WIND IN THE PERTURBED ENVIRONMENT:
ITS INFLUENCE ON WECS

by

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INTRODUCTION

Past experience with generation of electricity by windmills indicates that the most important factor controlling success or failure of these systems is site wind characteristics. Incorrect placement on a site sheltered by building, terrain, or agricultural growth may drop performance to one-third of the original expectations. Once a system is designed to operate optimally at one wind speed mechanical, aerodynamic and generating efficiencies may constrain subsequent performance to only linear improvement at higher annual velocities or more than a cubic loss at lower wind speeds! Recognition of wind characteristic importance has led to a series of papers and monographs on the subject. In the classical wind power books by Putman (1948) and Golding (1955) the authors devote 45 percent of the text to wind characteristics as they influence wind machine performance. A review of wind power characteristics research and a guide to early literature has been prepared by Meroney (1976). Recent insites on the influence of terrain, building wakes, and vegetative foilage or shelter belts are reviewed herein in separate sections.

TERRAIN AERODYNAMICS

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. Meroney, et al., (1976a) have recently reviewed field and laboratory measurements made over such variable surface features.

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 (1962) ranks sites based on the uniformity of the summit wind profile. He suggests:

QUALITY	$R = u_{40m}/u_{10m}$		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 irregular	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 irregular	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. A program is now underway to systematically understand the separate and/or combined influence of terrain aspect ratio, insolation, roughness, and stratification. The objectives and elements of this program have been previously described by Meroney, et al. (1976b). Measurements made in a meteorological wind tunnel of magnitude and spatial distribution of mean velocity, static pressure, and turbulence over two dimensional ridges have been reported by Meroney, et al. (1976c).

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 sites. 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).

Two dimensional ridges were 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 fractional speed up factor, ΔS, suggested by Jackson and Hunt (1974) is plotted in Figures 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 (1962), The variation 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.

Preston tube measurements of surface stress produce variations similar to those predicted by Jackson and Hunt (1974). 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 Figures 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 turbulence 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) 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.

Jackson and Hunt (1975) have analyzed flow over shallow hills ($h/L < 0.05$) in terms of an outer layer which perceives only perturbations due to a uniform inviscid flow and an inner region boundary layer driven by an externally generated pressure gradient. They concluded the fractional speed up factor is approximately

$$\Delta S = \frac{U_o(\tilde{y}L) - U(\tilde{y}L)}{U_o(\tilde{y}L)} \approx 2\frac{h}{L}$$

where $\tilde{y} = \frac{y - hf(x/L)}{L}$, h is hill height, and L is the distance from the top of the hill to the point where $f(x/L) = 1/2$. Subsequently Jackson (1976) suggested the methodology was appropriate for h/L as large as 0.73. Taylor and Gent (1974) numerically solved a turbulent boundary layer analog to conclude that the proportionality coefficient ranged from 3.2 to 1.0 over $0 < \tilde{y} < 0.2$ at the hill crest for $y_o/h = .002$ and from 5.2 to 1.0 over $0 < \tilde{y} < 0.5$ at the hill crest for $y_o/h = .0005$. The fractional speed up ratio ΔS is not a sensitive function of roughness, varying at most by 25% for a variation of y_o by a factor of 100.

Derickson and Meroney (1977) have solved the inviscid equations of motion including stratification effects for flow over two-dimensional ridges. Results compare very closely with typical results from Meroney, et al. (1976c). (See Figure 4.) It was found that ΔS falls off very rapidly with height for $h/L > 0.5$; however the approximation proposed by Jackson and Hunt (1975) has the right order very near the crest surface. Mild stability tends to decrease the speed up factor, whereas mild instability for a given approach velocity profile tends to increase the speed up factor.

BUILDING AERODYNAMICS

Wakes generated by buildings, individual tress, or shelter belts are usually characterized by regions of increased turbulence, decreased mean velocity, and often organized discrete standing vortices with their axis parallel to the main flow direction. Wind generators placed within such regions will perceive a loss of power and increased buffeting. Since modern wind generators spin at high speeds and tend to have long thin blades they are more susceptable to damage from wind turbulence than water pumping windmills.

Reviews of data pertaining to wind profiles and turbulence in building wakes have been prepared by Frost (1973) and Peterka and Cermak (1975). Aside from limited field testing, the primary guidance for building wake structure has been wind-tunnel tests. The flow in the immediate vicinity of a given building is extremely complex (see Figure 5). For most houses, sheds, barns, etc., this region extends from 2.5 to 4 building heights downwind, from 0.5 to 1 building heights to the side of the structure, and up to 0.5 building heights above the structure.

Beyond the immediate region of the structure the mean velocity defect and turbulent intensity excess tend to decrease with downwind distance as a power of x varying from -1.5 to -1.0 or -2.0 to -1.0 respectively depending on the width to height ratio of the structure (Figures 6 and 7). Typical vertical and horizontal growth of the mean velocity defect is displayed in Figures 8 and 9 where H:W:D = 1:2.5:0.75. In most cases the wind has returned to within 2% of its upstream value by $x/H = 20$, thus power available will be decreased by at most about 6%. Table 1 summarizes expected growth of the size of the wake, the probable maximum losses in wind speed and power, and the rate of decay of excess turbulence. Meroney, et al. (1977) have also found that wake velocity defect and turbulence excess behave similarly behind isolated buildings and small building complexes on the wake centerline. Lateral wake growth and behavior will vary depending upon the building arrangement.

VEGETATION AND SHELTER BELT AERODYNAMICS

Individual trees, groups of trees, or belts of vegetation may actually shelter a greater area than the equivalent size solid structure. Eimern (1964) reviewed the influence of density, shape, surface roughness, thermal stratification, wind angle and arrangement on wind speed, soil moisture, etc. Simplified insites from this material are incorporated in Table 1. Behind porous objects the velocity defect generally persists twice as far downwind; however the turbulence intensity excess is diminished. Maximum length of shelter will occur for long fences of near 50% permeability, i.e., 30% velocity defect may still exist at 0.5H for $x/H > 50$. The wind will return to its undisturbed condition in about half the distance if the shelter belt is only twice as long as it is high. Wind approaching a shelter belt at an angle increases its effective porosity, decreases the shelter, and increases turbulence excess.

SURFACE ROUGHNESS AND SURFACE ROUGHNESS TRANSITIONS

The power law coefficient n for the velocity profile over a homogeneous surface roughness may be related to roughness and stability by

$$n = \frac{1 + \beta\frac{z}{L}}{\ln\frac{z}{z_o} + \beta\frac{z}{L}}$$

where $\beta \simeq 5$, $z = 10$ m, and roughness length z_o and stability length L can be approximated from Table 2. Stratification may have a significant effect on the power law even at significantly large wind speeds. Recent measurements by Takle and Brown (1976) for a flat, short grass site in Iowa (i.e., $z_o \approx 0.01$) display a typical diurnal variation of n from 0.24 to 0.08. Even at wind speeds of 5 mps the power law coefficient varies from 0.20 to 0.10. Stratification effects aside, Figure 10, from Park and Schwind (1977) display six typical high wind speed profiles.

Sometimes a windmill location is in flat terrain but close to the boundary of two types of surface roughness. The wind profile near the ground will adjust to surface roughness changes as it moves downwind from the ground cover transition. Above a transition height which is a function of downwind distance the upper part of the wind profile will correspond to the wind profile for the roughness before the change in cover. Figure 11, also prepared by Park and Schwind (1977), consists of five curves that give the growth in transition height between the various profiles of Figure 10. Similar graphs in terms of other relative roughness lengths may be prepared in the manner of Plate (1971). Combining profile shape and transition growth information for a given site should permit estimation of a suitable height to obtain a required amount of generated power. Since the profiles and the transition layer growth curves are only average results the wise builder will allow a safety factor in height for uncertainty.

CONCLUSIONS

One is indeed fortunate if the planned site for a wind turbine is in flat, open windy terrain with no nearby obstacles. Frequently we do not have Candide's "best of all possible worlds;" thus selection of a suitable site must combine good judgement with available micrometeorological understanding. In the near future additional field, laboratory, and numerical data should further enhance wind turbine site selection; however, until such information becomes available, rules of thumb such as are contained herein must suffice.

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Table 2. SURFACE PARAMETER CHARACTERIZATION

	Surface Type	z_o(m)	n(L=∞)
1)	Expanse of water, coastal area, desert	0.001	0.12
2)	Flat gentle open country, grasses, moorland	0.01	0.15
3)	Numerous small obstructions, trees and buildings (farmland)	0.1	0.19
4)	Suburbs, cities (small)	0.5	0.26
5)	Large city center, tall buildings	1.5	0.35

Table 3. METEOROLOGICAL CONDITIONS DEFINING VARIOUS MONIN-OBUKHOV LENGTH RANGES (m)

Surface wind speed, m/sec	Daytime isolation			Nighttime conditions	
	Strong	Moderate	Slight	Thin overcast or $\geq$ 4/8 cloudiness+	$\leq$3/8 cloudiness
<2	- 2 to - 3	- 3 to - 4	- 4 to - 5		
2	- 3 to - 4	- 4 to - 5	-12 to -15	35 to 75	8 to 35
4	- 4 to - 5	- 5 to -12	-12 to -15	∞	35 to 75
6	-12 to -15	-15 to ∞	∞	∞	∞
>6	-12 to -15	∞	∞	∞	∞

+ The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

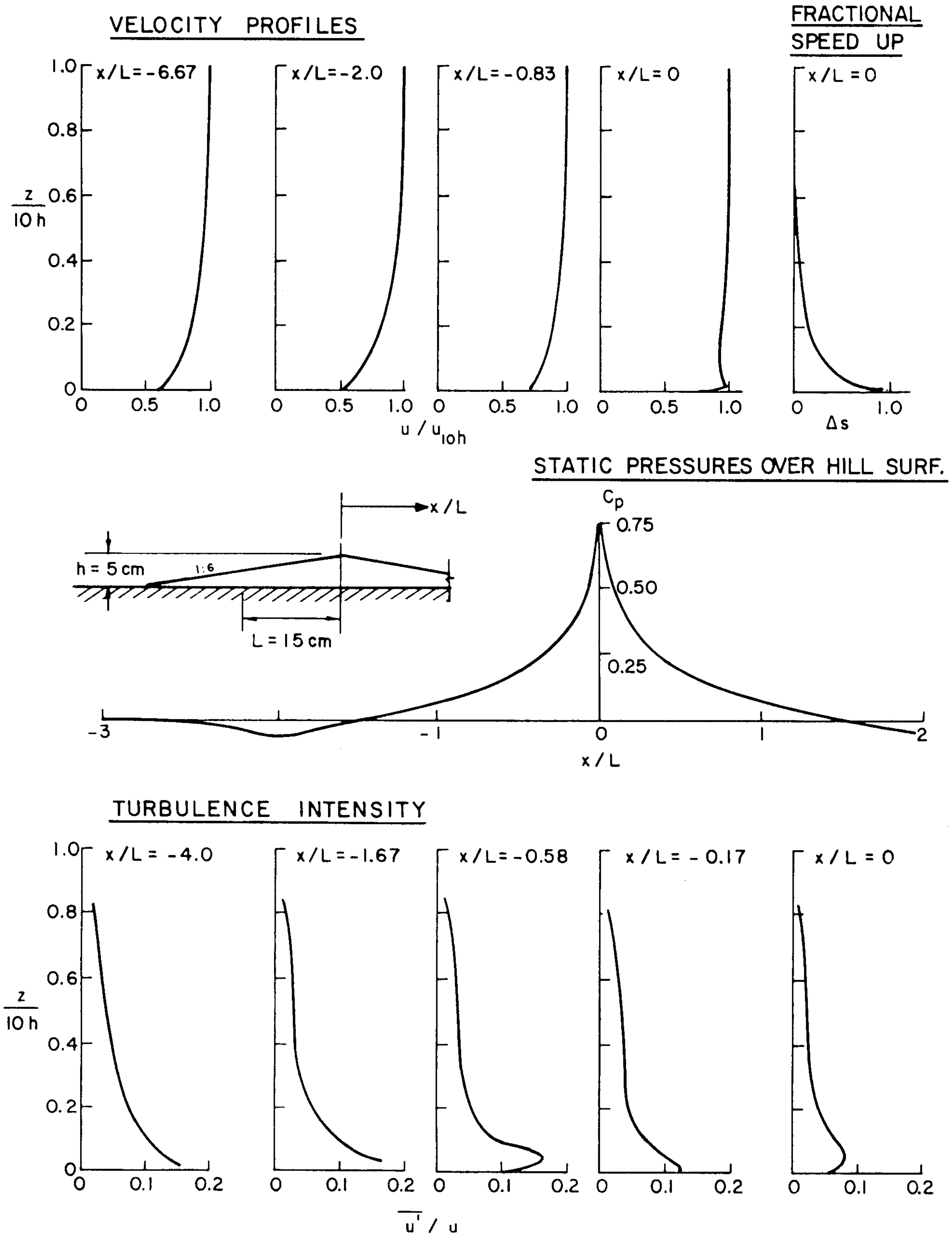


Figure 1. Velocity, turbulence, and static-pressure profiles over a 1:6 slope triangular hill. Meroney, et al. (1976a)

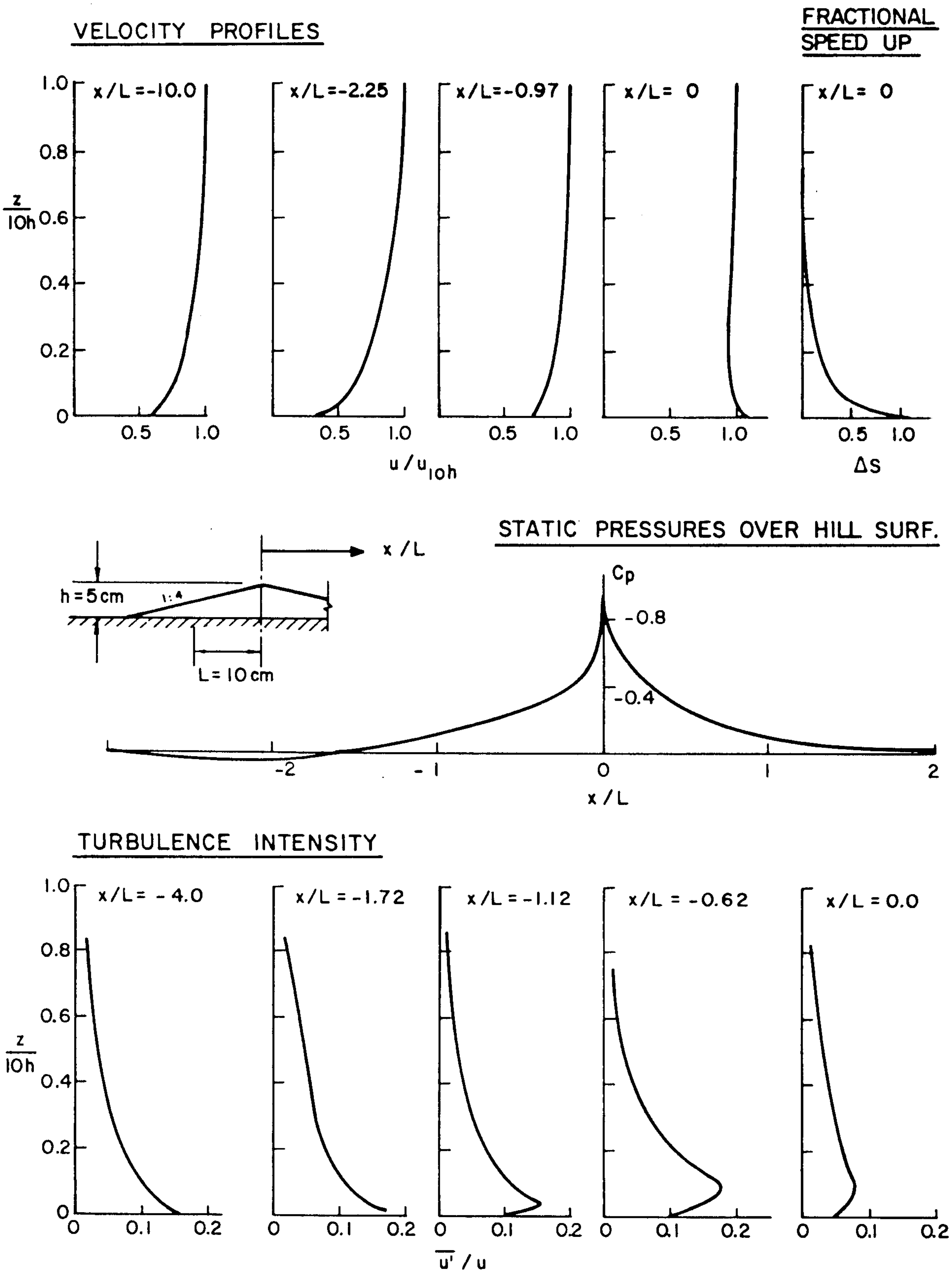


Figure 2. Velocity, turbulence, and static-pressure profiles over a 1:4 slope triangular hill. Meroney, et al. (1976a)

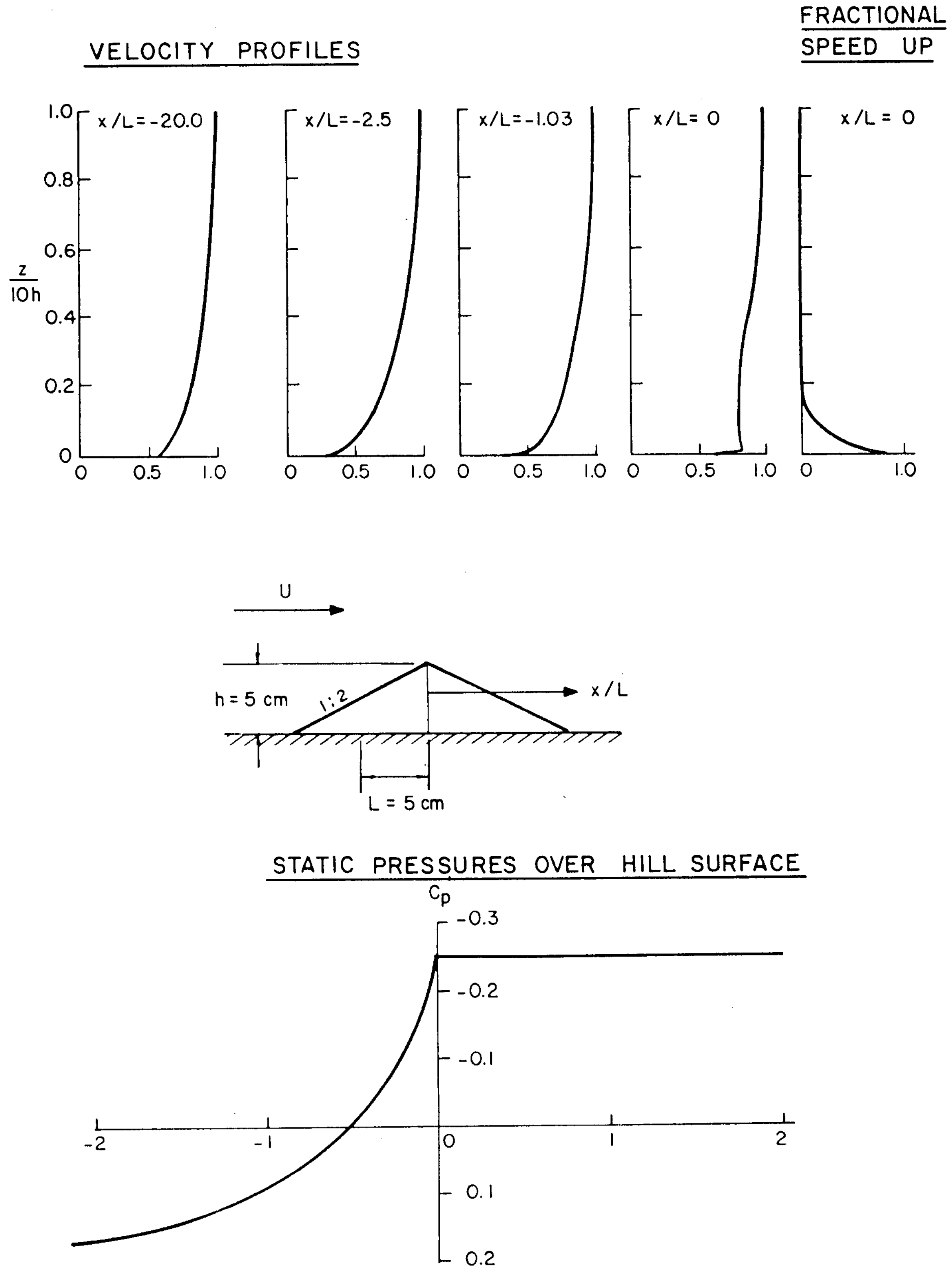


Figure 3. Velocity, turbulence, and static-pressure profiles over a 1:2 slope triangular hill. Meroney, et al. (1976a)

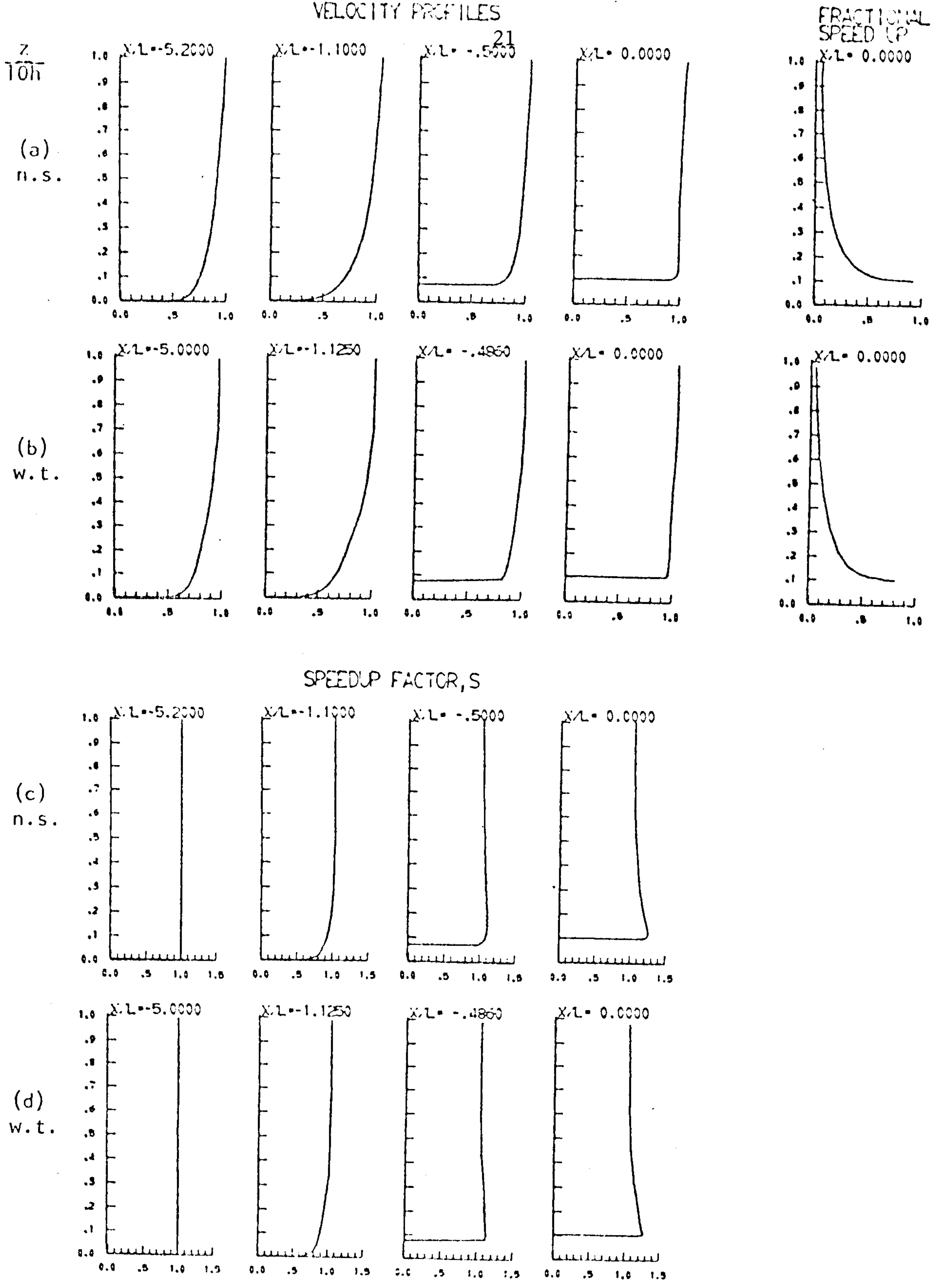


Figure 4. Comparison between wind tunnel data (w.t.) and numerical simulation (n.s.) results for a 1:4 sinusoidal hill. Velocities are normalized with respect to the inflow velocity at 10h, where h is the elevation at the hill summit. Speedup is defined as the ratio of the horizontal velocity, u, at a given elevation over the terrain to the inflow u value at the same elevation. Fractional speedup is defined by $[U_o(z+h)/U_i(z)]-1$ in which $U_o(z+h)$ lies above the summit and $U_i(z)$ is at the inflow boundary. x/L is the ratio distance upstream of the summit. L is the half-width of the hill. Derickson and Meroney (1977)

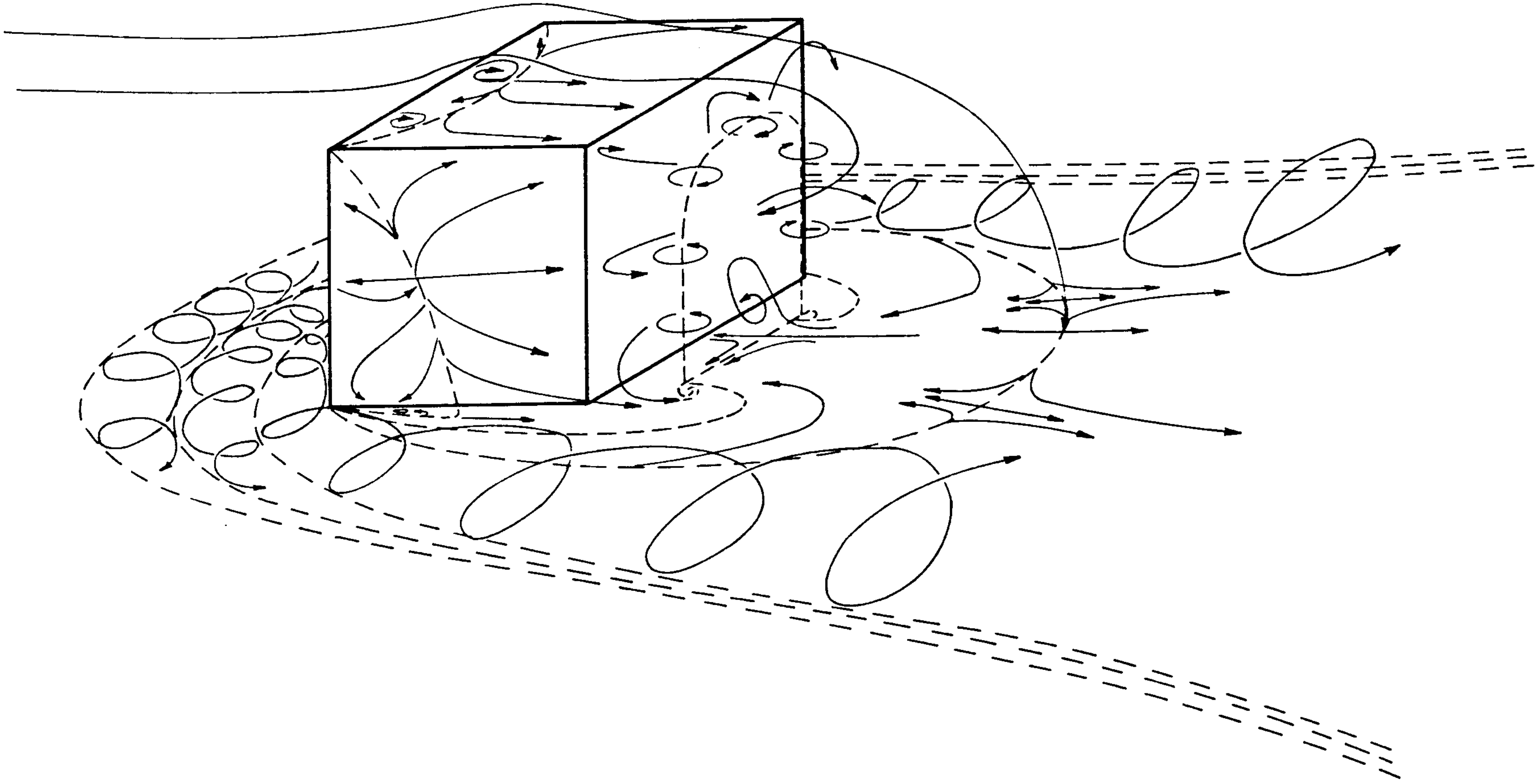


Figure 5. Flow Pattern around a Rectangular Block with Reattachment of the Free Shear Layer, Woo, et al. (1976)

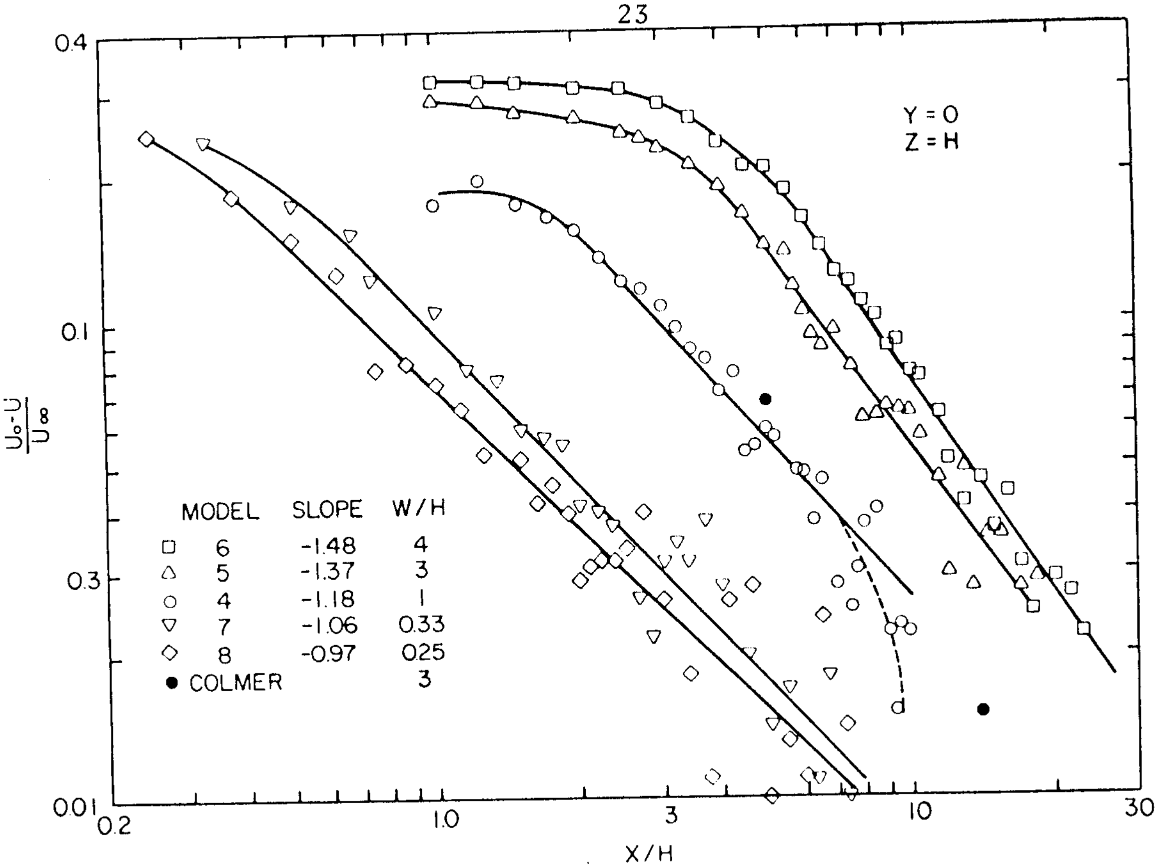


Figure 6. Decay of mean velocity defect in the wake of several buildings, Peterka and Cermak (1975).

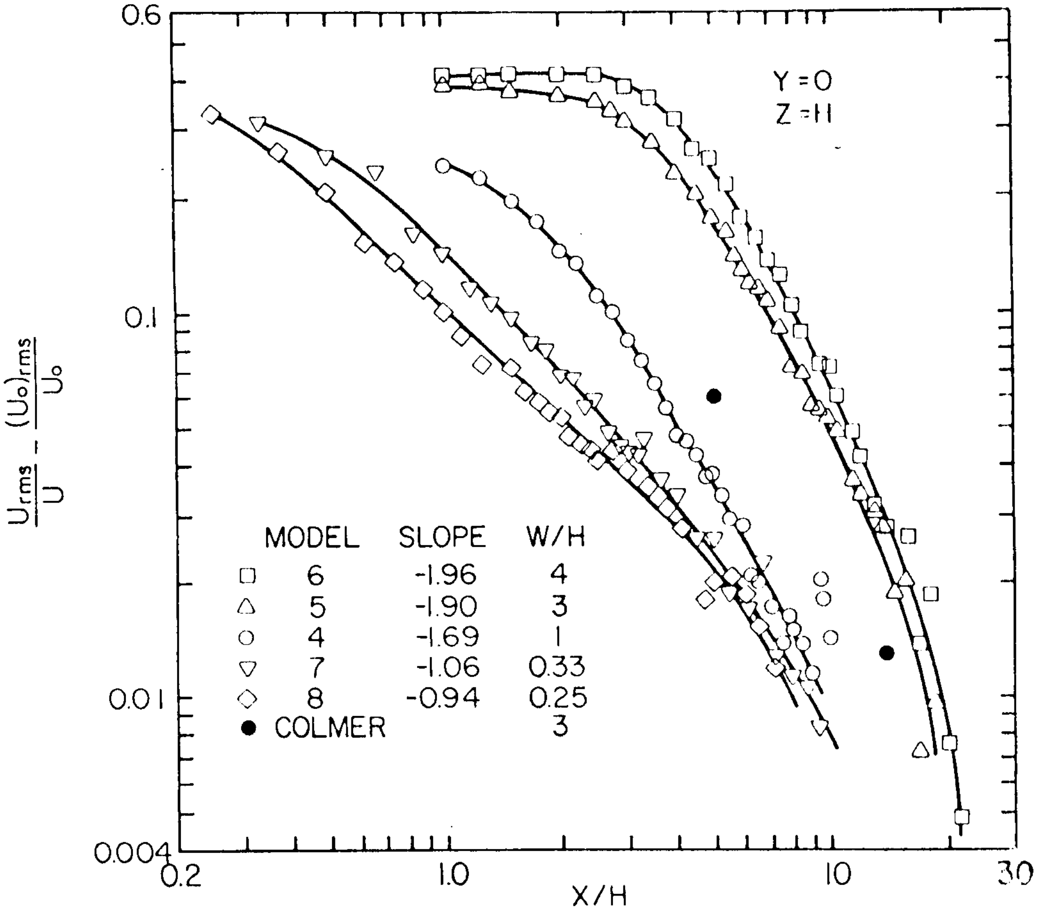


Figure 7. Decay of turbulence intensity excess in the wake of several buildings, Peterka and Cermak, (1975).

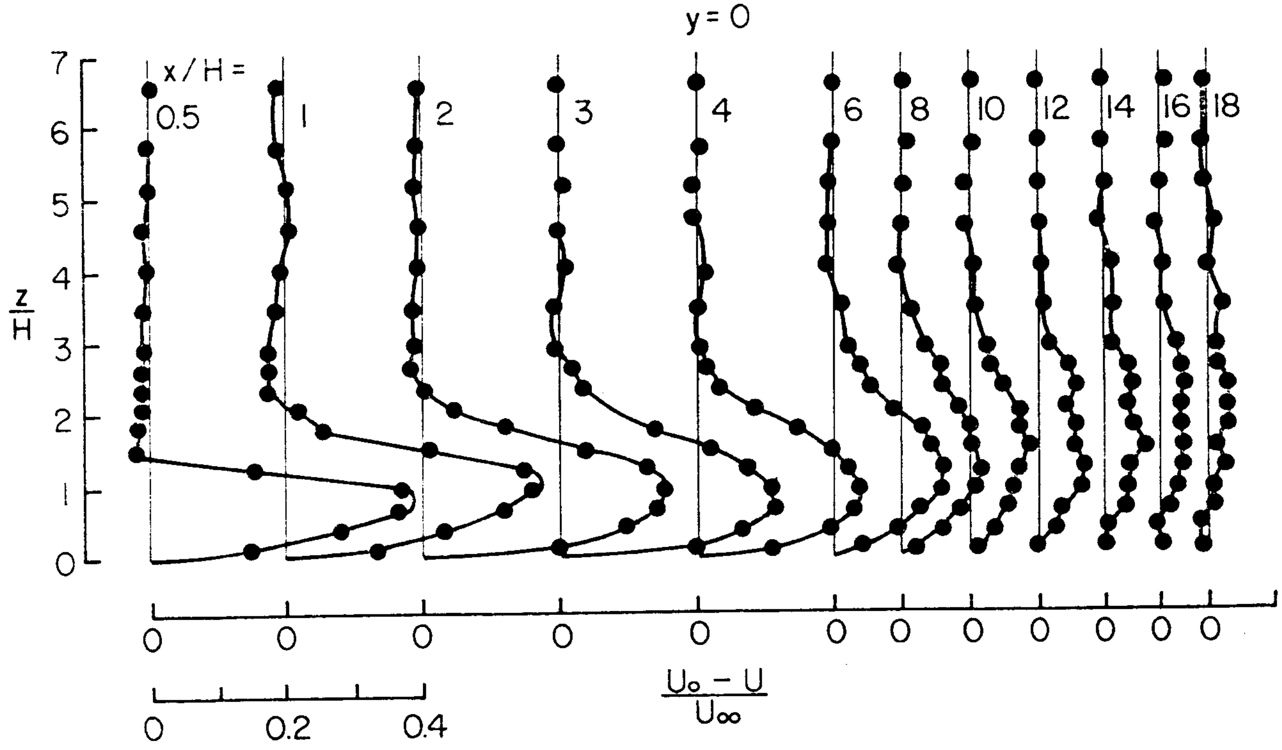


Figure 8. Vertical Profiles of Mean Velocity Defect behind Model Block
H:W:D = 1:2.5:0.75, Power law
Profile n = 0.25, Woo, et al. (1976)

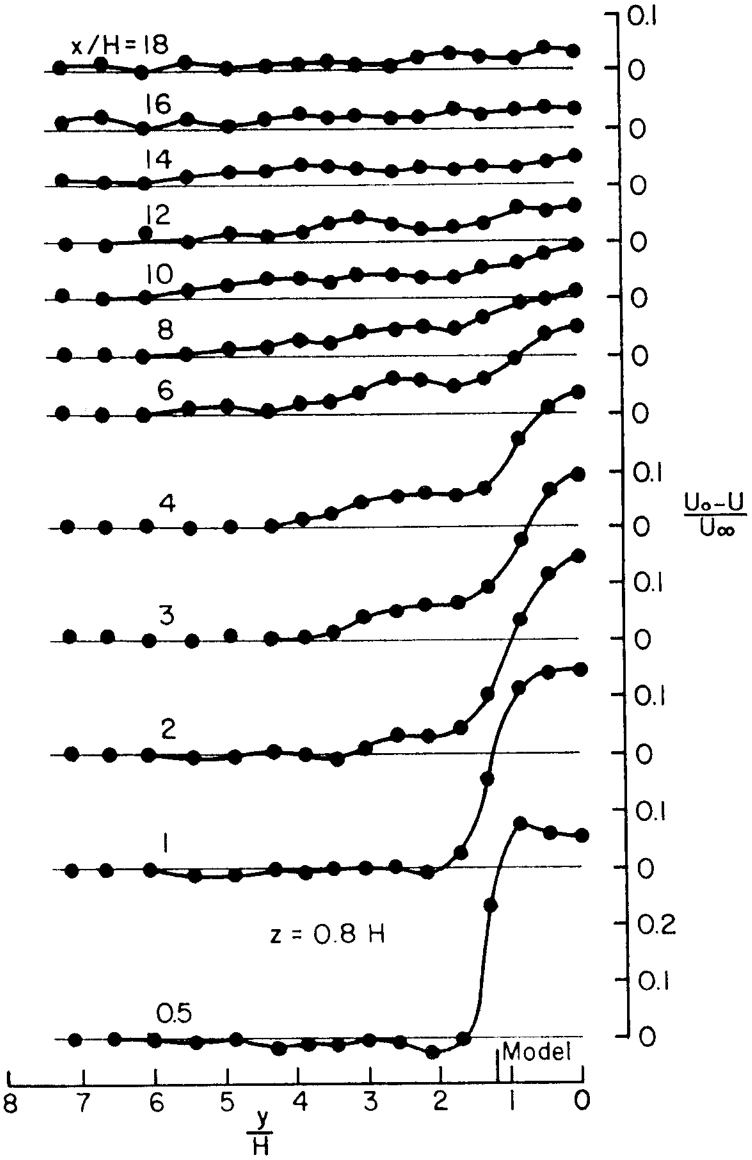


Figure 9. Horizontal Profiles of Mean Velocity Defect behind Model Block H:W:D = 1:2.5:0.75, Power law Profile n = 0.25, Woo,et al. (1976)

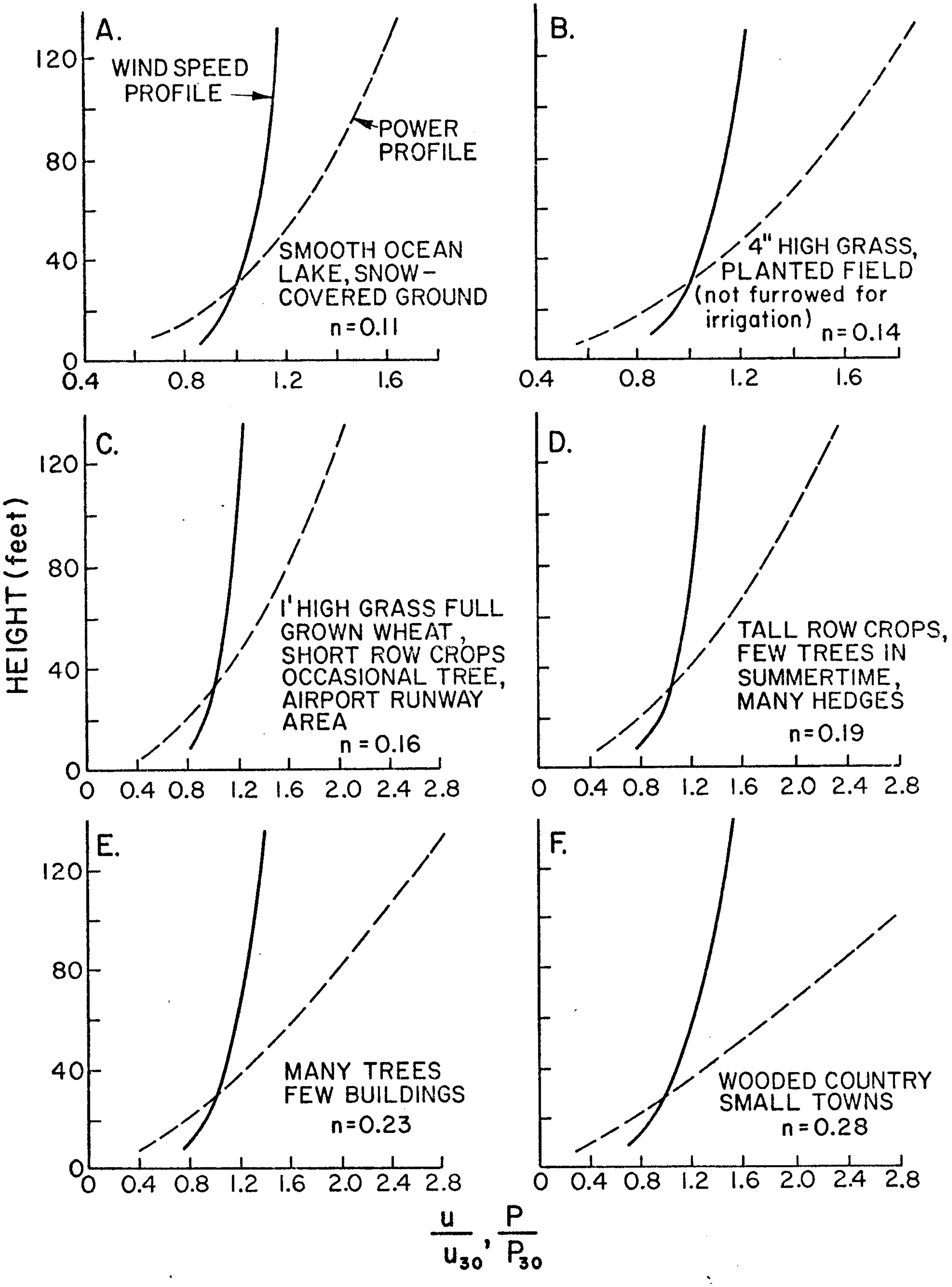


Figure 10. Wind speed profile shapes and wind power profile shapes for various types of flat terrain. Park and Schwind (1977)

FROM: \ TO:	A	B	C	D	E	F
A	-	1	1	2	3	4
B	5	-	2	3	3	4
C	5	2	-	3	4	4
D	5	2	3	-	4	5
E	5	3	3	3	-	5
F	5	4	4	4	5	-

HOW TO READ THIS PLOT

1) SELECT UPWIND & DOWNWIND TERRAINS IN FIG. 10
2) ENTER TABLE ON LEFT WITH APPROPRIATE LETTERS, SELECT NUMBER
3) USE CURVE BELOW WITH NUMBER

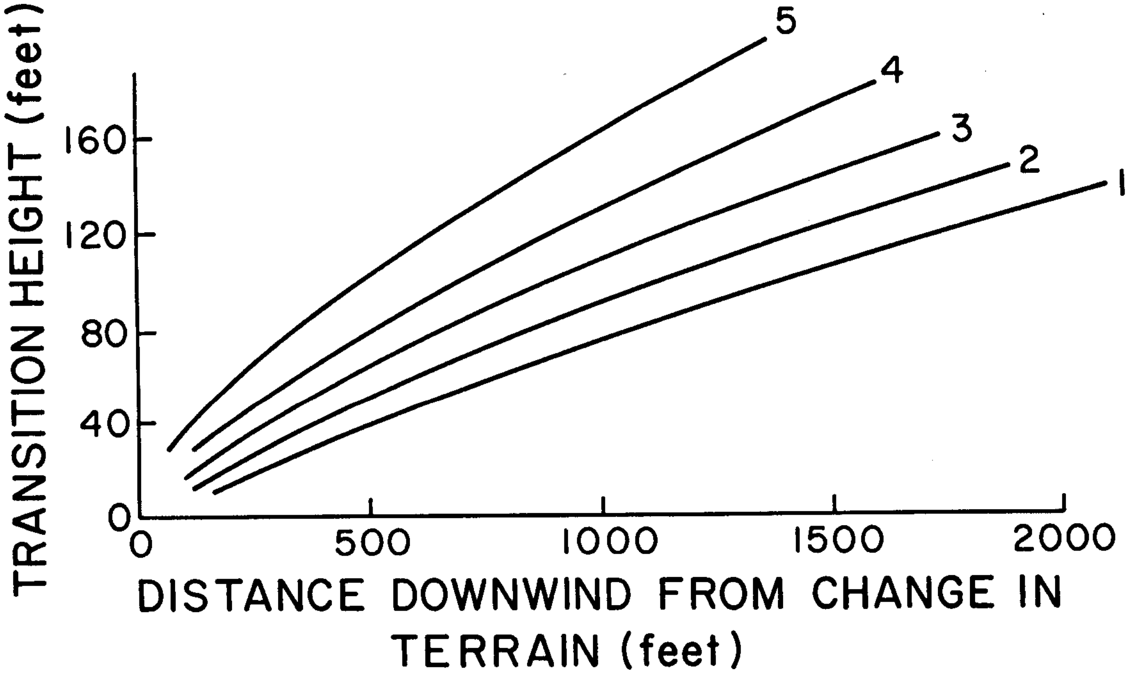
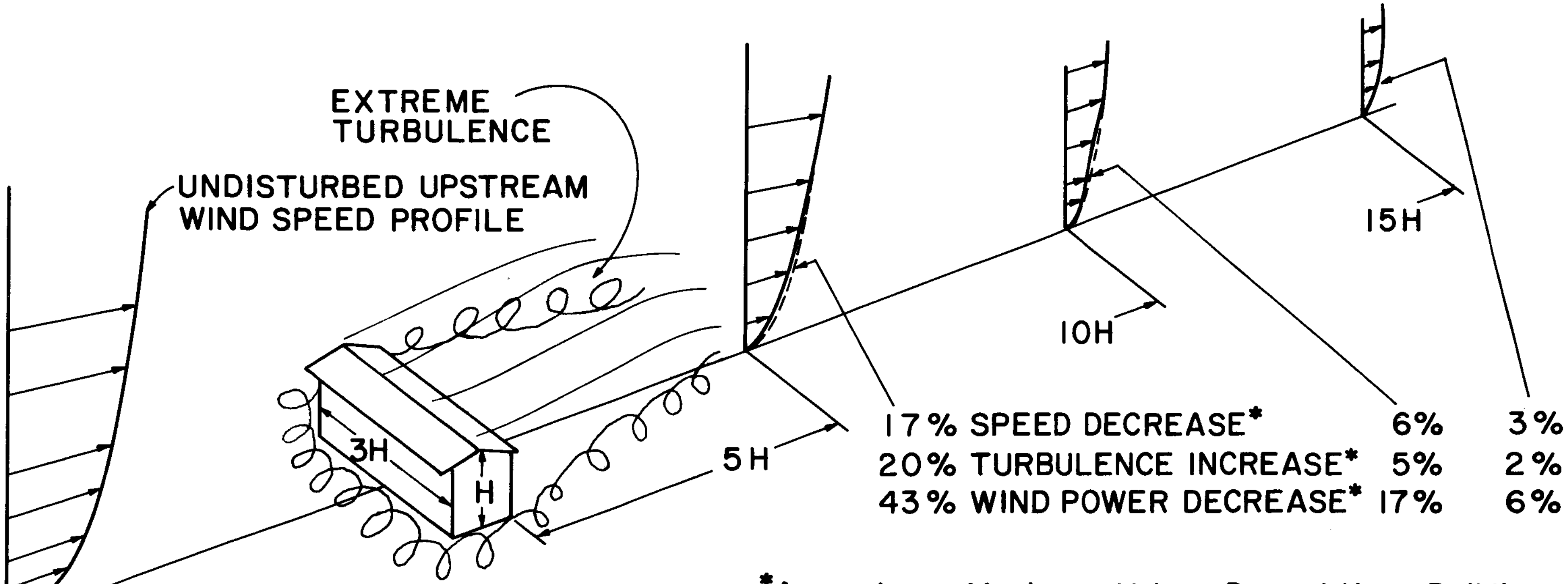


Figure 11. Transition height in wind speed profile. Park and Schwind (1977)



*Approximate Maximum Values Depend Upon Building Shape, Terrain, Other Nearby Obstacles

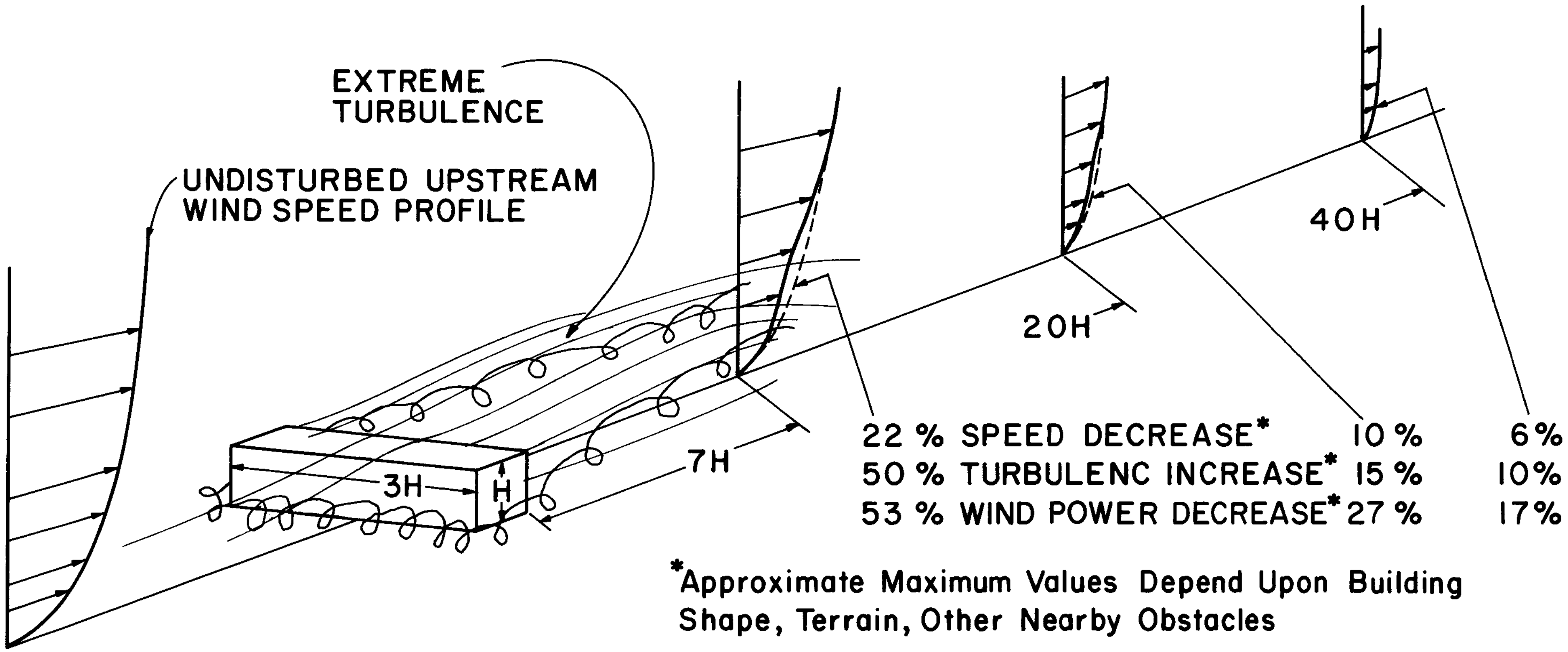

EXTREME TURBULENCE
UNDISTURBED UPSTREAM WIND SPEED PROFILE
3H
H
7H
20H
40H
22 % SPEED DECREASE* 10 % 6%
50 % TURBULENC INCREASE* 15 % 10%
53 % WIND POWER DECREASE* 27 % 17%
*Approximate Maximum Values Depend Upon Building Shape, Terrain, Other Nearby Obstacles

Table 1. WAKE BEHAVIOR OF BUILDINGS AND VEGETATION

DISTANCE DOWNWIND $\frac{X}{H}$	5			10			20		
Flow Variable	-ΔV%	-ΔP%	T%	-ΔV%	-ΔP%	T%	-ΔV%	-ΔP%	T%
STRUCTURES (wind directed at face at 90°, measurement at H)									
W/H = 4	36	74	25	14	36	7	5	14	1
= 3	24	56	15	11	29	5	4	12	.5
= 1	11	29	4	5	14	1	2	6	-
= 0.33	2.5	7.3	2.5	1.3	4	.75	-	-	-
= 0.25	2.0	6.	2.5	1.0	3	.50	-	-	-
INDIVIDUAL TREE Dense Foilage (Colorado Blue Spruce)	20	49	-	9	17	-	4	13	-
Thin Foilage (Pines)	16	41	-	7	18	-	3	8	-
SHELTER BELTS (Wind measured at ~ H) Porosity 0%	40	78	18	15	39	18	3	9	15
Loose Foilage 20%	80	99	9	40	78	-	12	32	-
Dense Foilage 40%	70	97	34	55	90	-	20	49	-
Typical Height of Wake Flow Region		1.5			2.0			3.0	

$$\Delta V\% = \frac{U_o - U}{U_o} \times 100$$

$$\Delta T\% = \frac{\overline{U'}}{U} - \left(\frac{\overline{U'}}{U}\right)_o \times 100$$

$$\Delta P\% = \frac{U^3 - U_o^3}{U_o^3} \times 100$$