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WIND TUNNEL SIMULATION OF THE INFLUENCE OF TWO DIMENSIONAL RIDGES ON WIND SPEED AND TURBULENCE

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Summary

The objective of this research was to increase technical capacity to locate favorable wind system sites, reduce uncertainty in the prediction or validation of the characteristics of sites, and thus assist in the sizing and performance prediction of wind systems. The research included evaluation of low speed aerodynamics over terrain and boundary flow conditions over ridges by means of modelling and analytic techniques.

Past experience with large power mills indicates that perhaps the single most important factor controlling success or failure of these systems is site selection! Incorrect placement of a site of only a few miles may drop performance to 1/5of the original expectations. The difference between the power available in an annual average wind of 10 mph versus 12.5 mph is 100 percent.

Measurements have been completed over triangular and sinusoidal shape hills of wind speed, static pressure variation, turbulence intensity, wall shear, and wind deflection. Hill aspect ratios studied range from 1/2 to 1/6 with some data available at 1/20. Measurements of wind overspeed, streamline patterns, and turbulence changes over the topography are compared with results from boundary layer theory and rapid distortion theories. Large overspeed effects over the hills are found for the shear layers investigated.

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Nomenclature:

α	- velocity power law coefficient for approach velocity profile.
C_p	- pressure coefficient - $(p-p_o)/q$
$E_u(k)$	- spectra energy content of longitudinal velocity
$f(x/L)$	- component shape of hill or ridge
h	- height of ridge or escarpment
L	- half-width of ridge
p	- static pressure
p_o	- static pressure for upstream of ridge at z = 10h
q	- dynamic pressure $\frac{1}{2}\rho u_o{}^2$
Re	- Reynolds number - $\rho\frac{hu_o}{\nu}$
Re_h	- (add subscript $_h$ to Re presently in list of nomenclature)
S	- speed up factor $u(\tilde{z})/u_o(\tilde{z}+\frac{hf}{L})$
ΔS	- fractional speed up factor $(u(\tilde{z})-u_o(\tilde{z}))/u_o(\tilde{z})$
u, v, w	- horizontal, lateral, and vertical mean velocity
u', v', w'	- horizontal, vertical, and lateral velocity fluctuations
$\sqrt{\overline{u'^2}}/u$	- local horizontal turbulence intensity
u*	- local friction velocity
u_o	- horizontal velocity far upstream of ridge
x, y, z	- horizontal, lateral, and vertical co-ordinates
$\tilde{x}$	- x/L
$\tilde{z}$	- (z-hf)/L
z_o	- roughness length
ΔS	- model boundary layer thickness
ν	- kinematic viscosity of air
ρ	- density of air
τ	- shear stress - $\rho\overline{u'v'}$

INTRODUCTION

Information on the general wind characteristics of a geographical region is a prerequisite for considering the utilization of wind power at a site. Climatological data gathered at area weather stations (usually located at flat open terrain near airports) will often provide information concerning wind speed, duration, return time, turbulence, etc., over a number of years. However, if the area in which wind power installations are to be made includes hilly country, an obvious desire is to choose sites on or near the top of hills or ridges, to take advantage of the faster moving stream of air which results from compression of streamlines near the summit. Thus, it is important to be able to correlate wind behavior approaching a hill and the hill topography with the character of flow over the hill.

Recognition of site selection importance has led to a series of monographs and papers on this subject. Unfortunately, there is only a limited amount of field and laboratory information from which the authors could draw conclusions. Indeed, because of the variability of the atmosphere and the presence of many factors which exist simultaneously, it is difficult to isolate the independent influence of topography profile, surface roughness or stability. In the 1940's and early 1950's, laboratory studies in aeronautical wind tunnels were also completed; unfortunately, the investigators found little resemblance between the field and wind tunnel results. P. C. Putnam, summing up wind investigation connected with the Grandpa's Knob aerogenerator, wrote, "...after five years of increasing familiarity with the problem of site selection, we can point to no analogy between the profiles of mountains and the profiles of airfoils by which one can predict mean wind velocities at hub height within limits which will be useful," and, again, "...we have found no criteria by which to make an economically useful quantitative prediction of the effects of topography upon wind flow." E. W. Golding seems to fully subscribe to Putnam's views, but he somewhat wistfully writes, "...it would be very convenient if it were possible to use a precise formulae relating the wind speed at a certain height over the summit of a hill of a given altitude and shape to the undisturbed wind speed at the same altitude but at a distance upwind from the hill. This would facilitate the choice of sites; one might almost choose them from close study of contoured maps, if sufficiently detailed, without being familiar with the actual localities. But no such method can be followed: it is not possible to work from the formulae." (Refs. 1 and 2). Early efforts to accomplish this goal were hindered by difficulties in determining the undisturbed wind at the level concerned (Ref. 3), and incorrect laboratory simulation of the effects of the atmospheric surface shear layer and stratification (Refs. 1 and 4).

Prediction of upper level flows in the undisturbed atmosphere has improved substantially in the last twenty-five years (Ref. 5). Successful modeling of atmospheric phenomena in a wind tunnel has only been accomplished in the last fifteen years. The thin surface layers developed in the short aeronautical tunnels failed to reproduce even the gross character of wind profile, stratification, turbulence, and spectra required. In addition, early attempts to produce thicker shear layers with grids produced flows which were not spatially stationary. By combining the best of present understanding of the atmospheric surface layer, laboratory simulation, and numerical extrapolation procedures, Golding's speculation may become a reality. In the following section, this paper will review the conclusions of past investigations of topographical flow fields, describe the wind tunnel facility and experimental design discussed herein, and present some of the results of laboratory simulation of flow over two dimensional ridges.

REVIEW OF PRESENT UNDERSTANDING OF WIND POWER SITE SELECTION

In what appears to be the most recent statement concerning the art of wind power site selection, the World Meteorological Committee, led by Ben Davidson (1954; Ref. 6) remarked that,

> "...the question of the variation of wind and of exchange coefficient with height above the surface layer is not at this stage in a very satisfactory state.... Still less satisfactory is the theory of wind flow in the neighborhood of obstacles. Here the conclusions of potential flow theory may be drastically modified by buoyancy forces, irregularities in slope of the obstacles and the small-scale roughness aspects of both the up and downwind slopes."

Since it is desirable to be able to analyze potential site locations quickly, it is unfortunate that the quantitative effect of all of these important variables is not known. One can nevertheless divide the influence of the atmospheric motion on wind power into four areas: a) Variation of wind speed over uniform terrain, b) Local wind circulations, c) Flow over slight or moderate relief, and d) Flow over high mountains. Each of these areas have received attention from past investigators. Indeed, a wealth of information exists on category a), the understanding of which has recently been summarized in an A.M.S. monograph (Ref. 5). However, if there is an abrupt change in roughness and heating for even flat terrain, major changes can occur as considered under category b) local wind circulations.

Local wind circulations may be driven by nonhomogeneities in roughness, temperature or pressure. A good deal has been learned recently in the field and the laboratory about these situations (Refs. 7 and 8). If a wind power site is placed near a sea shore, for example, the influence of the sea or land breeze may be significant. Similar effects may exist near an urban heat island. Saddle points, passes, or gaps offer possibilities for enhanced winds, especially if they are open to a prevailing wind direction (Ref. 9). Such local effects can greatly enhance energy potential, yet they do not usually show up in national wind survey results.

Flow over slight or moderate relief may result in enhanced wind speeds due to wind "over shoot" or "speed up." There do exist a few field measurement programs over terrain features carried out specifically to estimate wind power potential (Refs. 1, 2, 10, 11, 12, 13). These results are to a large degree site specific and do not cover a wide enough range of terrain types to allow more than a very limited and qualitative generalization to other situations. The combination of hill features, roughness, upstream topographies, and stabilities studied to date even appear to lead to a set of contradictory conclusions (Ref. 6). A number of additional field and laboratory investigations of flow over topography have been completed which were not specifically oriented toward understanding for wind power site selection. The characteristics of a number of these studies together with typical results have been compiled into Table 1. These studies span some forty-six years; over seven countries; and include gentle hills, cones, ridges, escarpments, and mountains. A number of the laboratory results include or were performed in parallel with field measurements.

Putnam (1948: Ref. 1) reports meteorological measurements made over eleven peaks and ridges, four of these were modeled in aerodynamical wind tunnels. Unfortunately, the observed speed up factors are much in doubt due to difficulties in determining the undisturbed wind at peak level (Ref. 3). The some 20,000 velocity measurements made over the wind tunnel models are of dubious value. Since the shear layer of the atmosphere was not pre-established, approach velocity profiles may have had power law coefficients near zero, in addition the absence of stratification modeling may result in either too high or too low values for speed up, S. Other investigators (Refs. 14 and 15) have also failed to model approach wind profile during atmospheric simulation.

Frenkiel (1962; Ref. 10) and Golding (1952 and 1956; Ref. 2) published results of measurements over four hill summits. No measurements are reported of the character of the approach wind. A correlation is reported, however, between hill slope and the power law uniformity of the wind profile above the hill. It is suggested this can be a good criteria of the quality of the site for wind power once measured.

Stratification can make a major difference in the dynamic and kinematic behavior of wind flow over topography. Refs. 16, 17, 18, 19, and 20 consider flow over topography in the presence of stable stratification. In each case there is quantitative field evidence of similarity including the effects of stratification but poor simulation without it. Whenever the atmosphere is stable, to conserve energy the wind will want to go around the obstacle rather than over it. This should result in increased wind speeds along the edges and in gaps of hills and ridges.

High mountain ridges are potential wind power sites. It is true such sites often produce very high winds of large gustiness--yet future designs for power mills may permit use of this extremely energetic wind. Stratified flow over mountain ridges may lead to lee waves or helm winds (Refs. 20 and 21). There is a very extensive literature dealing with orographic induced waves. Since most of it deals with cloud systems and upper atmospheric character far from the surface, it is not reproduced here.

On mountain tops speed up effects as well as "speed down" effects may be observed. These effects seem to depend on the orography, slope, roughness, stability, and insolation. Thus one even sees maximum winds, not on the highest peak but at some lower level (for example, the behavior of the Hump on Mt. Washington, Ref. 1) in a mountain range.

A number of field and laboratory investigations are recently available which specifically examine the influence of hill slope and profile. Plate and Lin (1965; Ref. 22), Plate and Shech (1965, Ref. 23), and Chang (1965; Ref. 24) report measurements of neutral and unstable shear flows downwind of triangular and sinusoidal ridges. de Bray (1973; Ref. 25), Freeston (1974; Ref. 26), and Bower and Lindley (1974; Ref. 27) considered shear flows over upwind facing escarpments. When the upstream wind profile and stratification were simulated close agreement appears between laboratory and field measurements.

The consensus of experience with wind site evaluation over low to medium height ridges or hills would suggest the following:

1. Ridges should be athwart the principal wind direction, but high velocities are not likely on upwind foothills.
2. Hill tops should not be too flat, slopes should extend all the way to the summit.
3. A hill on the coast as opposed to an inland hill surrounded by other hills is more likely to provide high winds (i.e., unobstructed upwind).
4. Speed up is greater over a ridge of given slope than over a conical hill of the same slope.
5. Speed up over a steep hill decreases rapidly with height.
6. The optimum hill slope is probably between 1:4 and 1:3 with 1:3.5 best (h/L between 0.5 and 0.67).
7. Topographical features in the vicinity of the hill produce the structure of the flow over it.
8. Frenkiel (Ref. 10) ranks sites based on the uniformity of the summit and profile. He suggests:

QUALITY	$R = u_{40m}/u_{10m}$	α	SLOPE	h/L
Optimum	R < 1.05	0.0	1:3.5	0.57
Very Good	1.05 < R < 1.10	0.07	1:6 smooth regular	0.35
Good	1.1 < R < 1.15	0.1	1:10	0.20
Fair	1.15 < R < 1.21	0.14	1:20 smooth 1:6 regular	0.10
Avoid	1.21 < R	>0.14	>1:20 <1:2	< .05 >1.0

9. Hills with slopes greater than 1:3 should probably be avoided.
10. Vertical wind speed above a summit does not increase as much with height above ground as over level terrain.

A great deal has been learned about atmospheric flows since the early wind power siting effort. Yet despite the variety of specific studies, no effort has been made to systematically understand the separate and/or combined influence of terrain aspect ratio, insolation, roughness, and stratification. A research program primarily experimented in nature is underway which will hopefully provide over a three-year period, a unified body of knowledge on terrain aerodynamics. The objectives and elements of this program have been previously described in Ref. 28. It is the intent of this report to present some of the typical results and conclusions of Part 1.--the influences of ridge cross-sections on wind speed and turbulence.

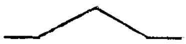
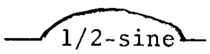
WIND TUNNEL FACILITY AND EXPERIMENTAL DESIGN

A wide range of natural wind characteristics can be simulated by means of the unique Meteorological wind tunnel of the Fluid Dynamics and Diffusion Laboratory which has been used for this research. Characteristics of major concern are magnitudes and spatial distribution of mean velocity, turbulence scales and turbulence spectra of winds approaching the wind power site. Verification that natural wind characteristics are simulated to a high degree of approximation by the long-test-section type wind tunnel has been reported by Cermak, et al. (1966; Ref. 29).

Only the influence of neutral airflow over a smooth boundary are reported herein. Two dimensional ridges have been constructed from plexiglass in triangular and 1/2-sine wave plan form. These hills have been tested for two hill height to boundary layer ratios and five hill slopes*1:2; 1:3; 1:4; 1:6; and 1:20. Each hill was instrumented with surface static pressure holes, Preston surface probes, and surface hot film gauges. Vertical measurements have been made of velocity, turbulence, and flow direction utilizing static and Kiehl stagnation pressure probes, hot wire anemometer probes, and three hole wedge probes to determine wind angle. The voltage signal from any pressure-transducer or anemometer was integrated for 30 seconds or more to assure stationarity in mean or rms signal. The probes were positioned above the surface by a calibrated traverse, while ground zero was accurately determined by use of electrical continuity through the probes on contact with an electrically conductive surface film. The flexible ceiling of the Meteorological wind tunnel was adjusted before the model hill was inserted to produce zero longitudinal pressure gradient.

* For sinusoidal hills slope equals hill height to half width ratio.

The following table depicts the test matrix which has been completed:

SHAPE	SLOPE	$\frac{h}{L}$	h(cm)	$u_o(10h)$ $(\frac{m}{sec})$	Re_h	$\frac{z_o}{h}$	$\frac{\delta}{h}$	$u_o^*/u_o(10h)$
	1:2	1.0	5.08	9.14	30,000	1.5×10^{-4}	10.5	.032
&	1:3	.67	15.24	9.14	50,000	9.0×10^{-5}	3.5	.032
	1:4	.50	5.08	15.24	88,000	5.0×10^{-5}	10.0	.032
	1:6	.33	15.24	15.24	147,000	3.0×10^{-5}	3.3	.032
	1:20	.10						

Typical results will be discussed in the next section.

DISCUSSION OF RESULTS:

Upwind surface layer characteristics:

The approach wind speeds utilized produced wind profiles with power-law coefficient, α, of 0.14. The smooth floor surface produces a constant skin-friction coefficient near .002 and surface roughness varying from $3. \times 10^{-5}$ to 1.5×10^{-4}. Measurements have been reported scaled by the hill half width L to permit straight forward comparison with the analytical predictions by Jackson and Hunt (1975; Ref. 30) and Jackson (1975; Ref. 31). The approach boundary layer has properties characteristic of a high Reynolds number atmospheric shear layer. These include an extensive -5/3 power law turbulence cascade region in the turbulence energy spectra, local isotropic turbulence, and similarity based on local friction velocity and roughness length scales (see Ref. 32).

Static pressure distributions:

Jackson and Hunt (1975) and Jackson (1975) suggest that the magnitude of the perturbation pressure Δp is the same order as that in an inviscid flow over a low hill driven by a uniform velocity upwind equal to the velocity in the boundary layer flow at a height equal to the length of the hill, i.e., $\Delta h = O\left[(\frac{h}{L}) u_o^2 \; (z = L)\right]$ The measurements of C_p found in Table 1 confirm this hypothesis. Indeed even as $h/L \sim 1.0$ the magnitude remains close; however, for the steeper slopes separation occurs and the hill summit is not necessarily the site of the maximum convergence of streamlines.

As shown in Figs. 1, 2, and 3, for three different hill slopes the approach velocity initially slows down as it moves upslope and then the pressure gradient accelerates the flow toward the crest. The large positive pressure coefficient at the foot of the 1:2 slope hill emphasizes the tendency toward creation of strong separation which occurs for such steep hills.

Contour plots of static pressure distributions obtained for the 1:6 and 1:2 hills are found in Figures 4 and 5 respectively. Observe the symmetry present for the shallow 1:6 hill. Significant pressure changes occur vertically out to a distance of $\tilde{z} \approx 1.0$. Such contours explain the ability of the inviscid potential flow solutions produced by Bowen and Lindley (1974; Ref. 27) to predict the right order of velocity "speed up" over hills. Jackson and Hunt (1975; Ref. 30) base their boundary layer solutions for flow over moderate relief on the existence of an extensive regime dominated by inertial effects. The contour plots of static pressure for the 1:2 slope hill are strongly asymmetric. Pressure disturbances extend upward far beyond the length scale $\tilde{z} = 1.0$. If one visualizes a large separation downwind of the hill and considers the hill height extended by a separation streamline, it is possible to interpret the contour picture as part of a flowfield over an effective hill profile taller and wider.

Mean velocity profiles:

Mean velocity measurements were made at points spaced logarithmically in the vertical at a sequence of longitudinal positions. Data were smoothed by spline procedures which minimized average total curvature in an adjusted (rotated) coordinate system. In some cases curves were splined on logarithmic coordinates, or otherwise evaluated to improve overall consistency. The fractional speed up factor, ΔS, suggested by Jackson and Hunt (1974; Ref. 30) is plotted in Figs. 1, 2, and 3 together with typical mean velocity profiles.

It would appear that the fractional speed up factor may be an appropriate measure of speed up for low slope hills (<1:10) since it does not vary with height quite as much as the speed up factor S. Unfortunately, for steeper hills, both speed up factor S and fractional speed up factor ΔS vary markedly with height. Except for a very small region near the surface where a low level jet seems to appear, the gradient of velocity with height is nearly zero in all cases studied. The results confirm the criteria perferred by Frenkiel (Ref. 10). The variation of S or ΔS with height may thus not be significant since a single value of S or ΔS at a reference height defines velocity over a finite depth for a near optimum hill. Separation generally reduces peak velocity, increases turbulence, and reduces negative pressure values at the summit.

For measurements over the 1/2-sine models of equivalent h/L values, the wide flat top resulted in much reduced values of S and ΔS. This agrees with field experience which recommends against flat topped peaks as prospective wind power sites.

Turbulence characteristics:

Preston tube measurements of surface stress produce variations similar to those predicted by Jackson and Hunt (1974: Ref. 30). Wall shear initially drops below upstream values in the region at the foot of the hill and then rapidly increases to a maximum at the summit. If separation does not occur, the shear stress again falls and rises in a symmetric manner.

Profiles of longitudinal turbulence scaled against local velocity are shown in Figs. 1 and 2 for the 1:6 and 1:4 slope triangular hills. The upstream profile exhibits a typical shape and a maximum at the wall surface. As the fluid slows in the forward stagnation region, turbulence production near the wall decreases and the maximum appears to move outward. Near the summit the velocity gradient is large only near the surface, thus only pre-existing turbulent energy is convected over the ridge at most heights. Since longitudinal velocity on a given streamline has increased local turbulent intensity decreases by almost one-half near the surface up to $z \simeq 2h$. This picture of turbulent energy rapidly convected through a flow convergence and divergence for moderate hills supports the contention by J. C. R. Hunt (1973, Ref. 38) that turbulent diffusion from the surface region should be small and turbulent character may be determined by the rapid distortion of vortex lines as fluid is convected over an abrupt bluff body.

Acknowledgements

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Table 1. Experimental Data of Flow Over Hills, Ridges, and Escarpments

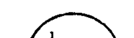
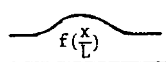
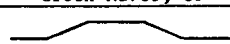
AUTHOR	METHOD	SHAPE RAMP OR HILL	$\frac{h}{L}$	STABILITY	α	$\frac{z_o}{h}$	$\frac{u_o^*}{u_o(L)}$	MEASUREMENTS REPORTED p	u	u'	τ	w'	$E_u(k)$	$-C_{p_{max}}$	ΔS	S
ΔField & Warden (1929-1930)	wind tunnel	Gibraltar	~1.10	N	~0	--	--			x		x		--	--	--
	field		~1.10	N						x		x		--	--	--
ΔPutnam (1948) (Petterssen, 1961)	field	Pond	1.27	--	.3	.05	--		x					--	--	0.84
		Glastenberg	--	--	.3	--	--		x					--	--	1.04
		Mt. Washington	.61	--	.3	.05	--		x					--	--	1.47
	wind tunnel	Pond	1.27	N	~0				x					--	--	1.29
		Glastenberg	--	N	~0				x					--	--	1.44
		Mt. Washington	.61	N	~0				x					--	--	1.30
Golding (1955)	field	Costa, Orkney U.K.	0.3-0.6	--	--	--	--		x					--	--	--
		Vestra Fiold, U.K.	0.2	--	--	--	--		x					--	--	--
Frenkiel (1961)	field	Hreiba Ridge, Israel	0.25	N,S	0.15	$1.4x10^{-4}$	--		x	x				--	--	--
		Givat Hamere Hill, Israel	~0.57	N,S	0.15	$9x10^{-5}$	--		x	x				--	--	--
ΔHalitsky et al. (1962-1963)	wind tunnel	Bear Mtn., NY	~0.46	N	--	--	--		x	x	x			--	--	--
Chang (1966)			1.0	N	.15		.036	x	x	x	x			.33	.27	1.0
Plate & Lin (1965)	wind tunnel		1.0	US*	.19	$1.5x10^{-4}$	.033		x		x			--	.24	1.15
			2.0	N	.15	.	.036	x	x	x	x			.33	.35	1.1
			0.5	N	.15		.036	x	x	x	x			.33	.35	1.0
		 $\frac{1}{2}$ sine	0.8	N	.15	$1.5x10^{-4}$	.035	x	x	x	x		x	.55	.76	1.38
				US**	.19		.032		x		x			--	--	--
ΔCermak & Peterka (1966)	wind tunnel	Pt. Arguello, CA	0.11	N	0.25	--	--		x					--	--	--
			0.11	SΔΔ	0.25	--	--		x					--	>3.0	1.25
ΔMeroney & Cermak (1967)	wind tunnel	San Nicolas Is., CA	0.12	N	0.14	$1.2x10^{-2}$	.032		x	x		x		--	--	--
			0.12	SΔΔ	0.20	--	--		x					--	--	--
Lin & Binder (1967)	wind tunnel		0.67	S					x					--	--	1.2
			1.33	S		Lee Waves			x					--	--	2.6
Garrison & Cermak (1968)	wind tunnel	San Bruno Mtn., CA	~0.43	S	0.16	$2.5x10^{-3}$	.125		x					--	0.5	1.07
ΔHsi et al. (1968)	wind tunnel	Green River, UT	~.09	N	0.14	$2x10^{-4}$	--		x					--	--	1.14
ΔBeryland et al. (1968)	field		0.1	N	--	--	--		x					--	0.25	--
Zrajevsky, Doroshenko & Chepik (1968)	wind tunnel	"	"	N	~0	--	--		x					--	0.1	1.1
ΔKitabayashi et al. (1971)	wind tunnel	Elk Mtn., WY	0.35	N	0.21	$7x10^{-3}$	0.149		x	x				--	0.37	1.04
				S***	0.32	--	--		x						0.29	1.29

Table 1. Experimental Data of Flow Over Hills, Ridges, and Escarpments (con't)

AUTHOR	METHOD	SHAPE RAMP OR HILL	$\frac{h}{L}$	STABILITY	α	$\frac{z_o}{h}$	$\frac{u_o^*}{u_o(L)}$	MEASUREMENTS REPORTED p	u	u'	τ	w'	$E_u(k)$	$-C_{p_{max}}$	ΔS	S
Eliseev (1971)	field	Razdan Valley, USSR	0.61	N	--				x					--	0.35	--
$^\Delta$Orgill & Cermak (1971)	wind tunnel	Climax, CO	.10	N	0.25	3.0×10^{-4}	--	x	x	x	x	x		--	1.86	1.18
			.10	S$^{\Delta\Delta\Delta}$					x					--	0.67	1.00
			.10	N	0.57	--	--		x	x		x		--	1.20	0.75
de Bray (1973)	wind tunnel	20°	0.72	N	0.14	--	--		x					--	0.41	1.13
		sine	0.5	N	0.14	--	--		x					--	0.34	1.07
		source	--	N	0.14	--	--		x					--	0.30	1.04
				N	0.11	--	--									
Freeston (1974)	wind tunnel	20°	0.72	N	0.14	--	--	x	x					0.40	0.38	1.10
		40°	1.67	N	0.14	--	--	x	x					0.90	0.45	1.16
		60°	3.46	N	0.14	--	--	x	x					1.00	0.18	0.94
		sine	0.5	N	0.14	--	--	x	x					0.50	0.34	1.07
		source	--	N	0.14	--	--	x	x					0.40	0.30	1.04
$^\Delta$Bowen & Lindley (1974)	field	26°	0.98	N	0.1	5×10^{-5}	0.102		x					--	0.39	1.06
	New Zealand		∞	US	0.45	1×10^{-2}	--		x					--	1.13	1.16
	wind tunnel	26°	0.98	N	0.18	4×10^{-3}	0.160		x					--	0.40	1.12
			∞	N	0.18	5.3×10^{-3}	0.160		x					--	0.47	1.10
Meroney et al. (1976)	wind tunnel		1.0	N	0.14	9×10^{-5}	.032	x	x	x	x	x	x	0.25	0.71	1.07
			0.67	N	0.14	"	"	x	x	x				.26	0.79	1.15
			0.50	N	0.14	"	"	x	x	x				0.93	1.41	1.53
			0.33	N	0.14	"	"	x	x	x	x	x	x	0.77	1.11	1.35
			0.10	N	0.14	"	"	x	x	x	x	x	x	0.15	.40	0.90

$$C_{p_{max}} = \frac{\Delta p}{\frac{1}{2}\rho\, u_o(\delta)^2}\ ,\ \Delta S = u(z)/u_o(z)\ ,\ S = \frac{u(z)}{u_o(z+hf/L)}$$

$^*Ri_{8h} = -.016$

$^{**}Ri_{4h} = -.019$

$^{***}Ri_\delta = 1.70$

$^\Delta$Field comparisons available

$^{\Delta\Delta}Ri_\delta = 0.30$

$^{\Delta\Delta\Delta}Ri_h = 6.0$

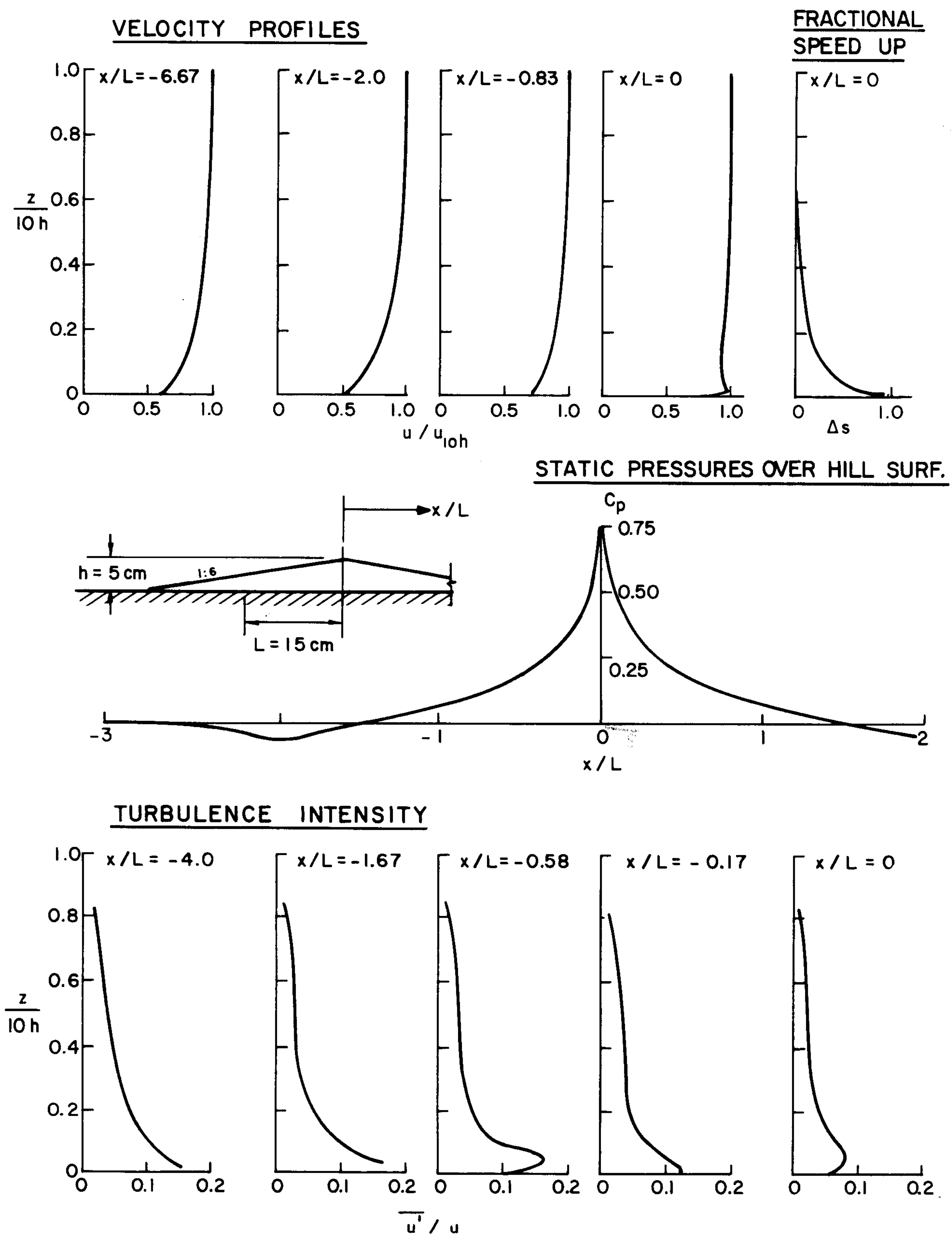


Figure 1. Velocity, turbulence, and static-pressure profiles over a 1:6 slope triangular hill.

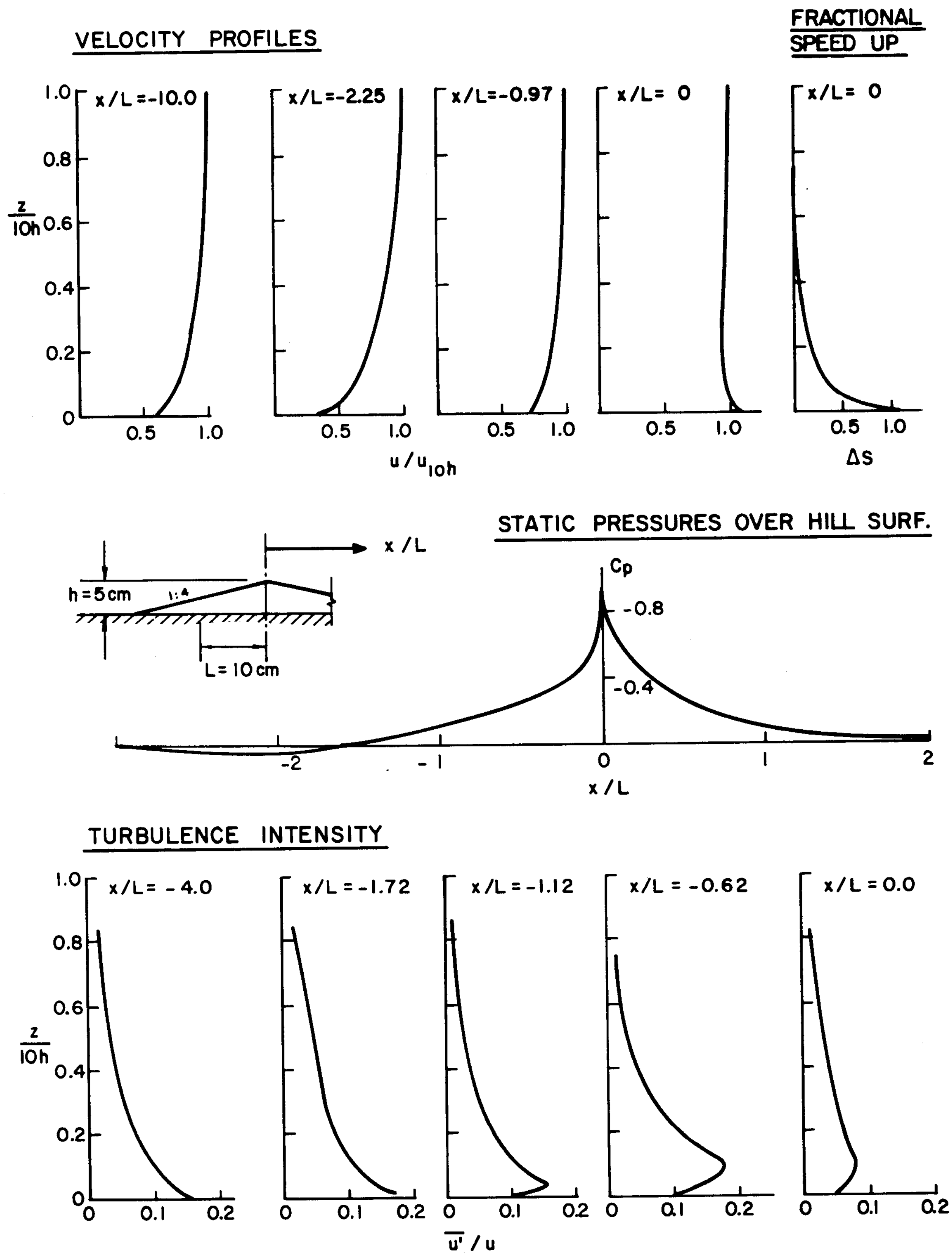


Figure 2. Velocity, turbulence, and static-pressure profiles over a 1:4 slope triangular hill.

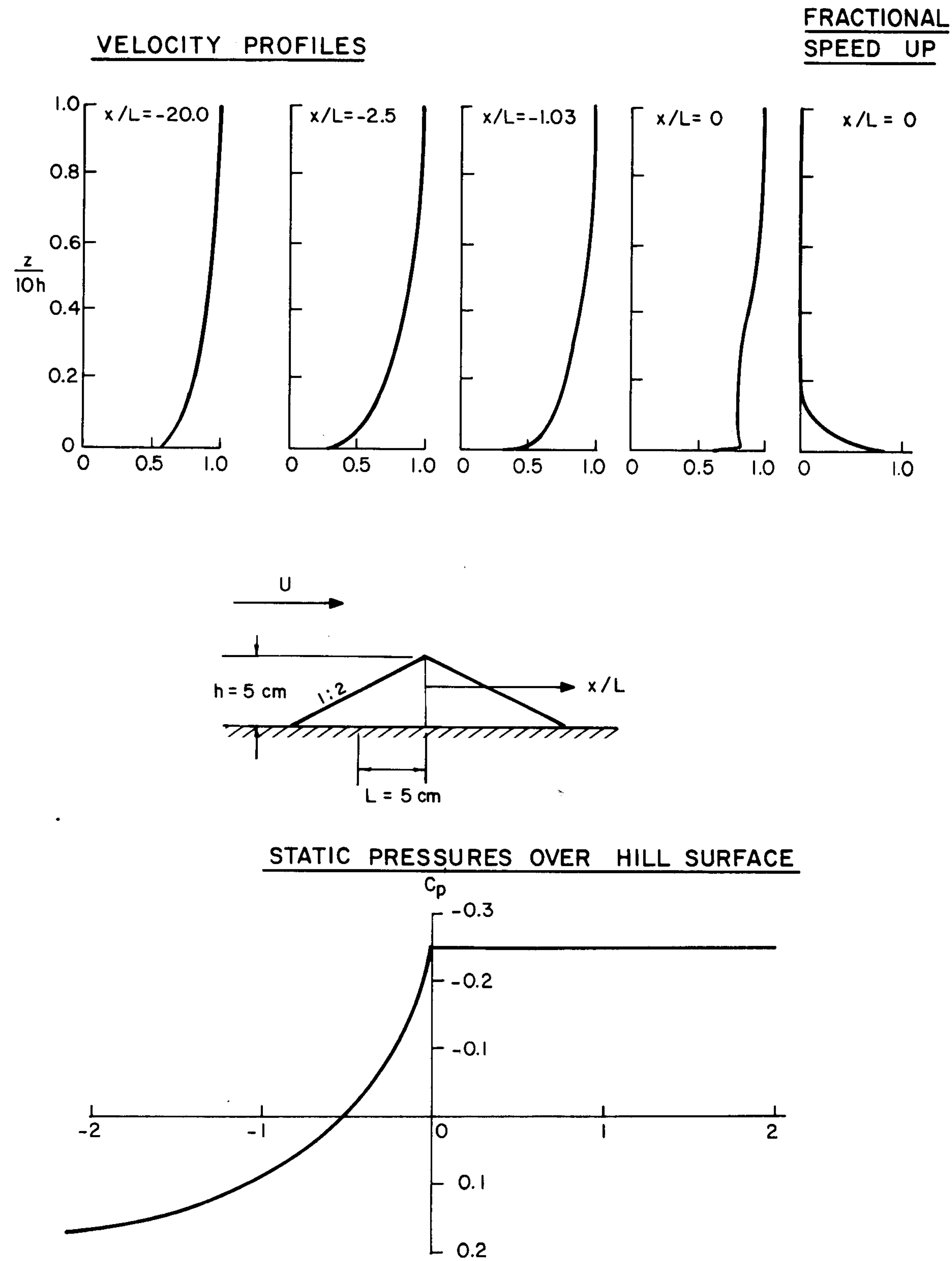


Figure 3. Velocity, turbulence, and static-pressure profiles over a 1:2 slope triangular hill.

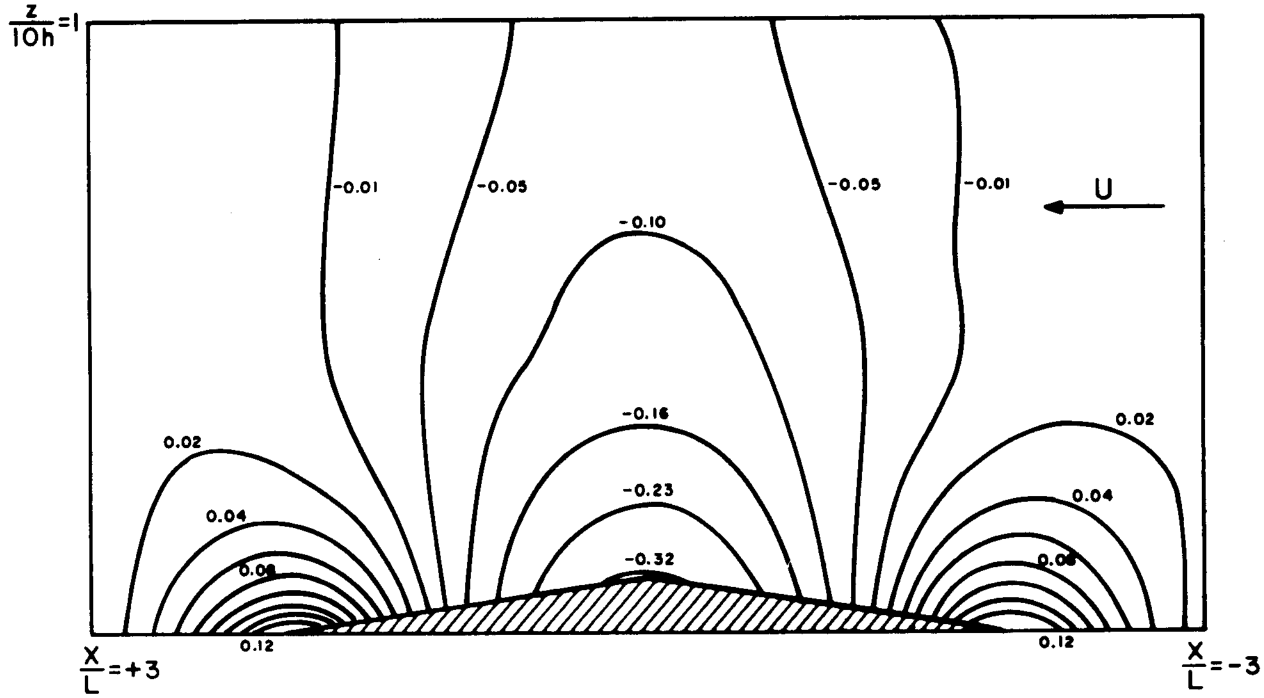


Figure 4. Static pressure contours over a 1:6 slope triangular hill.

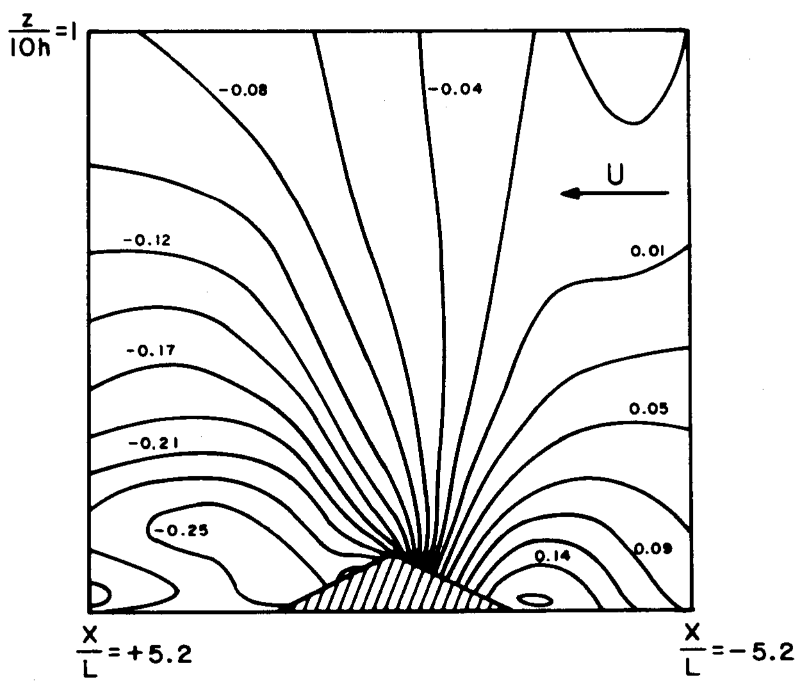


Figure 5. Static pressure contours over a 1:2 slope triangular hill.