement of surface wind distribution was made using more than a dozen of observing points within the area of about 5 km in every typhoon seasons from 1956-1960. The distribution of the design wind speed in the cross section of the strait up to about 200 m was estimated from the results of these observations of the surface airflow. The estimation was checked by the wind measurements on the towers (146 and 115 m in height) of the power line for about five years after the completion of the power line in 1961.

The distribution of stations in the surface network in the former five years are shown in the detailed map of Fig. 2. The area with shade is the part which is higher than 50 m from the sea surface. Most of the stations are installed with cup anemometers at the height of about 6 m from the ground and wind vanes for about a half of them.

In this figure an example of distribution of the observed winds in a typhoon is shown with arrows. The wind speed shown in this figure is one hour mean wind speed. As is clear from this figure, wind is extremely strong in the straits. The station (8) at the point of the eastern cape is lower in height from sea surface than the second one (9) but its wind speed is much larger than that of the second one. Moreover at this point the wind speed at 5 m from the ground (8A) is larger by about 5 % on average than that at 10 m (8B) on the same place as shown in the followings.

The averaged intensification factor of wind speed at each station was computed from the whole data of southeastly strong winds during the typhoon passages and is shown in Fig. 2. The reference wind speed is the value of the station (1) at the entrance of the strait. These factors show the topographic intensification of wind speed at the anemometer level in this strait. Almost the same value of intensifying factor for each station can be also seen for the wind flowing into the straits from the reverse side (NW) but wind from this direction is not so strong as southeasterly wind in the typhoon in this area. While airflow crossing the strait is not affected by the topography of this strait.

These observed facts show that airflow flowing into the strait tends to go horizontally around the cape and to flow into the gap resulting extremely strong wind at the points and in the gap. Of course, some part of airflow goes straight on and passes over the cape resulting relatively strong wind on the ridge. To explain the wind speed distribution in this strait the following simplified procedure was followed. The airflow in the channel of 5 km in width was divided into two parts. One is the purely horizontal flow which flows horizontally and goes around the obstucle and the other is the purely two dimensional flow in the vertical plane and goes straight on crossing over the obstucle without changing its wind direction. The wind speed distribution for each flow can be easily computed assuming potential flow characteristic for the horizontal flow and non-divergent and vorticity conserving flow for the vertical flow. The wind profiles at the entrance and the exit are assumed to be the same as the profile which is expected over the open sea. The proportion of the two two-dimensional flow components in the stormy conditions can be determined to obtain the best fit estimates to the observed intensifying factors at every stations by trial. The value estimated from the factors shown in Fig. 2 is 50 to 50 %. The relative wind speed (relative to the reference wind speed at the reference height of 10 m at the entrance) distribution in the cross section of the gap, thus obtained, is shown in Fig. 3. The maximum expected wind speed distribution can be estimated from these values by applying the maximum expected wind speed over the coastal sea for this area obtained by the traditional method.

The verification of the estimated wind profile was made by the use of the two high towers (shown by cross in Fig. 2) after the completion of the power line. In this case, the air temperature profile was also measured at the eastern tower to test the dependency of the wind profile upon the thermal stability of airflow.

An example of the wind profile obtained during a typhoon passage is shown in Fig. 4 with the estimated wind profile fitted to the wind speed at the top of the tower. Relatively low wind speed at the lowest level of the eastern tower may be caused because the position of the tower is not on the ridge but on the slope a little lee side from the ridge (the height is measured from the ground around the tower). Anyway, the vertical profile is clearly different from the one over the flat land as estimated.

The dependency of the wind profile to wind speed at the top and the stability of airflow is shown in Fig. 5. As is clear from this figure, the wind maximum at the lower level is more clearly seen in low wind speed cases than in the stormy conditions, in which the effect of stability is not so effective. And the maximum wind speed at the lower level increases with decreasing stability. This tendency is quite discrepant from the knowledge over the long extending ridge[2] which shows appearance of low level maximum of wind speed on the ridge in the night time stable current rather than unstable flow. This discrepancy may come from the fact that the stable current is difficult to climb the ridge[3] and tends to go arround the obstacle if there's a way, while less stable current has less difficulty to go up the slope. This explains also the fact that the wind maximum again decreases a little in unstable flow.

4. WIND OBSERVATIONS ON MT. KASATORI

The second example is the results of wind observations near Mt. Kasatori which is in the central part of the main island of Japan. This mountain is on a small mountain range running parallel to the coast line from NE to SW which is about 700 m in height from sea level. The experiment was made at the site on the long straightly extending ridge about 2 km to the southwest from the summit (see Fig. 6). Strong wind from southeast in a typhoon blows perpendicularly to this range and will be intensified on the ridge. The purposes of the study at this site were to clear the turbulent structure of strong wind on the ridge in relation to its micro-structure of topography and the magnitude of wind inclination over the slope and the ridge.

Turbulent Structure— The study of the turbulent structure was made by using eight anemometers installed on the ridge line with about 40 m intervals as shown in Fig. 7 with rough topography. The height of anemometers are about 10 m from the ground. The strongest southeasterly wind was observed during the passage of Typhoon 6718 on August 22, 1967. The characteristics of wind observed at each observing point in the strongest 10 minutes are shown in Table 1. During this period wind was from ESE and is about normal to the ridge. The maximum 10 min mean wind speed observed at the Tsu Weather Station, which is on the upwind side coast of the range, was 15.7 m/sec (E). The mean wind speed observed on the ridge changes from place to place as shown in this table. The averaged value of all points is 28.5 m/sec and is about twice as large as the maximum wind speed on the foot of the range at Tsu. The variation of mean wind speeds may come from the effects of small scale topography near the observational site but no definite relation can be seen from these data. And a wind tunnel experiment is under preparation to clear the problem.

The fluctuation of wind speed at each point was sampled at every 1 sec during this period and the statistics of turbulent character is also shown in Table 1. This table shows that the standard deviation of wind speed is not so different from point to point. Therefore relative intensity of turbulence is small at the point of large mean wind speed. The bottom line of this table shows the characteristics of the line averaged value of instantenuous wind speeds at all points. The standard deviation of line averaged wind speed is about a half of the local value but the gust factor is fairly large and almost the same as the local value.

Fig. 8 shows the power spectra of fluctuations of wind speeds at all points. As is clear from this, the spectra are quite different from place to place. In the spectra of stations A, B and C, a peak of about 100 m in wavelength can be seen, but at D, E, F and G no peaks can be seen in the analyzed frequency range. This shows the turbulent structure of surface wind on the ridge is also affected greatly by the small scale topography and spatial correlation is not so good. This can be seen on the space correlation distributions of 1 sec wind fluctuation shown in Fig. 9, which shows rapid decrease and inhomogeneity in space, and the cospectral correlation with refference to point E, where the strongest wind is observed, shown in Fig. 10. The fluctuations in the low frequency side below 0.05 cps show also small correlations between stations separating more than 40 m or so. This shows that even the lower frequency fluctuations are affected greatly by the small scale topography.

Wind Inclination— On the slope of the mountain, wind flowing across the contour is not horizontal. The inclination of wind is an important factor in the studies of wind effects to some kinds of structure such as the electric power line. A study of wind inclination was made on the windward slope of this mountain range in 1969. The instrumentations used in this study were a set of a bivane and a Aerovane type anemometer on the ridge and a set of a small three cup anemometer and a Gill anemometer on the slope. The topography is shown in Fig. 11 and wind blew from left to right.

The results of the observation are shown in Table 2. The mean inclinations are different for two runs. The value is smaller in stronger wind.

The mean inclination on the slope in the lower wind speed case is almost the same as the inclination of the mountain slope. And even on the ridge, fairly large upslope of wind is seen. This shows the existense of flow separation behide the ridge.

The power spectrum of the fluctuations of horizontal wind speed and wind inclination on the slope in the wind of 7 m/sec are shown in Fig. 12. As is clearly seen from these figures, a large energy peak is seen at about 0.3 cps in the wind inclination spectrum which is not seen in the horizontal component of wind. The peak of this kind may be caused by the topography and has not been seen over the flat land.

5. DISCUSSION

The mountain gap wind in the Gibraltar Straits was studied by Scorer[4]. According to his study, strong wind seen in the Gibraltar Strait is caused by the pressure difference between the both sides of the mountain range. This is different from strong wind in the Naruto Straits. Strong wind of this type is often seen in the gap of large scale mountain range in relatively low external wind condition, and the strong wind is concentrated in the gap. While the intensification of strong wind in the Naruto Straits is caused by the mechanical effects of the topography because it is seen even in neutral stability condition, and the maximum wind speed of this type may be stronger than the former type. The wind study of the same type was made also over the Akashi Straits to the north of the Naruto Straits by the present author, but large intensification like Naruto can not be found. This may be because the width of the Akashi Strait is large (4 km) and surrounding mountains are relatively low.

As is clear from the results of the Kasatori experiment the spectrum of wind fluctuation on the ridge is quite different from that over the flat land and wind characteristics are greatly influenced by small scale mountain topography and fluctuations at two points are less correlated than the case over the flat land. Wind inclination on the slope varies with wind speed and is not zero even on the ridge. And spectrum of wind inclination on the slope shows an apparent peak, which is not seen on the wind speed spectrum, in the high grequency part at about 0.3 cps in the wind of 7 m/sec. These facts shows that application of the design criteria established over uniform flat land to the design of the structure on the hill is dangerous and more detailed studies are required.

ACKNOWLEDGEMENTS

The author is indebted to many colleagues who have helped him throughout the study, and also to Kansai Electric Power Co., Chubu Electric Power Co., and Sumitomo Electric Industry Co. in performing the feild observations.

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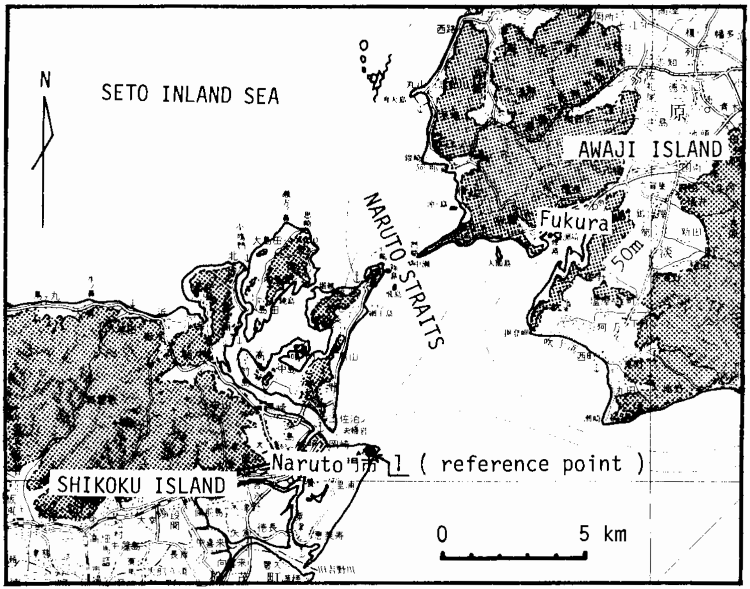


Fig. 1 General topography of the Naruto Straits.

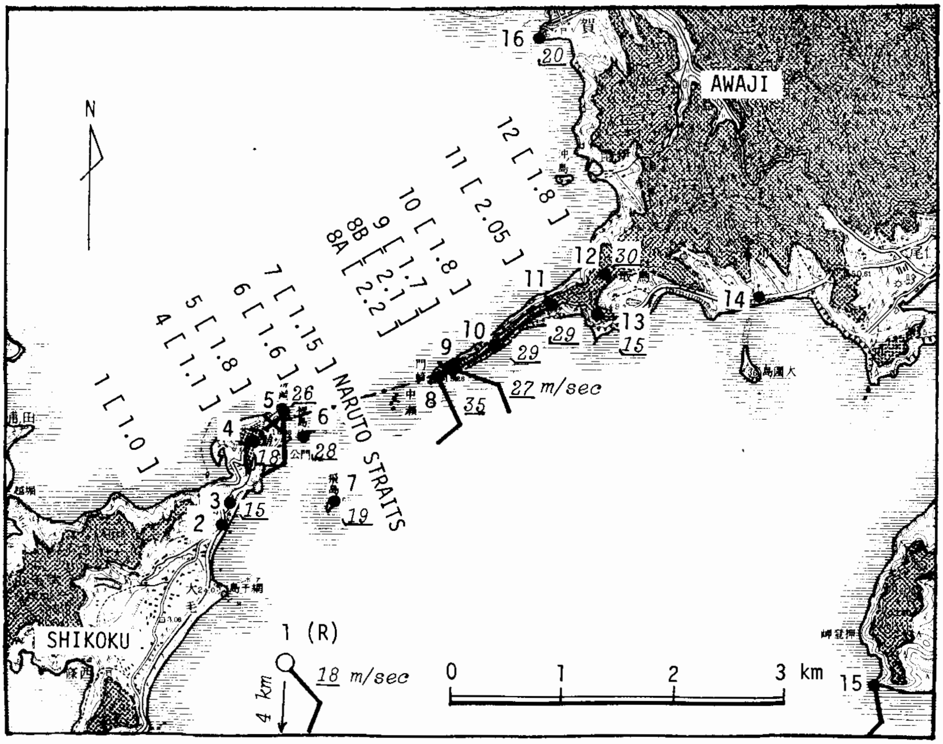


Fig. 2 Detailed map of the Naruto Straits, which shows the distribution of the observing stations. The arrows and numbers in italic show the wind distribution in the strait observed in the Typhoon 6710 at 1600 JST Sept. 7, 1967. The bold figures in the branckets are the intensification factors determined by the observational results of southeasterly storm winds.

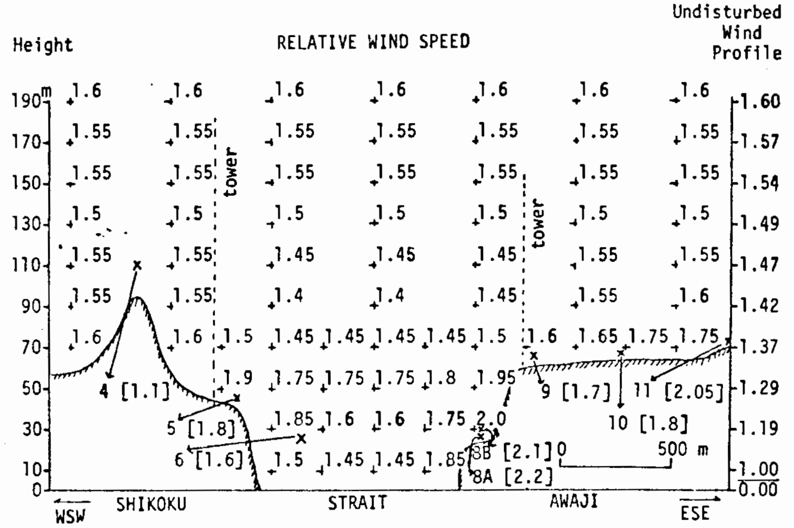


Fig. 3 Distributions of estimated and observed (in the bracket) relative wind speeds in the cross section of the strait.

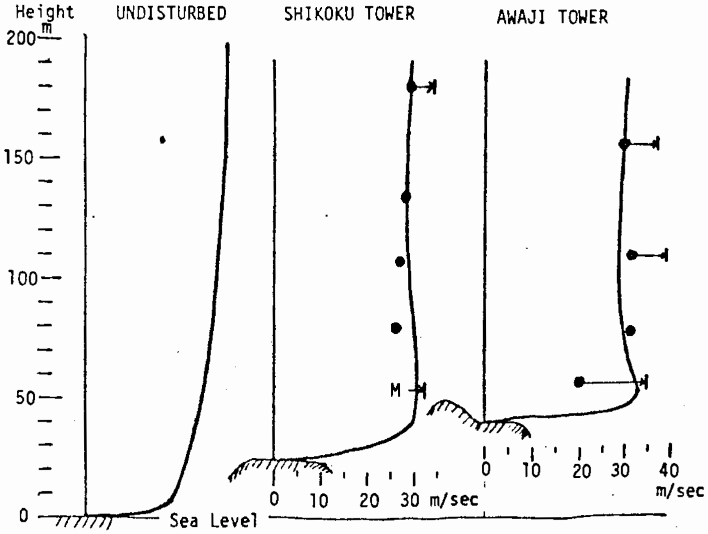


Fig. 4 Estimated and observed wind profiles. The black dot shows mean wind speed and the arrow means peak gust observed in the Typhoon 6414, at 1700 JST Aug. 24, 1964 when wind direction was from southeast.

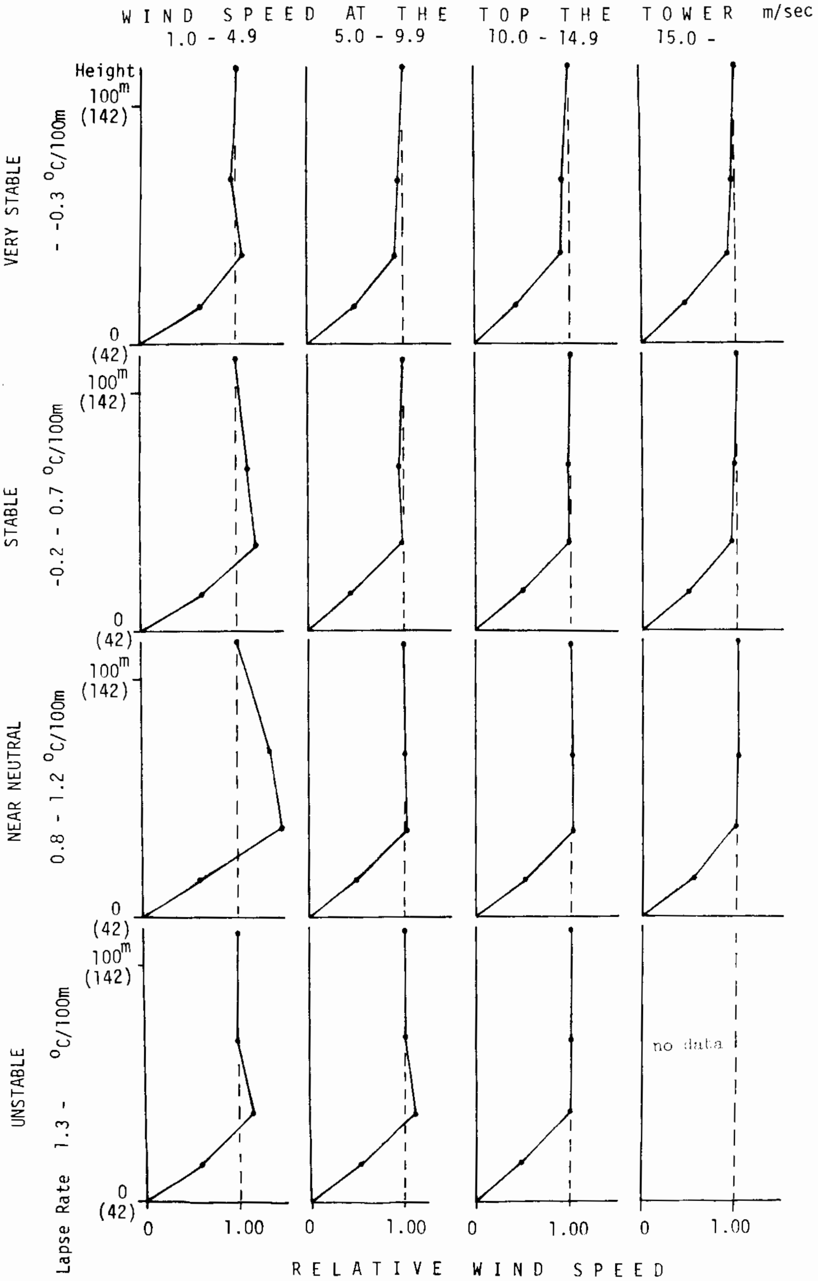


Fig. 5 Dependency of wind profiles at the Awaji Tower on wind speed and thermal stratification of the airflow.

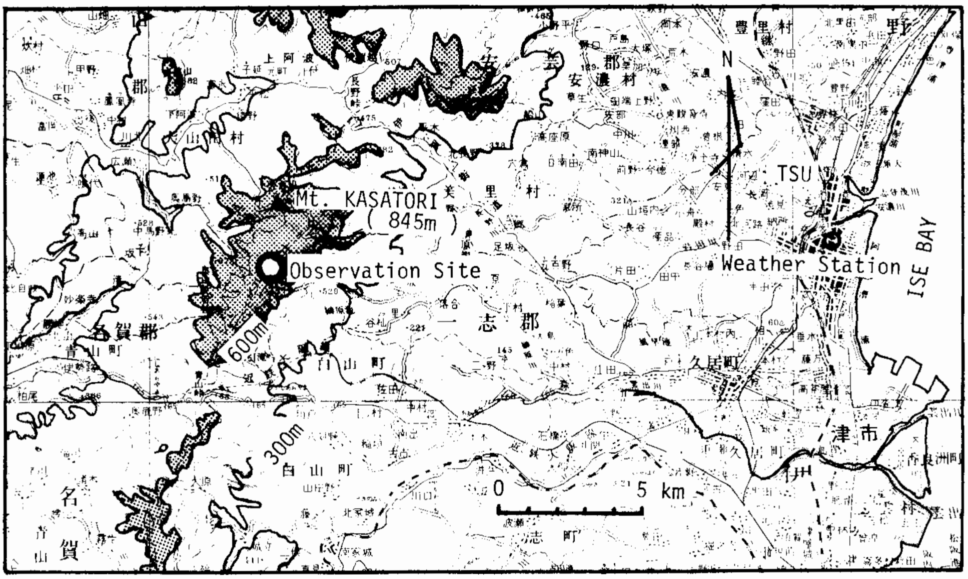


Fig. 6 General topography of Mt. Kasatori.

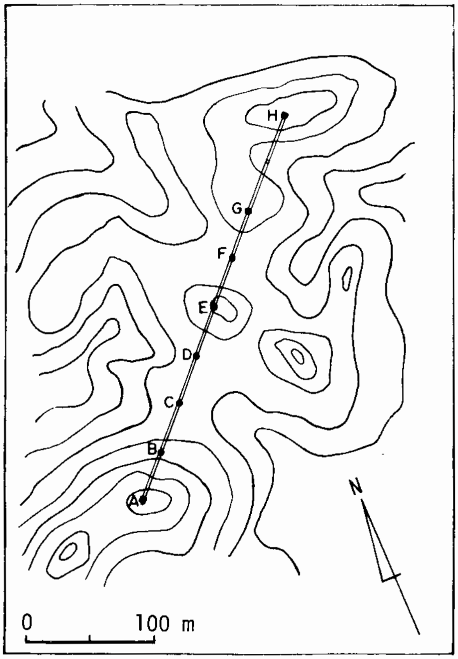


Fig. 7 Distribution of observing points and the surrounding topography. Contour spacing is 5 meters.

Table 1 Characteristics of wind observed on the ridge during Typhoon 6718 on Aug. 22, 1967. Wind was recorded for 10 min in the highest winds and sampled at every 1 sec. Wind direction was from ESE.

OBSERV. POINT	WIND SPEED			INTEN. TURBL.	GUST FACTOR
	Mean	Stand. Dev.	Peak Gust		
	$\overline{V}$	σ_v	V_{max}	$\sigma_v/\overline{V}$	$V_{max}/\overline{V}$
	m/sec	m/sec	m/sec		
H	29.3	6.3	48	0.21	1.6
G	20.7	3.5	32	0.17	1.5
F	36.5	4.6	45	0.13	1.2
E	47.1	4.4	68	0.09	1.4
D	25.6	4.7	39	0.19	1.5
C	13.6	6.4	41	0.48	3.0
B	30.5	5.9	49	0.19	1.6
A	24.4	5.7	39	0.23	1.6
Line Aev.	28.5	2.5	39	0.09	1.4

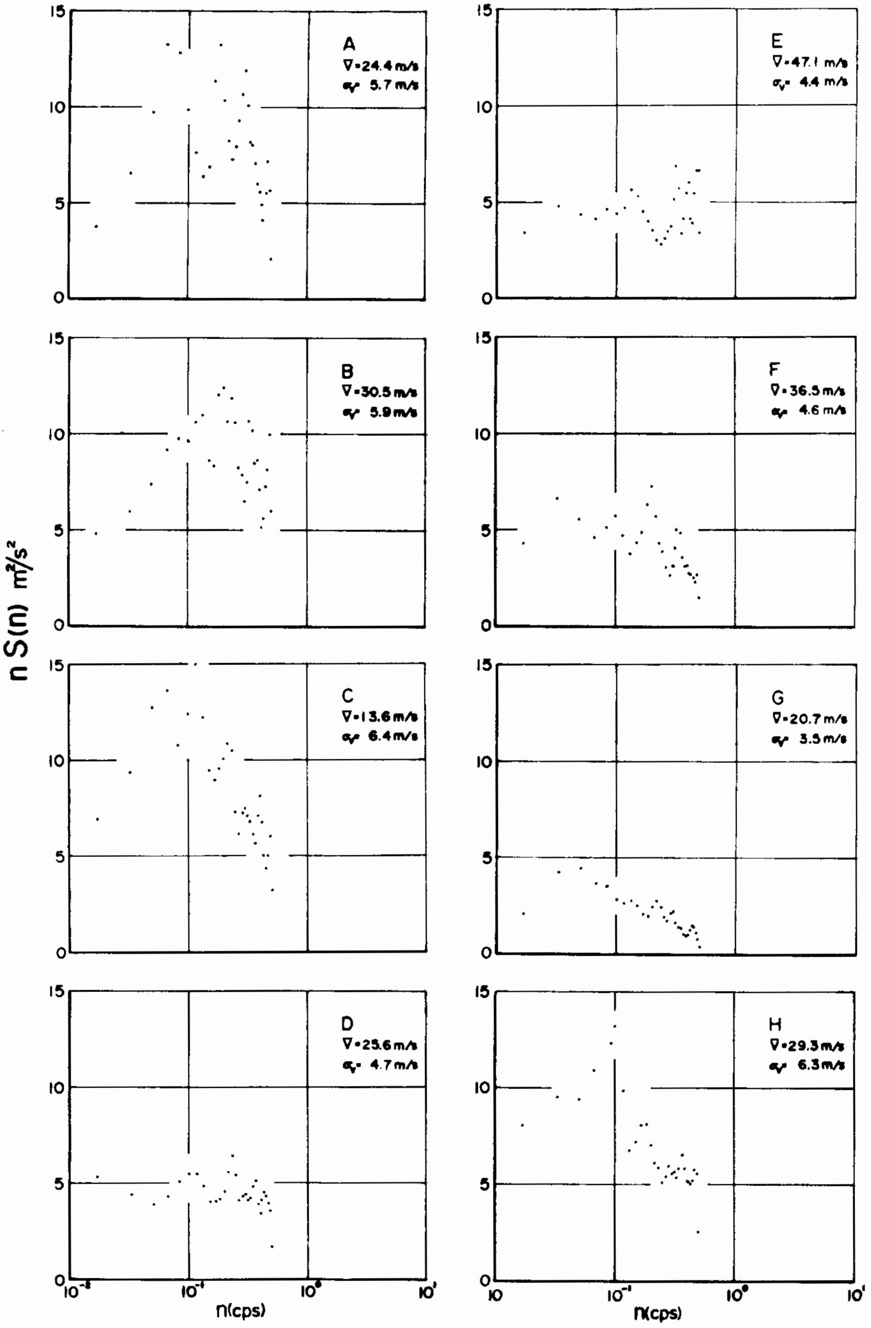


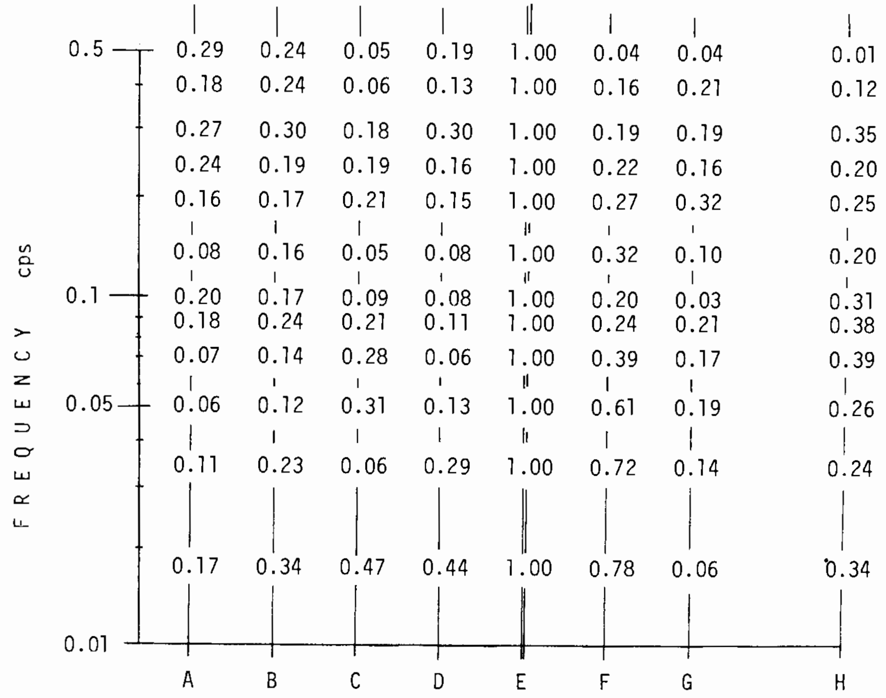
Fig. 8 Power spectra of wind speed fluctuations observed on the ridge during the period shown in Table 1.

	A	B	C	D	E	F	G	H
A	1.00	0.12	-0.04	-0.03	-0.04	0.08	-0.04	0.01
B	0.12	1.00	-0.09	0.09	0.10	----	0.00	----
C	-0.04	-0.09	1.00	0.29	0.13	0.09	0.08	0.15
D	-0.03	0.09	0.29	1.00	0.16	0.20	0.08	0.06
E	-0.04	0.10	0.13	0.16	1.00	0.46	-0.05	0.14
F	0.08	----	0.09	0.20	0.46	1.00	----	----
G	-0.04	0.00	0.08	0.08	-0.05	-0.03	1.00	0.06
H	0.01	----	0.15	0.06	0.14	----	0.06	1.00

A B C D E F G H

←40m→←40m→←40m→←40m→←40m→←40m→←80m→

Fig. 9 Spatial distribution of correlation coeficient of wind speed fluctuations relative to each point.



FREQUENCY cps	A	B	C	D	E	F	G	H
0.5	0.29	0.24	0.05	0.19	1.00	0.04	0.04	0.01
	0.18	0.24	0.06	0.13	1.00	0.16	0.21	0.12
	0.27	0.30	0.18	0.30	1.00	0.19	0.19	0.35
	0.24	0.19	0.19	0.16	1.00	0.22	0.16	0.20
	0.16	0.17	0.21	0.15	1.00	0.27	0.32	0.25
	0.08	0.16	0.05	0.08	1.00	0.32	0.10	0.20
0.1	0.20	0.17	0.09	0.08	1.00	0.20	0.03	0.31
	0.18	0.24	0.21	0.11	1.00	0.24	0.21	0.38
	0.07	0.14	0.28	0.06	1.00	0.39	0.17	0.39
0.05	0.06	0.12	0.31	0.13	1.00	0.61	0.19	0.26
	0.11	0.23	0.06	0.29	1.00	0.72	0.14	0.24
	0.17	0.34	0.47	0.44	1.00	0.78	0.06	0.34
0.01								

Fig. 10 Cospectral correlation distribution with refference to the point E, where the strongest wind was observed.

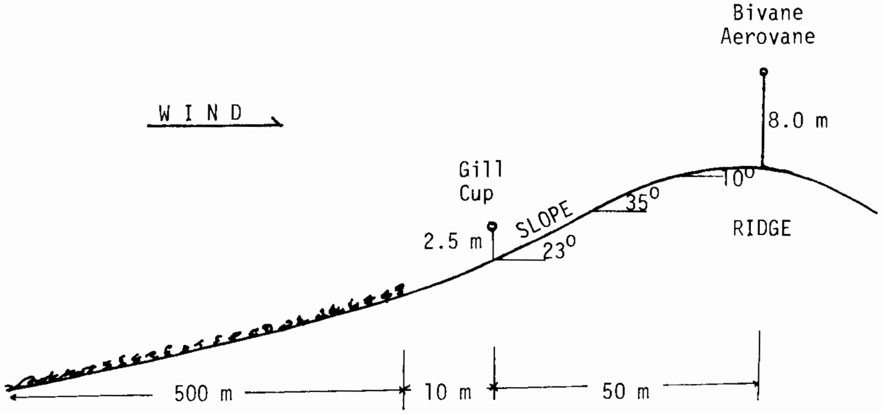


Fig. 11 Cross section of the ridge where wind inclination measurements were made.

Table 2 Results of wind inclination measurements

RUN No. 69 - KaS -			2	S	3
RIDGE	Horizontal Speed	Mean m/sec	4.8		12.8
		Sd Dev m/sec	1.0		1.9
	Inclination	Mean deg	+11.0		+ 4.9
		Sd Dev deg	5.4		0.4
SLOPE	Horizontal Speed	Mean m/sec	4.5	6.7	9.8
		Sd Dev m/sec		5.5	
	Inclination	Mean deg	+22.8	+15.4	+14.2
		Sd Dev deg		5.9	

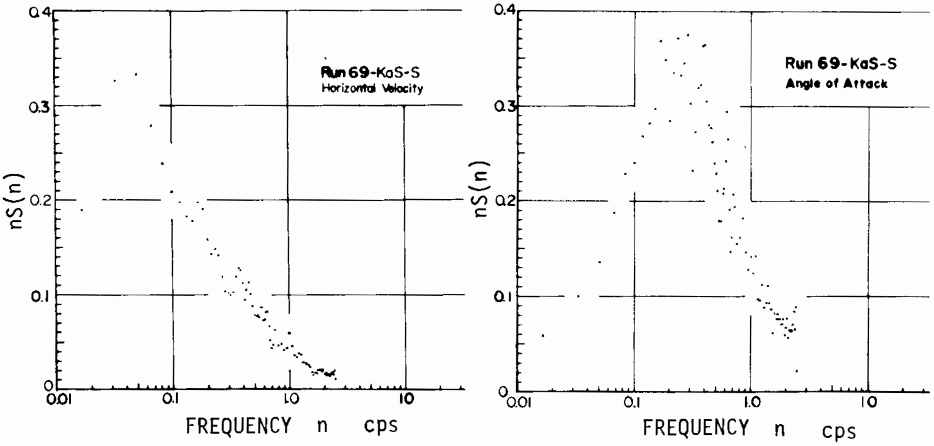


Fig. 12 Spectra of horizontal wind speed (left) and wind inclination (right) observed at the height of 2.5 m on the slope.