WECS SITE SCREENING BY PHYSICAL MODELING

by

Robert N. Meroney*

Presented at

Conference and Workshop on Wind Characteristics
and Wind Energy Siting

June 19-21, 1979

Portland, Oregon

May 1979

CEP78-79RNM34

*Professor, Fluid Mechanics and Wind Engineering
Colorado State University

WECS SITE SCREENING BY PHYSICAL MODELING

Robert N. Meroney

Fluid Mechanics and Wind Engineering Program
Colorado State University
Fort Collins, Colorado

1.0 INTRODUCTION

This paper summarizes the results of a physical modeling program to study the interaction of wind and topography. The program's primary purpose was to provide information of use to wind-power site selection; however, the results will also be of interest to those involved in architectural planning, wind loading on buildings, forest blowdown, ballistics, or snow drifting.

The purpose of this research was to improve techniques for predicting wind velocities over ridges and hills in general as well as evaluate the efficacy of site specific model structures over complex terrain. Section 2.0 suggests the appropriate time and space domain for physical model experiments when preparing a WECS siting strategy. Section 3.0 discusses the program to determine local wind profiles and turbulence over two and three dimensional hills or ridges as influenced by hill or ridge profile, upwind surface roughness, stratification, hill slope or aspect ratio, and downslope hill configurations, which influence separation or reattachment. Sections 4.0 and 5.0 review results from field/laboratory programs for Rakaia Gorge, New Zealand, and Kahuku Point, Oahu, chosen to evaluate the validity of laboratory simulation methods and to provide a confidence bound for laboratory data.

2.0 PHYSICAL MODELING STRATEGY

The physical model method consists of obtaining velocity and turbulence measurements over a scale model of selected terrain placed in a simulated atmospheric flow. The wind characteristics of the simulated flow are chosen to reproduce the wind profile shape and length scales of the equivalent prototype situation. Since field profiles are rarely available in advance, velocity profiles and turbulence characteristics are chosen to fit an equivalent class of conditions as recorded by earlier investigators over terrain of similar roughness.

The viability of a given simulation scenario is not only a function of the governing flow physics but the availability of a suitable simulation facility and the measurement instrumentation to be employed. It would seem appropriate, therefore, to suggest bounds for the range of field situations which can reasonably be treated by physical modeling. When one combines operational constraints into a performance envelope, a picture appears of the performance region for typical wind tunnel facilities. Figure 1 is such a performance envelope prepared for a large 3 x 4 m cross-section boundary-layer wind tunnel. Limiting criteria include model size, instrument resolution, scales of simulated turbulence, and minimum acceptable Reynold's number. Assuming an upper value of length scale of 6,000 and a useable tunnel length of 5 meters, a distance of 10 km is well within the capacity of existing facilities to contain in the windward direction.

The joint consideration of time and space scales modeled in such meterological wind tunnels can be overlaid upon the characteristic time and horizontal scales of atmospheric phenomenon. Wind events are rarely stationary and independent for more than a few hours; hence, the flow field measured over a scale model resembles the character of an ensemble of equivalent field measurements averaged over time periods of the order of one to several hours. One can, however, synthesize the average statistics of a flow field over larger periods by associating a given measurement set with a recurring meteorological situation for which climatological probability distribution information is available. Two resultant domains in time and space for which physical modeling can provide WECS siting information are displayed on Fig. 2.

3.0 WIND CHARACTERISTICS OVER RIDGES AND HILLS

Given a location to erect a WECS system the user is concerned as to whether:

- the local terrain modifies wind speed data gathered at some other nearby location, or
- the local terrain intensifies the turbulence environment the WECS hardware must experience.

A series of measurements of flow over hill models has been conducted to investigate the effect of terrain features on the mean wind flow and turbulence.

Measurements have been made of wind speed, turbulence intensity, static pressure, skin friction, and spectra over a number of generic two-dimensional model hill shapes. Measurement techniques are described in Meroney et al. (1976a, 1976b, 1977) and Bouwmeester et al. (1978). Data are tabulated in detail in Meroney et al. (1976b), Bouwmeester et al. (1978), and Rider and Sandborn (1977a) for neutral stratification situations. Additional measurements over a set of six different model hill shapes are described by Rider and Sandborn (1977b). A set of measurements associated with stratified flow over two-dimensional model hills are archived in Meroney et al. (1978b). Three-dimensional flow field data over symmetric cone and Gaussian shaped model hills are tabulated by Chien et al. (1978). An evaluation of the WECS siting significance of all two-dimensional measurements are contained in the report by Bouwmeester et al. (1978).

3.1. Mean Wind Speed Behavior

Speedup of the wind is highest for ridge slopes that just avoid flow separation. Separation just upwind or downwind of the crest causes reduction of the minimum static pressure over the hill surface and lower wind speeds. Figures 3a and 3b show the dramatic changes in velocities and static pressures over symmetric triangular ridges which result from flow separation. No separation occurs for the ridge defined by $h/\delta = 0.1$, $h/L_u = h/L_d = 1/4$; whereas, flow separation occurs for the ridge defined by $h/\delta = 0.1$, $h/L_u = h/L_d = 1/3$.

Flow separation over triangular ridges depends primarily on upwind and downwind hill slopes. Based on a series of measurements of flow over triangular hills with alternate upwind and downwind slopes the domain for flow separation has been identified as noted in Fig. 4. A round-crested hill results in flow separation downwind of the crest. The results obtained for the triangular ridges are, therefore, somewhat conservative if applied to round-crested hills. Essentially identical downwind separation regions are obtained for an uniform approach velocity profile and for values of $h/\delta = 0.1$ to 0.3. Flow separation may occur for more gentle upwind slopes if the upwind surface roughness is less than that over the ridge or if the flow has stable stratification.

The effect of detailed ridge shape on the velocity field has been investigated by comparing flows over symmetric triangular models with those developed over sinusoidal-shaped ridge models but with the same slope, h/L. Almost identical velocity fields were measured. Flow over alternate hill shapes with the same height and with the same distance from crest to the foot of the hill were compared. The models included full sine wave, half-sine wave, triangular, trapezoidal, and box shaped hills. Hills with similar average slope had similar velocity perturbations.

A methodology was developed to predict mean velocities above a ridge crest. The factorial increase in velocity is defined by an amplification factor $A(z) = \bar{u}_c(z)/\bar{u}_o(z)$, where $\bar{u}_c$ are crest velocities and $\bar{u}_o$ are upwind velocities at a similar height above ground. The amplification factor may be determined from

$$A(z) = A(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\frac{1-A(h)}{2.3}} \qquad (1)$$

where A(h) is to be calculated iteratively from the transcendental expression

$$A(h) = 1 + \frac{2.3}{\log_e\left(\frac{z_{ref}}{h}\right)} \log_e\left(\frac{A(h)}{A(Z_{ref})}\right), \text{ and} \qquad (2)$$

$A(z_{ref})$ is determined from site measurements where $z_{ref} > 0.067\, z_o^{0.1} L^{0.9}$. Alternatively, when $z_{ref} = h$, then A(h) may be estimated from Fig. 5. To correct for variations in approach flow power law exponent let

$$A(h,\alpha_o) = A(h,\alpha_o')\frac{1.15 + \alpha_o}{1.15 + \alpha_o'}, \qquad (3)$$

where $\alpha_o' = 0.13$.

Equations (1), (2), and (3) deviated from wind-tunnel data by less than five percent. Bradley (1978) recently measured wind flow over a heavily wooded hill in Australia. A comparison between predicted and measured amplification factors, given no reference crest velocities, leads to an average error of 15 percent. Given a reference amplification factor at heights above the inner layer ($z_o > 0.067 z_o^{0.1} L^{0.9}$), errors are less than five percent.

3.2 Turbulence Behavior

When air passes over a hill, the turbulence structure is distorted causing Reynolds stress gradients different from those upwind. Generally the longitudinal turbulence intensity increases toward the base of a hill, then decreases over the crest. The vertical turbulence intensity shows a decrease at the base of the hill and an increase over the crest. For hills where $h/\delta < 2h/L_u$ (short hills) the changes in turbulence do not interact with the mean velocity profile to produce any significant perturbation; hence the flow behaves in an inviscid manner. Prediction models based on an inviscid approximation by Derrickson and Meroney (1977) or Astley (1977) reproduce the flow fields measured over model hills very accurately.

Directional redistribution of the turbulent kinetic energy along a hill streamline is the most significant turbulence phenomenon observed. The frequency distribution of turbulent energy and the probability density function of the velocity fluctuations change only slightly. The turbulence flatness factor at the crest increases slightly indicating that extreme high or low values are less likely.

4.0 WIND CHARACTERISTICS AT RAKAIA GORGE, NEW ZEALAND

New Zealand and the United States have a common WECS siting problem. The are both geographically complex, contain many potentially attractive wind power sites, and yet in many such areas of complex terrain there are "meteorological data" deserts. Once such area is the Rakaia River Gorge region on the eastern slope of the Southern Alps in New Zealand. Climatological records obtained from stations somewhat removed from the area suggest moderate to very high wind energy. Local farmer and fishermen wisdom and folklore speak of incredible winds in the gorge canyon. Extended field measurement programs are invariably expensive and time consuming; hence, a survey program was proposed to utilize laboratory simulation of the relevant wind characteristivs in a meterological wind tunnel. To evaluate the validity of laboratory simulation methods and provide a confidence measurement bound for laboratory data, a simultaneous limited field measurement program was organized.

4.1 Wind Tunnel and Field Experiment

The area studied by means of a laboratory model is located along the Rakaia River as it emerges from the Southern Alps, South Island, New Zealand. The primary terrain features consist of the Rakaia River Gorge which runs generally in a northwest-southeast direction. Gorge walls rise 180 meters, surrounding hills rise to 460 meters. To the south lies the Mount Hutt range which climbs to 2188 m. The range parallels the course of the Rakaia River in this area. To the north lies the Rugged Range, but nearby Fighting Hill and Round Hill are the largest features. A model section 6100 m wide by 18,300 m long centered over the Rakaia River Gorge was constructed to a scale of 1:5000. The hill sides to either side of the Rakaia River are primarily devoted to sheep paddock. To protect flocks and paddock surface during the high wind event, farmers have planted shelterbelts around most fields. Most of these shelterbelts are mature coniferous tree stands about 20 m high. Pipe cleaner shelterbelts were added to the model to simulate the prototype vegetation.

The Rakaia River Gorge model was studied in an Atmospheric Boundary Layer Wind Tunnel at the University of Canterbury, Christchurch. Laboratory measurements include horizontal and vertical profiles of mean wind velocity, longitudinal turbulence, wind direction, turbulence spectra and correlations utilizing hot wire anemometry, pitot-static pressure probes, and cobra pressure probes.

Measurements of wind velocity and directions were desired over the Rakaia River Gorge test region to provide a basis for validation of laboratory methodology and physical modeling. Ideally, a network of permanent meteorological instruments would be installed on multiple towers with data recording equipment versatile enough to intercept and record a northwesterly wind event. The cost of capitalization and maintenance of such a network was, unfortunately, prohibitive. An alternative proposed was to place a simple, lightweight cup anemometer on each of several collapsible pole towers and to move the towers frequently during a wind event. The effectiveness of such a procedure will depend upon spatial correlation of wind velocities over the same 100 square km region, the quasi-stationarity of the wind event over a 3 to 6 hour period, and the statistical significance of a 15 minute sample at a given point taken once during a 3 to 6 hour recording period. Recent climatological analysis by Corotis (1977) suggest high correlation (0.76 - 0.83) over distances less than 22 km and autocorrelation time constants from 3.5 to 7 hours.

On two spring days, selected for strong adiabatic down valley wind flow, three teams of investigators surveyed up to 27 sites on either side and within the river gorge. Measurements consisted of wind speed and direction at a 10 meter height on lightweight portable towers. All measurements were completed during the course of a five hour stationary wind event and normalized against continuous records taken from a new Zealand Wind Energy Task Force anemometer near terrain center.

4.2 Results and Conclusions

A series of contour diagrams were prepared from the laboratory velocity and turbulence intensity measurements into isotach and isoturb charts. A wide variation in wind speed near ground level existed between points within the gorge and the nearby hill top. Simultaneously, large relative gustiness existed within the river gorge when compared to the hill crest. Horizontal sections prepared for a 10 meter equivalent height revealed the river valley and gorge consistently had lower wind energy than the surrounding ridges as shown in Fig. 6.

The laboratory simulation results were compared with the available field data by means of statistical correlation and scatter diagrams. The model and field results were used to assess the value of the laboratory experiemnts for assisting WECS siting field programs.

Specific results and conclusions resulting from this research are

1. Physical modeling can reproduce wind patterns produced by the atmospheric shear layer flowing over complex terrain to within the inherent variability of the atmosphere to produce stationary results;
2. Physical modeling reproduced the relative wind speeds found over complex terrain by rank to sample correlation coefficient levels equal to 0.78 to 0.95;
3. Physical modeling reproduced the individual day to day quantitative wind speeds found over complex terrain to sample correlation coefficient levels equal to 0.70 to 0.76;
4. Physical modeling reproduced the two field day average quantitative wind speeds found over complex terrain to a sample correlation coefficient level equal to 0.81;
5. Physical modeling reproduced the individual day to day site wind directions found on complex terrain to sample correlation coefficient levels equal to 0.65 to 0.67;
6. Adequate physical modeling of adiabatic shear flow over complex terrain requires attention to surface roughness, terrain shape, and vegetation as well as upstream velocity profile, turbulence intensity, and turbulence eddy structure.
7. Over complex terrain local wind speeds may vary by over 100% in a distance of a few hundred meters as a result of terrain shadowing, flow separation, or flow enhancement;
8. In the Rakaia River Gorge area preferred WECS locations are the surrounding hills and ridges, and not the gorge or river bottoms.

5.0 WIND CHARACTERISTICS AT KAHUKU POINT, OAHU

Tropical islands such as Oahu, located in the persistent trade wind belt and adorned with ridges and hills which accelerate the surface winds, are attractive locations for WECS machines. The Kahuku Point pennisula on northern Oahu has good exposure and annual mean wind speeds near 8 m/sec (18 mph). Lindley (1977) has proposed a WECS farm for the locality capable of generating 450 Megawatts. The Department of Meteorology, University of Hawaii, proposed an extensive field program in this area; hence, a parallel laboratory program was prepared to extend the measurement domain in the vertical and to survey additional sites.

5.1 WIND TUNNEL AND FIELD EXPERIMENT

The area studies by means of a laboratory model is located along the northeast end of the Koolau Range on the island of Oahu, Hawaii. The primary terrain features consist of a fan-shaped set of ridges opening to the north from the mountain ridge itself. The trade wind approaches most of the year from the East or Northeast and passes over sparsely vegetated abandoned cane fields and shrub covered foothills. A model section 12,730 m in diameter centered over the northern end of the mountain ridge was constructed to a scale of 1:3840. Graded gravel was added to the model surface to represent orchards and forested areas noted on maps from a land use survey.

The Kahuku model was examined in the Environmental Wind Tunnel, Colorado State University. Laboratory measurements include a series of vertical profiles of mean wind velocity, longitudinal turbulence, and turbulence spectra utilizing hot wire anemometry for three different wind directions.

Field measurements were performed by the University of Hawaii in the fall of 1978 utilizing a series of mobile vans equipped with 10 meter telescoping masts. Vans were parked at a series of measurement sites for periods ranging from several days to several weeks. Wind speed and wind direction at 10 meters above the local ground surface were recorded on a standard magnetic cassette tape recorder. Humidity and solar insolation at cab height were also recorded. Each tape was subsequently analyzed by computers at University of Hawaii to provide average wind speed, wind direction at different wind speeds, and wind direction all referenced to a site located at Opana, a flat-topped hill at the northern end of one of the minor ridges extending seaward from the northern Koolau Range. The hill falls away rather steeply toward the flatcoastal belt. Local exposure is good toward the northeast.

5.2 Results and Conclusions

A series of vertical profiles of amplification factor, A, were prepared from the laboratory velocity measurements over typical Kahuku survey sites. These factors have been compared against the prediction formula proposed in Section 3.1 as well as the average field average amplification factor for wind speeds in excess of 10 mph at the 10 meter height.

The model data and calculational technique consistently agree. The model data and field data agree to simple correlation coefficient levels equal to 0.55. If field data are eliminated from the comparison that have abnormally high turbulence levels, that include approach wind directions outside the range of 45° to 90°, or for which a site visit suggested strong influence at 10 m of nearby vegetation, the sample correlation coefficient equals 0.79.

6.0 ACKNOWLEDGEMENTS

Financial assistance was provided by Department of Energy Contracts EG-77-S-06-1043 and EY-76-S-06-2438, a Fulbright Hays Travel Grant, and an Erskine Lectureship at the University of Canterbury

7.0 REFERENCES

Astley, J. (1977),"A Finite Element Frozen Vorticity Solution for Two Dimensional Wind Flow Over Hills," Proceedings of 6th Australian Hydraulics and Fluid Mechanics Conference, 1977, Adelaide, Australia, December 5-9, pp. 443-446.

Bouwmeester, R.J.B., Meroney, R.N., Sandborn, V.A. (1978), "Sites for Wind Power Installation, Final Report Part I: Wind Characteristics Over Ridges," Colorado State University Technical Report CER77-78RJBB-RNM-VAS51, 223 p.

Bradley, E.G. (1978), "An Experimental Study of the Profiles of Wind Speed, Shearing Stress and Turbulence at the Crest of a Large Hill," Division Environmental Mechanics, CSIRO, Canberra, Australia.

Chien, H., Meroney, R.N., Sandborn, V.A., and Bouwmeester, R.J.B. (1978), Preliminary Measurements of Flow Over Model, Three Dimensional Hills," Colorado State University Research Memorandum No. 29, CEM-77-78HCC-RNM-VAS-RJBB29, 34 pp. (This report is included in Meroney et al. (1978b)).

Corotis, R.B. (1977), "Stochastic Modeling of Site Wind Characteristics," Department of Civil Engineering, Northwestern University, DOE Report ERDA/RLO/2342-77/2, 143 pp.

Derickson, R.G. and Meroney R.N. (1977), "A Simplified Physics Airflow Model for Evaluating Wind Power Sites in Complex Terrain," Proceedings of Summer Computer Simulation Conference, July 18-20, Chicago, Illinois, 14 pp.

Lindley, C.A. Melton, W.C. (1977), "Wind Energy Systems Application in Hawaii", Proceedings of the 3rd Biennial Conference and Workshop on Wind Energy Conversion Systems," September 19-21, Washington, D.C., Vol. I pp. 237-250.

Meroney, R.N., Sandborn, V.A., Bouwmeester, R.J.B., Chien, H.C., and Rider, M. (1978a) "Sites for Wind Power Installations, Final Report Part II: Executive Summary," Colorado State University Technical Report CER77-78RNM-VAS50a.

Meroney, R.N., Sandborn, V.A, Bouwmeester, R.J.B, Chien, H.C., and Rider, M. (1978b) "Sites for Wind Power Installations, Final Report Part II: Appendix", Colorado State University Technical Report CER77-78RNM-VAS50b.

Rider, M.A. and Sandborn, V.A. (1977a), "Boundary Layer Turbulence Over Two Dimensional Hills," Colorado State University Technical Report, CER77-78MAR-VAS4, 125 pp. (This report is included in Meroney et al. (1978b)).

Rider, M.A. and Sandborn, V.A. (1977b), "Measurements of the Mean and Longitudinal Velocities Over Varying Hill Shapes," Colorado State University Research Memorandum CEM77-78MAR-VAS28, 30 pp. (This report is included in Meroney et al. (1978b)).

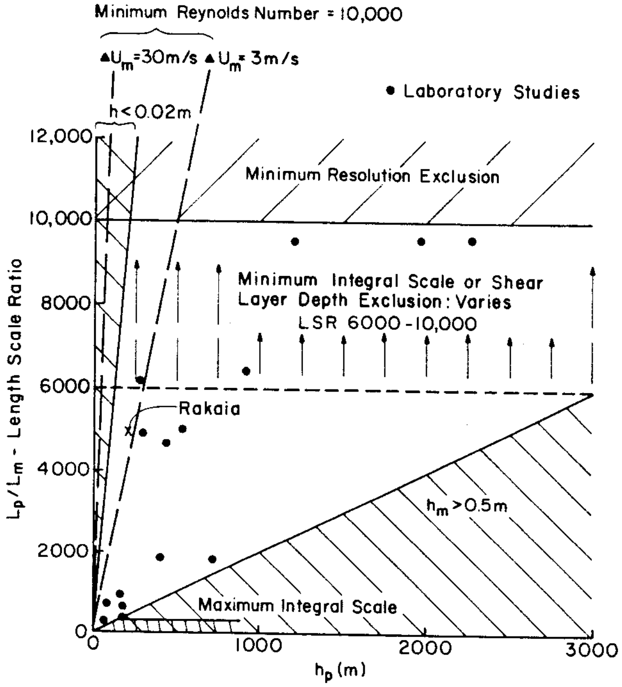
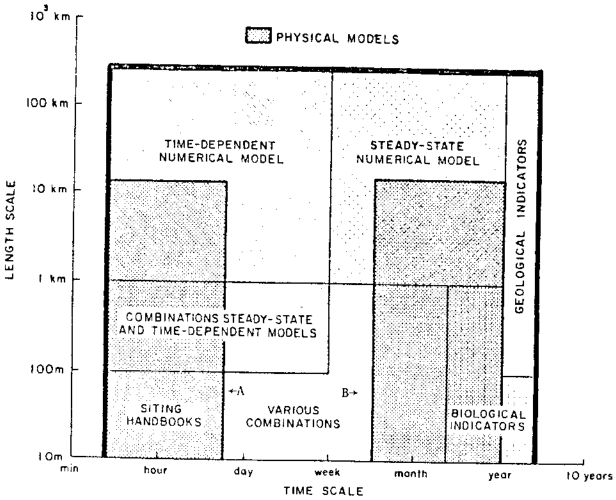


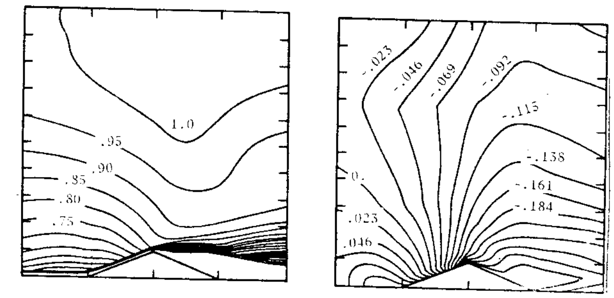
Fig. 1. Performance Envelope for Physical Modeling of Shear Flows Over Complex Terrain



A. Results During a Single Meteorological Episode

B. Results Averages and Weighted by Probability Density Distributions

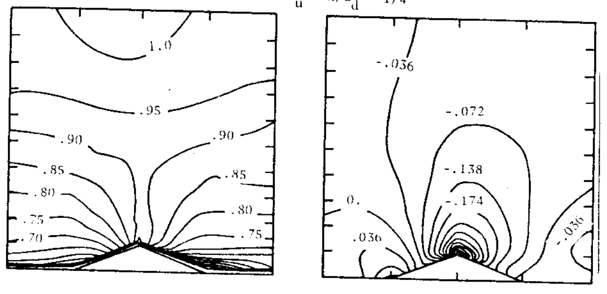
Fig. 2. Physical Modeling Domain Among Time and Space Scales for WECS Site Selection



a) Velocity contours, h/L_u = 1/3 contour interval $\Delta u/u_\infty(\delta)$ = .05

a) Static pressure contours h/L_u = 1/3 Contour interval ΔC_p = .023

h/δ = .1, h/L_u = h/L_d = 1/4



b) Velocity contours h/L_u = 1/4 interval, $\Delta u/u_\infty(\delta)$ = .05

b) Static pressure contours h/L_u = 1/4 contour interval, ΔC_p = .036

h/δ = .1, h/L_u = h/L_d = 1/3

Fig. 3. Mean Velocity and Static Pressure Contours Over Triangular Hills

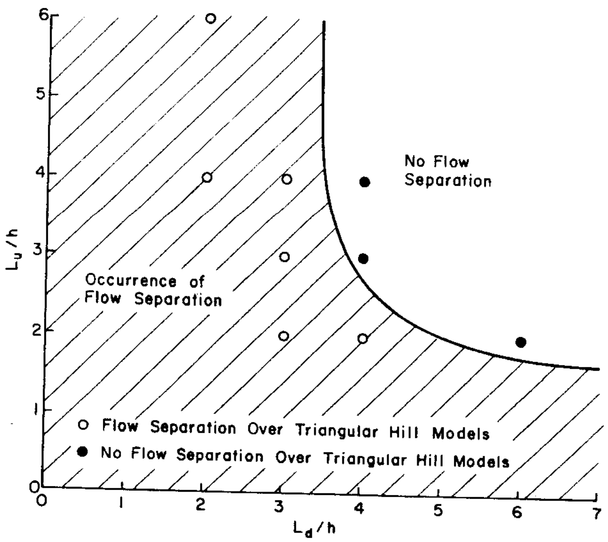


Fig. 4. Criterion for Flow Separation Over Ridges

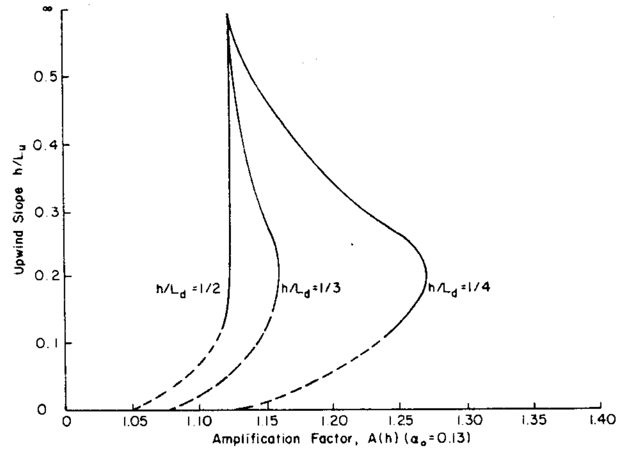


Fig. 5. Dependency of Crest-Amplification Factor on Upwind Slope for h/L_d = 1/2, 1/3, and 1/4

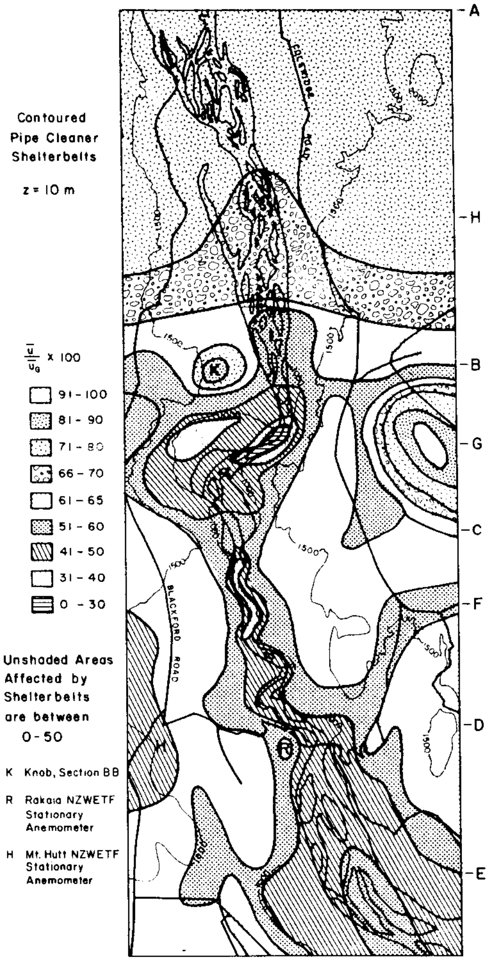


Fig. 6. Horizontal Isotachs, Contoured Model, z_p = 10 m. Rakaia Gorge, New Zealand