PHYSICAL MODELING OF FLOW OVER COMPLEX TERRAIN

by

Robert N. Meroney*

D. Lindley**

A. J. Bowen***

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*Professor, Civil Engineering, Colorado State University
**Taylor Woodrow Construction Ltd., U.K.
***Senior Lecturer, Mechanical Engineering,
University of Canterbury, New Zealand

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SUMMARY

Physical simulation of wind regimes found over complex terrain offer significant advantages in terms of time, expense, and control of independent variables. The viability of such an approach has been examined by a consideration of inherent physical modeling constraints together with a joint field verification/laboratory simulation study of air flow patterns over complex terrain in the Southern Alps of New Zealand.

1. INTRODUCTION

Meteorologists are increasingly faced with problems requiring quantitative estimates of air flow patterns and turbulence characteristics over complex terrain. Use of the wind information includes air pollution zoning, prediction of smoke movement from forest fires or slash burning, mine tailing dispersal calculations, estimation of the movement of vegetation disease vectors or pests, and the siting of wind powered electrical systems. In view of the extreme difficulties in obtaining practically useful results in this area of meteorology over complex terrain, whether by theoretical analysis or field investigation, it is natural to explore the possibilities of simulating the flow over irregular terrain by means of physical model experiments on the laboratory scale. Similitude criteria and previous laboratory case studies have been reviewed by Meroney et al.[1] This paper considers the results of a joint field/wind tunnel simulation program which has been completed for a mountain valley/river gorge region in New Zealand.[2]

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*Professor, Civil Engineering, Colorado State University
**Taylor Woodrow Construction Ltd., United Kingdom
***Senior Lecturer, Mechanical Engineering, University of Canterbury, New Zealand

2. SIMULATION BY PHYSICAL MODELS

The basic tool of laboratory simulation is similitude or similarity, defined as a relation between two mechanical (or flow) systems (often referred to as model and prototype)* such that by proportional alterations of the units of length, mass, and time, measured quantities in the one system go identically (or with a constant multiple of each other) into those in the other. In order that the flow in any laboratory model should be of value in interpreting or predicting the observed flow in the atmosphere, it is essential that the two flow systems should be dynamically, thermally and kinematically similar. This means that it must be possible to describe the flow in the two systems by the same equations after appropriate adjustments of the units of length, time and other variables.

A number of authors including Cermak (1966, 1975),[3,4] McVehil et al. (1967),[5] Bernstein (1965),[6] and Snyder (1972)[7] have derived the governing parameters for atmospheric heat, mass, or momentum transport by dimensional analysis, similarity theory, and inspectional analysis. Another group justify similitude by considerations of turbulence theory and recent reviews of full scale wind data which present the characteristics of the prototype atmospheric wind on a parametric basis (Nemoto (1961, 1962),[8] Counihan (1969, 1973),[9,10] Cook (1977),[11] and Melbourne (1977)).[12] Although all investigators do not agree concerning details, most would concur that the dominant mechanisms can now be identified and are understandable.

The laboratory method thus 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 atmospheric flow are

*Prototype--actual airflow involving full scale
Model--airflow involving smaller scale than prototype but usually with geometrically similar boundaries

chosen to reproduce the wind profile shape and length scales of the equivalent prototype situations. 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. With few exceptions, scientists seem to make rather poor prophets; there is always the danger of what Arthur Clarke (1958)[13] calls "failures of nerve" or "failures of imagination." Nevertheless, let us propose limitations of simulation for complex terrain.

A number of boundary layer wind tunnels exist at various laboratories. Generally these tunnels range in size from facilities with cross-sections of 0.5 m x 0.5 m to 3 m x 4 m. Several of these facilities are equipped with movable side walls or ceilings to adjust for model blockage. By utilizing a variety of devices such as vortex generators, fences, roughness, grids, screens, or jets a fairly wide range of turbulence integral scales can be introduced into the shear layer. Varying surface roughness permits control of surface turbulence intensity, dimensionless wall shear, and velocity profile shape. Density stratification can be induced by means of heat exchangers, use of different molecular weight gases, or latent heat adsorption or release during phase changes.

When one combines various operational constraints into a performance envelope, a clear picture appears of the performance region for wind tunnel facilities. Figure 1 is such a performance envelope prepared for a large facility such as the Environmental Wind Tunnel at Colorado State University. The criteria selected to specify operational ranges are:

Maximum model height $h \leqq 0.5$ m

Minimum convenient model height $h \geqq 0.02$ m

Minimum Reynolds number $Re_h = \frac{U_o h}{\nu} \geqq 10{,}000$

Maximum model integral scale $L_{u_x} \leq 0.5$ m

Minimum model integral scale $L_{u_x} \geq 0.05$ m

Minimum model measurement resolution $\Delta z \geq 0.1$ mm

Maximum model boundary depth $\delta \leq 2$ m

Minimum model boundary depth $\delta \geq 0.1$ m

Since field values for some parameters are uncertain, the prototype values of δ and L_{u_x} are assumed to range as follows over complex terrain

$300 \text{ m} < \delta < 1000 \text{ m}$, and

$100 \text{ m} < L_{u_x} < 1000 \text{ m}$.

Not all previous laboratory studies meet such similitude restrictions, some experiments were performed to meet other objectives than similitude of turbulence or mean velocity profiles; nevertheless almost all cases noted fall within the indicated operational envelope or just outside the predicted region.

Based on Coriolis force considerations, Snyder (1972)[7] suggests a 5 km cut-off point for horizontal length scales for modeling diffusion under neutral or stable conditions in relatively flat terrain. Mery (1969)[14] suggests a 15 km limit, Ukejurchi et al. (1967)[15] suggest 40 to 50 km, and Cermak et al. (1966)[2] and Hidy (1967)[16] recommend 150 km. A middle road would be that of Orgill et al.

(1971)[17] who suggest for rugged terrain in high winds that a length scale of 50 km is not unreasonable.

Assuming an upper value of length scale ratio of 10,000 and a tunnel length of 25 meters, a distance of 50 km is well within the capacity of existing facilities to contain in the windward direction. Assuming a lateral width restriction of 4 m suggests a 40 km lateral maximum for the field area modeled.

3. LABORATORY MEASUREMENT PROGRAM

New Zealand and the United States are both geographically complex, face similar applied meteorology problems, and yet in many such areas of complex terrain there are "meteorological data" deserts. One 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 suitable for wind energy conversion system sites. 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 characteristics in a meteorological 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.

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 an undistorted scale of 1:5000.

A contoured model constructed of polystyrene bead-board was examined for three separate surface roughness conditions--a surface textured to represent typical paddock grass roughness only ($z_o \simeq$ 0.15 m), the same surface with zero porosity surface shelterbelts added, and the same surface with porous shelterbelts added. The total model length was 7.3 meters. A 2.5 cm high trip fence and a square bar turbulence grid were placed upwind of the model to produce the desired approach wind similitude characteristics. The Rakaia River Gorge model was studied in an Atmospheric Boundary Layer Wind Tunnel at University of Canterbury, Christchurch, New Zealand.

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. The tree stands often consist of several rows and appear quite dense. Aerodynamic studies of flow fields behind shelterbelts in New Zealand have been performed by Sturrock (1972).[18] Measurements behind 4 mm high yarn and pipe cleaner wind breaks revealed they simulate the velocity and turbulence field for 1:5000 scale very well.

Figures 2 and 3 compare the velocity defect and turbulence excess measured behind such shelters with full scale behavior. Pipe cleaner shelterbelts were added to the model to simulate the prototype vegetation. Laboratory measurements included horizontal and vertical profiles of mean wind velocity, longitudinal turbulence, wind direction. turbulence spectra and correlation utilizing hot wire anemometry, pitot-static pressure probes, and cobra pressure probes.

4. FIELD MEASUREMENT PROGRAM

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 is to place a simple, lightweight cup anemometer on each of several collapsible pole towers and 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)[20] suggest high correlation (0.76 - 0.83) over distances less than 22 km and autocorrelation time constants from 3.5 to 7 hours. The criteria for a field station were thus light weight, rapid erection, and low cost.

Three masts were constructed of 5 cm diameter thin wall aluminum tube. The tubes were made in two 5 meter sections which could be connected via a simple sleeve joint. Three nylon rope ties were attached at 7.5 m to the upper section and when erected the ties attached to three steel stakes driven at convenient distances from the mast base. The three cup RIMCO anemometers were attached to the top of the mast by a threaded fitting. A 3 lead supply and signal cable led from the anemometer to a power supply and counter module placed at the base of the mast. The entire system was conveniently light and easy to handle. It could be carried on the luggage rack of a passenger car or in the back of a jet boat. Two or three men could erect the tower in 5 minutes and remove it in somewhat less time.

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 fixed anemometer near model terrain center.

5. RESULTS AND CONCLUSIONS

A series of contour diagrams were prepared from the laboratory velocity and turbulence intensity measurements into isotach and isoturb charts. Figures 4 and 5 show a typical pair of such drawings. Note the wide variation in wind speed near ground level between points within the gorge and the nearby hill top. Simultaneously large relative gustiness exists within the river gorge when compared to the hill crest. Horizontal sections prepared for a 10 meter equivalent height (Figure 6) reveals the river valley and gorge consistently has lower windspeed and greater gustiness than the surrounding ridges.

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 experiments for predicting wind over complex terrain. A thorough search of the literature reveals that few authors have chosen to compare field and model (either numerical or physical) results in other than qualitative terms. Recently Fosberg et al. (1976)[21] compared a numerical model which includes terrain, thermally, and frictionally induced perturbations against seven field data sets. Correlation coefficients determined for the velocity and direction results were 0.60 and 0.62 respectively. These limited results may be used as a context within which to judge the efficacy of the present physical model or as a statement of reasonably current alternative modeling capacity. A typical scatter diagram result is shown in Figure 7. Plotted on the scatter diagram are the co-correlation lines of the result of regressions of abscissa against ordinate and ordinate versus abscissa. When $r = \pm 1$ these lines will be colinear, when $r = 0$ the lines will be perpendicular. The lines thus provide visual evidence of the quality of correlation. Correlation between equivalent field measurements at the same sites taken on independent days were $r = 0.68$. This suggests that there may be an inherent limitation to the replication of any single realization of a wind flow pattern by any synthetic model whether physical or numerical.

It would appear that the conventional simulation wisdom developed in the past few years is appropriate for physical modeling of flow over complex terrain. Since the flow region of interest is usually in the lowest surface layer ($z < 100$ m) for Wind Energy Conversion Systems siting, great care must be taken that horizontal inhomogenuities in roughness and terrain are faithfully reproduced. Specific conclusions suggest that:

1. A wide range of scales and meteorological conditions may reasonably be simulated in existing boundary layer wind tunnel facilities; (See Performance Envelope).

2. To produce equivalent wind speeds near ground level require accurate reproduction of surface roughness, shape, and vegetation.

Hence terraced models, adequate for certain dispersion simulations, are not appropriate for Wind Energy Conversion Systems site analysis; and

3. Current meteorological data in complex terrain is not yet adequate to stipulate inflow conditions to either numerical or physical models with confidence. Hence an adequate approach flow length must be provided to allow the surface layer to come to an equilibrium with underlying terrain undulations.

4. 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.

5. 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.*

6. 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.

7. 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.

8. 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.

9. 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.

10. 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.

6. ACKNOWLEDGEMENT

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*These numbers are somewhat sensitive to the sites chosen to normalize and compare model to field results.

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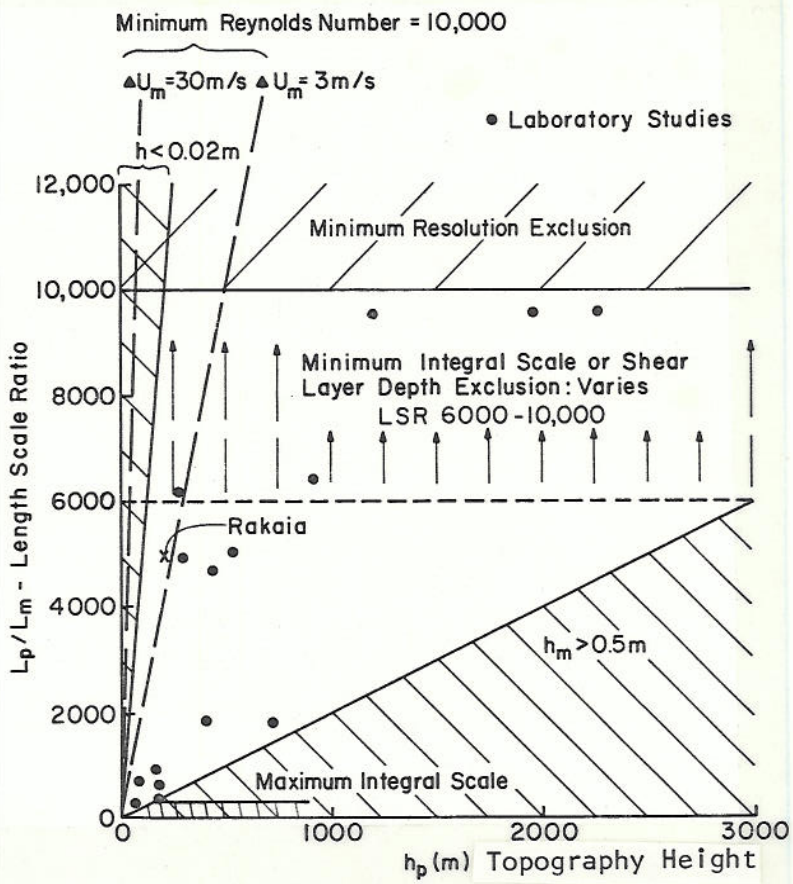

Figure 1. Performance Envelope for Physical Modeling of Shear Flows Over Complex Terrain

SYMBOL	z/H	H/z_0	H/Lu_x	H/δ	SHELTERBELT
□	2.50	450	0.05	0.04	YARN
○	1.25	450	0.05	0.04	H ≃ 4 mm
△	0.50	450	0.05	0.04	———
(horizontal hatching)	0.50	40→ 100	0.17	—	RAINE (1977) (WIND TUNNEL-20%)
(vertical hatching)	0.07→ 0.125	500	0.10→ 0.13	—	STURROCK (1971) (FIELD)

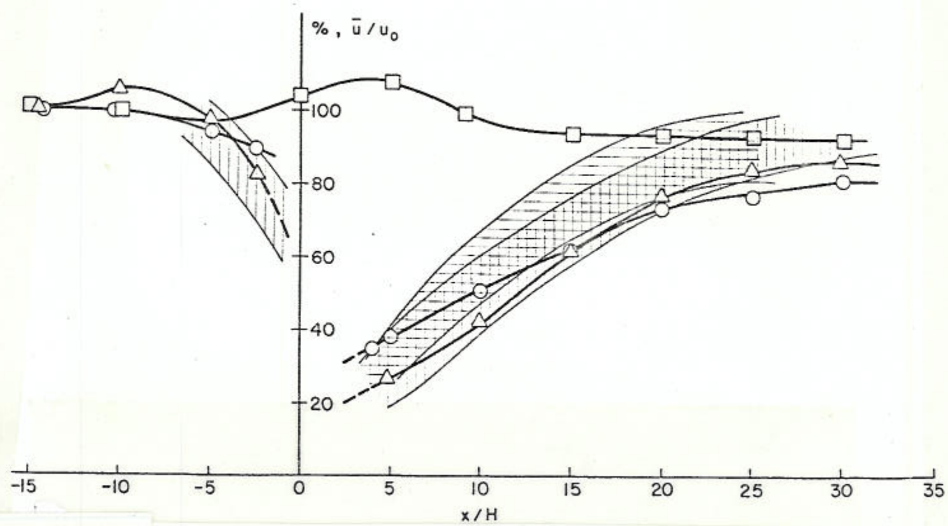

Figure 2. Comparison of Wind Shelter Produced by Yarn Barriers With Typical New Zealand Shelterbelt Behavior.

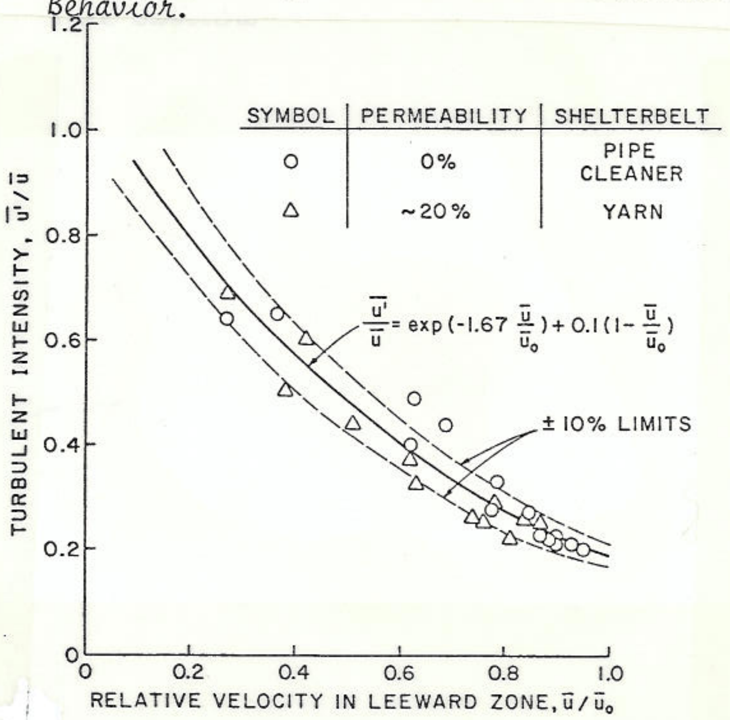

Figure 3. Correlation of Turbulent Intensity and Relative Velocity Behind Model Shelterbelts. Solid line--Proposed by Raine and Stevenson (1977)[19]

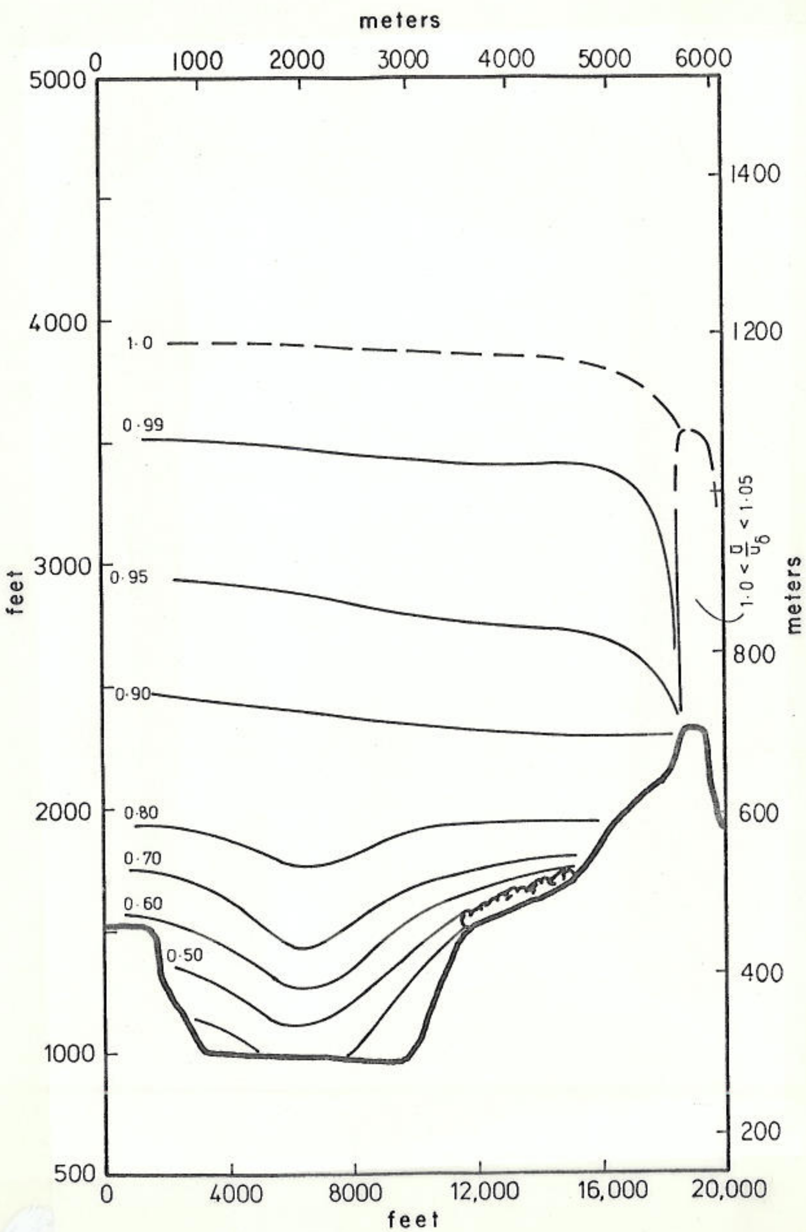

Figure 4. Typical Vertical Section Isotachs

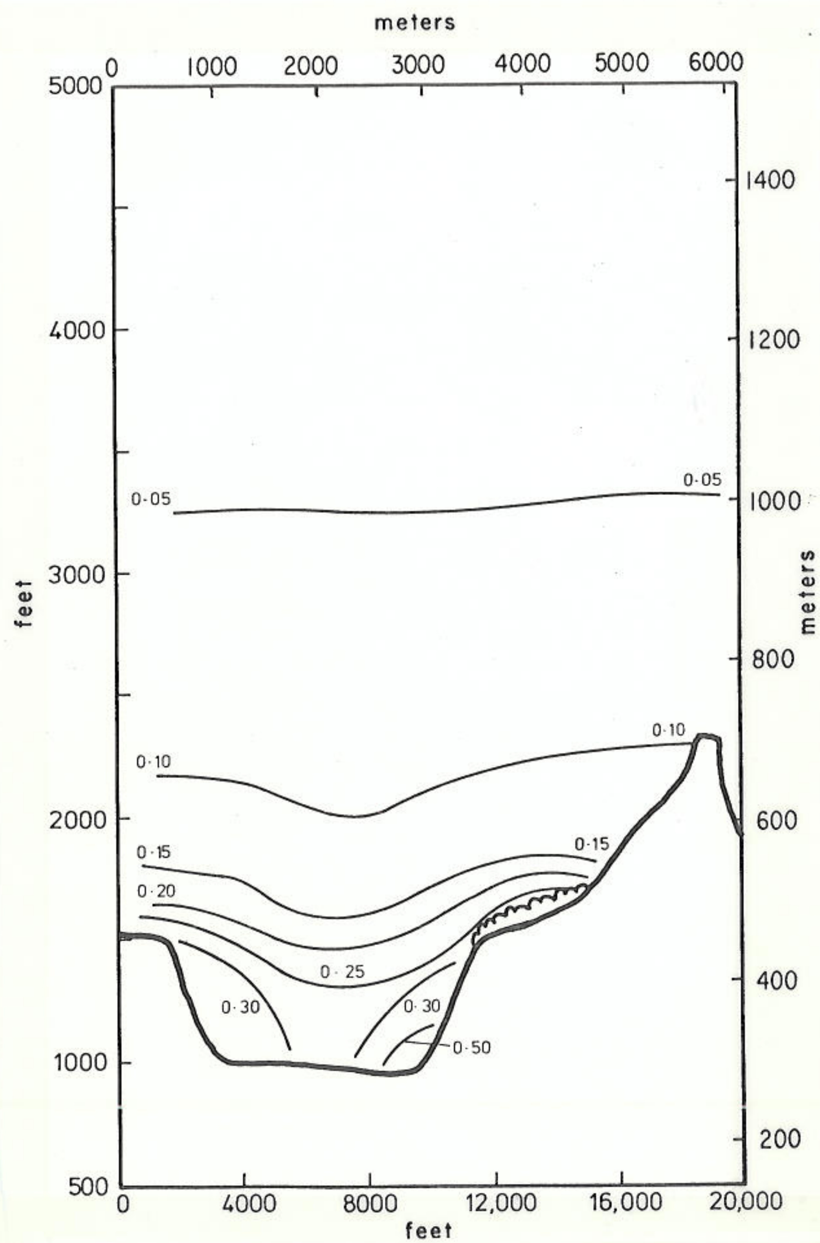

Figure 5. Typical Vertical Section Isoturbs

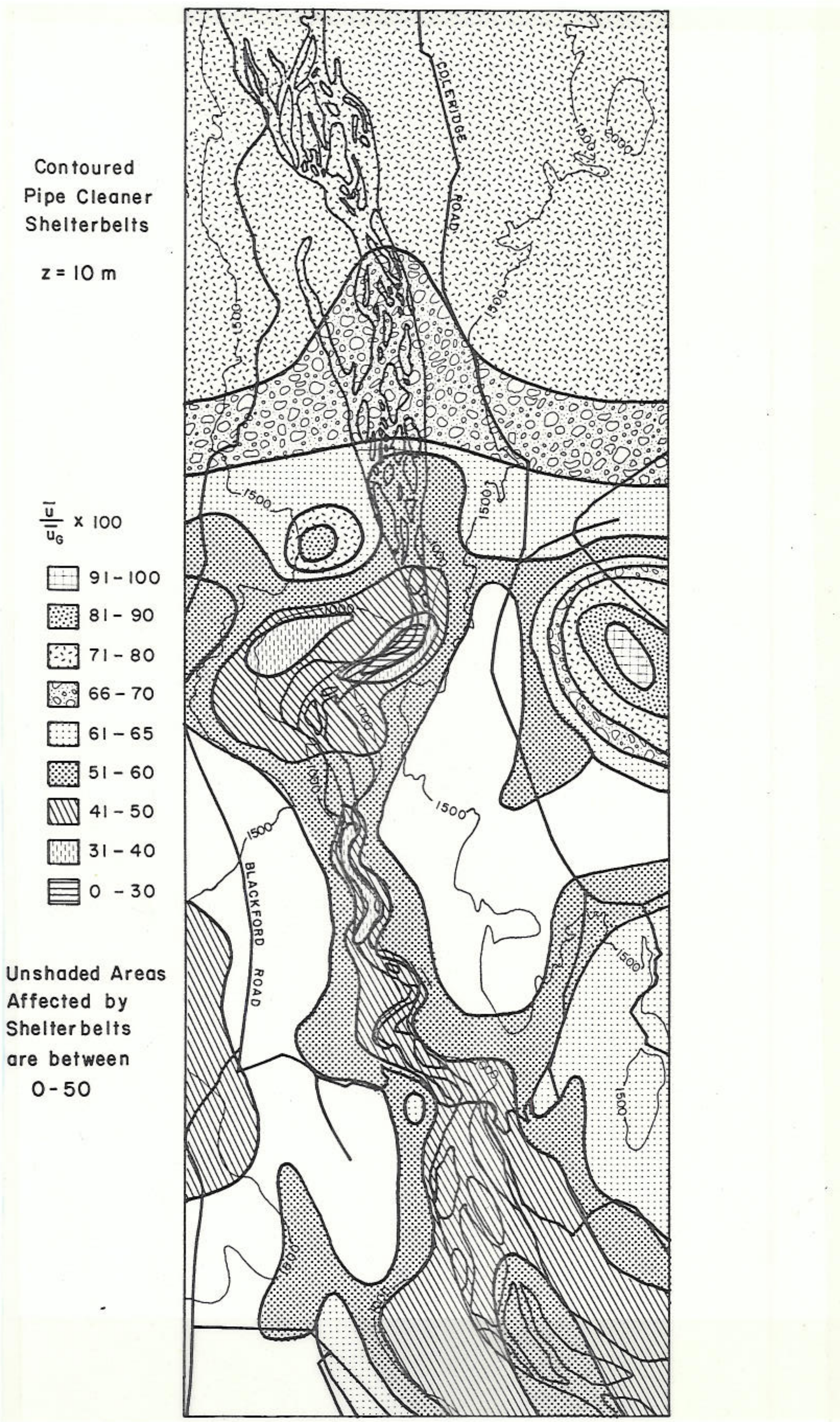

Figure 6. Horizontal Isotachs, Contoured Model, $z_p = 10$ *m. Rakaia Gorge, New Zealand*

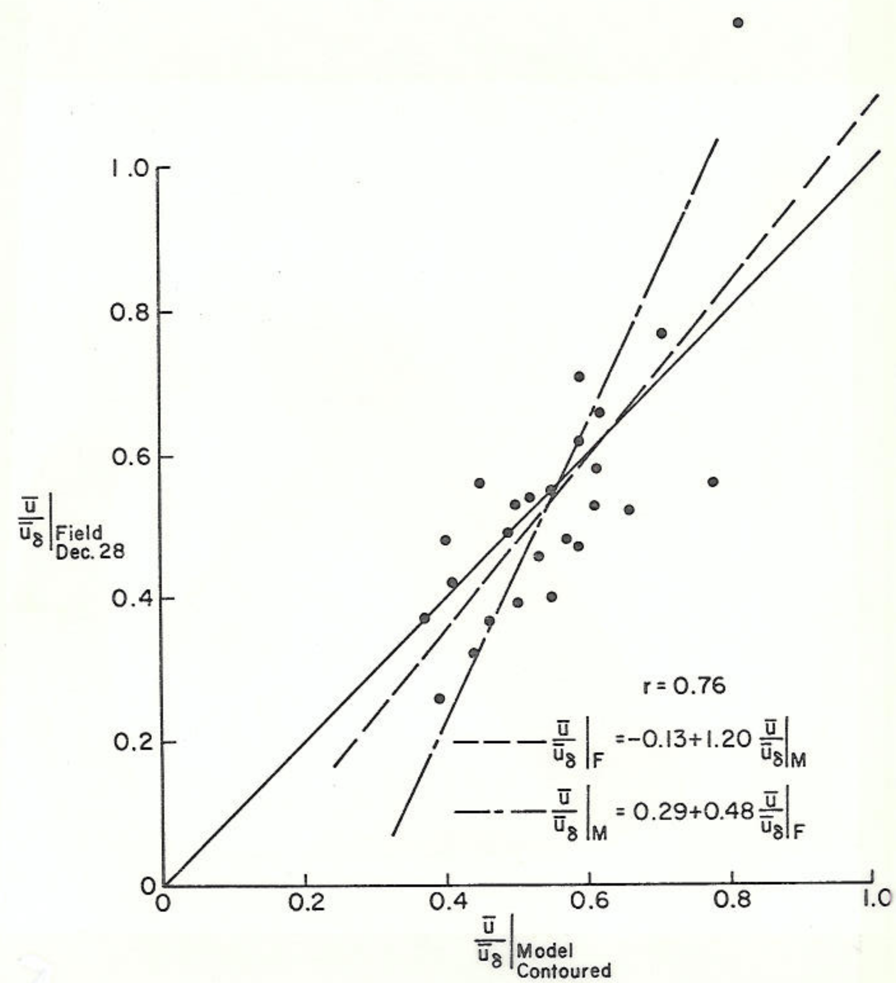

Figure 7. Scatter Diagram Field Test Data, December 28 Versus Contoured Model Data