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WIND-TUNNEL MEASUREMENTS IN THE WAKE OF A SIMPLE STRUCTURE IN A SIMULATED ATMOSPHERIC FLOW

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16. ABSTRACT

Measurements of longitudinal mean velocity and turbulence intensity were made in the wake of a rectangular model building in a simulated atmospheric boundary-layer wind. The model building was a 1:50 scale model of a structure used in a wake measurement program at the George C. Marshall Space Flight Center 8-tower boundary-layer facility. The approach wind profile and measurement locations were chosen to match the field site conditions. The wakes of the building in winds from azimuths of 0 and 47 degrees referenced to the normal to the building long axis were examined. The effect of two lines of trees upwind of the building on the wake and the importance of the ratio of the building height to boundary-layer thickness on the extent of the wake were determined.

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FOREWORD

This study was initiated to determine the feasibility of studying wakes behind buildings and natural obstacles using a scaled model in a wind tunnel. If feasible, the wind tunnel approach has many appealing assets, such as minimal cost, high versatility, and ease of placement of sensors. This report is the first report of a continuing program sponsored by the Aerospace Environment Division of the Space Sciences Laboratory of the Marshall Space Flight Center, National Aeronautics and Space Administration.

The authors are indebted to Mr. John Enders of NASA Headquarters for his support in this program. Appreciation is extended to Dr. George H. Fichtl, Mr. Dennis W. Camp, and Dr. William C. Cliff, who were the Contract Monitors for this work. The authors also wish to extend their thanks to Mr. Herbert Gwochang Woo, who assisted in the data acquisition and analyses.

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LIST OF SYMBOLS

Symbol	Definition
x	Coordinate axis along wind tunnel centerline, positive downwind, zero at rear face of structure.
y	Horizontal coordinate with zero on tunnel centerline
z	Vertical coordinate, measured positive upwards, zero at ground level.
U	Local mean velocity in x direction with model in place.
U_o	Local mean velocity in x direction in absence of the building model.
ΔU	$= U_o - U$
U_{rms}	Root-mean-square velocity fluctuation in the x direction.
$U_{o_{rms}}$	Root-mean-square velocity fluctuation in the x direction in the absence of the building model.
U_∞	Value of U above the boundary layer.
A, B, n	Coefficient in the hot-wire anemometer calibration.
E	Anemometer bridge output mean voltage.
E_{rms}	Root-mean-square of anemometer voltage fluctuations.
H	Building height.
δ	Boundary-layer thickness
m	Wake decay rate

1. INTRODUCTION

An increasing need exists for rapid interurban transportation systems to improve the ease, comfort, and efficiency of intercity travel and to reduce the current congestion at major aiports. One very promising alternative that will ease transportation problems is V/STOL aircraft operating from smaller airports near large population centers. The many advantages of such a transportation system are apparent. But there are questions that must be addressed before embarking on construction of airports in or very near urban areas. One important question deals with the effect of natural winds in and near the airport on aircraft operation. The proximity of large buildings to a V/STOL airport will alter the wind patterns and may significantly change the environment in which aircraft must fly. Increased turbulence and mean wind shear caused by buildings upwind of flight paths may pose serious operational problems for some aircraft. Strong, highly-structured vorticity generated by the flow around buildings (similar to the trailing vortices in the wake of an aircraft) could subject aircraft to large pitching and rolling moments and deterioration of aircraft control which could cause passenger discomfort.

Until recently very little has been known about even the most basic characteristics of the wake behind a building exposed to the turbulent planetary boundary-layer wind. In conjunction with the NASA, George C. Marshall Space Flight Center, Colorado State University is engaged in a study of the wake of a rectangular building deeply submerged in a modeled atmospheric boundary layer. The study has concentrated on defining, in some detail, the structure of the wake and confirming modeling criteria by comparison of laboratory and field data. Model studies in the Meteorological Wind Tunnel at Colorado State University have yielded mean velocity, longitudinal turbulence intensity, and wake geometry information for a selected set of test conditions. The study is continuing with measurement of two-point correlations, longitudinal spectra, and autocorrelations in the wake. In addition, comparison of simulation data will be made with field data taken at the Marshall Space Flight Center eight-tower atmospheric boundary-layer facility, as that data becomes available.

Wakes generated by buildings or other obstacles are characterized by increased turbulence, a mean velocity defect, and in certain situations by organized, discrete standing vortices. The detailed characteristics of these wakes must be known to determine their effect on aircraft performance and operational safety. The distance downwind to which significant wake effects are felt is not presently known for typical airport structures. Only approximate estimates of wake extent and characteristics can be made at present, and then only for very simply shaped obstacles. If highly structured vorticity persists through the near wake of a building the entire character of the far wake will be altered significantly. Just as the vortex wake of an aircraft can persist for many minutes after passage of the aircraft a vortex wake of a building would be expected to extend much farther downwind of a building than a wake containing no standing vortex pattern.

To estimate the effects of buildings or natural obstacles on aeronautical systems, theoretical/empirical models of various types of wakes are required. The most basic wake is that of a building with the approach wind directed normal to its face. This situation has interest both as a reference case for comparison with more complex situations, and of course, for its own intrinsic value. Another basic situation of interest occurs when the building is oriented to the wind in a direction known to result in vortex shedding from the leading corner of the roof. Measurements in the wakes of these two fundamental building configurations are contained in this report.

Knowledge of the structure of building wakes has application to diverse fields. Diffusion of any material released in the wake of a building will be strongly altered by the wake conditions, particularly if the pollutant is released within the separation bubble in the lee of an obstacle or if the wake contains standing vortices. Wind forces on any structure or building in the wake of a second building will be determined in great part by the character of that wake. Airport designers or architects can optimize human comfort, avoid undesirable pockets of high air pollution concentrations, and minimize buffeting of structures and aircraft by considering, perhaps with the aid of a wind-tunnel study, the wind engineering aspects of their designs.

1.1 A Survey of the Literature

The first major efforts to examine the wakes of obstacles placed in a natural wind were the extensive field and wind-tunnel measurements of shelterbelt and windbreak effects. An excellent review of the extensive literature on shelterbelts and a complete list of references can be found in the World Meteorological Organization report on shelterbelt effects (1). Though the windbreak is essentially a two-dimensional obstacle many of the general observations should apply qualitatively to the wake of a three-dimensional body. Of prime interest to the present study of building wakes was the confirmation of the prediction that increasing the surface roughness upwind of the windbreak reduced the extent of sheltered area in the lee of the windbreak. The improved mixing due to the increased turbulence intensity in the approach flow caused more rapid recovery to the undisturbed flow condition. Also of interest was the verification of wind tunnel modeling techniques for the shelterbelt studies.

Only recently has an effort been made to determine the structure and characteristics of full-scale building wakes. Measurements in the wake of a hangar at R.A.E. Bedford reported by M. J. Colmer (2) are the best field measurements available to date. The test site was on a flat low plateau. The hangar was 10 m high and isolated from other airport buildings by 100 m or more. Unfortunately, some large buildings were located upwind of the structure and off to the side of the approach wind vector. The hangar may have been in the meandering edge of the wake of these buildings. Three instrumented towers were located on the lee centerline aligned with the anticipated wind direction and one tower was located five building heights to the side of the centerline. In addition, a tower upwind of the hangar measured the approach flow conditions. Mean velocities, rms velocities, and several autocorrelations and spectra were measured. Only one experimental case was reported, with a one-hour period of measurement. The boundary layer was estimated to be 600 m thick on the morning of the test. Thus, the building was only 1/60 the height of the boundary layer. Colmer drew the conclusions for this particular test that the mean velocity deficit had completely decayed by 14 heights downstream and the turbulence intensity excess, although small, was still apparent at 14 heights downstream.

Tower and flight measurements were made by Cass, Scoggins, and Chevalier (3) in the vicinity of an airport. Their results showed an increase in turbulence levels and a decrease in mean velocities over the runway when the wind blew over the airport buildings and across the runway. The measurement grid had insufficient resolution to draw any conclusions about the extent of the building wake or its structure.

Useful wind-tunnel measurements were made in 1973 by Lemberg (4) in the Boundary Layer Wind Tunnel at the University of Western Ontario. Lemberg examined the wakes of six bluff bodies. Four- and six-inch cubes with flow both normal to the face and at 45° to a face as well as two four-inch diameter cylinders of heights four inches and six inches were used as models. The boundary layer was 24 inches thick at the test location and the approach velocity profile followed a power-law profile with an exponent of 0.16. Extensive mean velocity and turbulence intensity measurements were made. Several general conclusions were drawn: i) the mean velocity wake had effectively decayed in 12 building heights downstream, ii) the turbulence wake extended to 50 heights behind the cubes and up to 80 heights behind the cylinders, iii) three dimensional wakes decayed more rapidly than two-dimensional wakes. Lemberg compared his results to those of Colmer and found that the model wakes were more persistent than the hangar wakes. He attributed this to the order-of-magnitude difference in the ratios of the building height to boundary-layer height between the model and field studies. It is reasonable to expect an obstacle whose height is a significant fraction of the boundary-layer height to be a larger relative disturbance to the boundary layer than the disturbance due to a small obstacle. Also, the turbulence intensity at the model height will be greater for the smaller model and in accordance with the findings for windbreaks the wake will not extend as far downwind.

Earlier, Counihan (5) made wake measurements in a small wind tunnel with an artificially stimulated thick turbulent boundary layer. Limitations in the instrumentation made it necessary to hold the measuring probe fixed and move the model in the tunnel. At each measurement location the model was in a different approach flow condition making the results difficult to interpret. Counihan had a model to boundary-layer height ratio of 1/8. Again, this large ratio is useful for modeling wakes of moderately tall buildings but will predict too long a wake extent for wakes of small buildings.

Some theoretical treatments of three-dimensional wakes are available. Sforza (6) provided a simple linearized theory. Hunt (7, 8) showed a theory for a three-dimensional wake and compared it to Counihan's (5) experimental results. Arbitrary constants were required to obtain a best fit. Insufficient experimental data is available to test the breadth of that theory. Lemberg (4) presented a theory to fit his data, but assumed the form of much of the solution.

1.2 Wind-Tunnel Modeling--Similarity Criteria

Wind-tunnel simulation of atmospheric flows offers the great advantage of providing accurate, detailed information taken under closely controlled and well-known conditions at a fraction of the cost of a less extensive field study. Naturally, modeling the aerodynamic flow around a building or structure requires special consideration of the flow conditions to guarantee similitude between model and prototype. A detailed discussion of the similarity requirements is given in references (9) and (10). In general, the requirements are that the model and prototype be scaled in geometry, that the approach mean velocity at the building site have a vertical profile shape similar to the full scale flow, that the turbulence characteristics of the flows be similar, that the Reynolds number for the model and prototype be equal, and that the thermal stability characteristics of the flows be similar.

These criteria are satisfied by constructing a scale model of the structure and its surroundings and performing the wind tests in a wind tunnel specifically designed to model the important characteristics of atmospheric boundary-layer flows. Reynolds-number similarity requires that the quantity UL/ν be equal for model and prototype. Since ν, the kinematic viscosity of air, is identical for both, Reynolds numbers cannot be made precisely equal with reasonable wind velocities. The wind velocity in the tunnel would have to be the model scale factor times the prototype wind. However, for sufficiently high Reynolds numbers ($>2 \times 10^4$) the flow about the structure will be essentially Reynolds number independent (9). Typical values encountered are 10^7 for a 50 ft high building and 5×10^4 to 10^5 for a scale model. Thus, acceptable flow similarity is achieved without precise Reynolds number equality. Thermal similarity of the model and prototype flows requires equality of the Richardson numbers of both. However, for the case of strong winds considered in this study, the thermal stability is essentially neutral. Thus, thermal similarity is achieved using isothermal wind-tunnel flows.

2. TEST FACILITIES AND MEASUREMENT METHODS

2.1 The Wind Tunnel

The wind study was performed in the Meteorological Wind Tunnel located in the Fluid Dynamics and Diffusion Laboratory at Colorado State University, Figure 1. The tunnel is a closed circuit facility driven by a 250 hp variable-pitch, variable-speed propeller. The test section is nominally six ft square and 88 ft long fed through a 9-to-1 contraction ratio. The test section walls diverge 1 inch/10 ft and the roof is adjustable to maintain a zero pressure gradient along the test section. The mean velocity can be adjusted continuously from 1 to 120 fps. The wind speed in the test section does not deviate from that set by the speed controller by more than 1/2 percent. The tunnel is equipped with a refrigeration system to maintain the air temperature at a constant level (±1°F). The facility is described in detail by Plate and Cermak (11).

2.2 Test Configuration

The floor of the wind tunnel was covered with a nylon shag carpet selected to produce an approach wind profile similar to that expected at the NASA Huntsville field site. The approach flow velocity profile followed a power-law profile with an exponent of 0.25 and the boundary-layer thickness at the building site was 24 inches. There are two lines of trees upwind of the field site. These treelines were modeled in the wind tunnel for many of the experiments using both nylon net screens and plastic artificial plants of scale height and appropriate porosity. Building models were constructed from styrofoam and mounted on a 1/8 inch thick steel plate. The steel plate was then placed on the carpet so that the shag fibers extended above the height of the plate. This arrangement made it possible to remove and replace the model several times without elaborate anchoring procedures.

2.3 Experimental Apparatus and Data Reduction Procedures

Two instruments were used to make velocity measurements in the wake of the model building. A survey of the wake was made first with a pitot-static tube connected to an MKS Baratron Pressure Meter (Type 77). The pressure meter output and probe position output were connected to an x-y recorder to obtain a continuous profile of dynamic pressure in either a horizontal or vertical traverse of the wake. This preliminary survey of mean velocities was useful in determining the extent of the wake and in identifying points where more detailed measurements should be made.

More detailed mean velocity and turbulence measurements were made using a constant temperature hot wire anemometer system. Initially a tungsten hot wire was used as the velocity sensor. The wire had a diameter of 0.0005 inch. For later work a hot-film sensor was used. The film was a Thermo-Systems, Inc., TSI-10 quartz coated cylindrical film with a 0.001 inch diameter and a 0.020 inch sensitive length. The use of a hot film resulted in increased calibration stability and reliability with virtually no compromise of frequency response or other desirable hot-wire characteristics.

The hot wires (films) were calibrated daily using a Thermo-Systems, Inc., model 1125 calibrator and the MKS Baratron Pressure Meter. Calibration data were fit to a variable exponent form of King's Law

$$E^2 = A + BU^n$$

using a least-squares fitting program. From this equation it can be shown that the local turbulence intensity is given, to a first order approximation, by

$$\frac{U_{rms}}{U} = \frac{2E\ E_{rms}}{n(E^2 - A)}$$

Mean values of the anemometer bridge output were measured using a Hewlett-Packard integrating digital voltmeter (Model 2401C). True root-mean-square voltages were read by averaging for one minute the d-c output of a DISA Model 55D35 rms voltmeter with the integrating voltmeter.

It was not feasible to calibrate the hot wires in air at the same temperature as the air in the tunnel test section. To avoid any error due to the difference in calibration and test temperatures the method of Bearman (12) was used to correct the measured voltages to the value that would be measured if the sensor were in air at the temperature of the calibrator flow. There are two basic conditions that must be met to ensure accuracy of the Bearman correction. Temperature differences must be small (less than approximately 20°F) and wind speeds must be greater than 3-5 ft/sec. Both of these conditions were met in all tests performed.

To obtain an accurate measure of the influence of the building model on the boundary layer flow, mean velocity and turbulence intensity profiles were taken both with and without the model in place. The profile without the model in place was always taken immediately after the measurement of the profile with the model in the tunnel. Since the time required for significant drift in the hot-wire calibration is greater than the time required to measure two velocity profiles the effect of any drift was small and tended to cancel when the velocity defects and turbulence excesses were calculated.

2.4 Test Program Details

A primary objective of the study was to model in the wind tunnel a structure for which corresponding measurements were to be made in a prototype situation. A small structure under test at the Marshall Space Flight Center was selected. A schematic of the test site is shown in Figure 2. Measurement locations were selected to correspond to locations of instrumented towers at the field site. The model building was constructed to a scale of 1:50. This scaling resulted in a model 2.56 inches high, 6.24 inches long, and 1.92 inches wide. The tunnel was operated at a free-stream velocity of 53 ft/sec. The Reynolds number based on the model height and the velocity at the height of the model in the undisturbed boundary layer was 4.2×10^4. This value is above the value where Reynolds number effects are no longer important for flow over sharp-edged obstacles. The ratio of model height to boundary-layer height was 1/9.4.

With the model oriented with its long face normal to the wind (0^o wind), measurements of longitudinal mean velocity and turbulence intensity were made along horizontal traverses in the lateral direction. Profiles were measured at the following locations which included the positions of instrumented towers in the full scale experiment:

1. Tower 1 (x/H = -6.3) z = 2.4" and 4" (z/H = 0.94, 1.56)
2. Tower 2 (x/H = 0.56) z = 2.4" and 4"
3. Tower 3 (x/H = 2.55) z = 2.4" and 4"
4. Tower 3 1/2 (x/H = 4.86)z = 1 3/4", 2", 2.4", 3", 4"
(z/H = 0.68, 0.78, 0.94, 1.17, 1.56)
5. Tower 4 (x/H = 7.17) z = 2.4" and 4"
6. Tower 4 1/2 (x/H = 12.9) z = 2.4" and 4"
7. Tower 5 (x/H = 18.55)z = 2.4" and 4"

8. Tower 30H (x/H = 30) z = 2.4" and 4"

9. Tower 6 (x/H = 45.6) z = 2.4" and 4"

All of these tests were without the model trees in the wind tunnel. Measurements with the trees in place were made at locations 1, 2, 3, 5, 7, 8, and 9 at a height of z = 2.4" only. Another series of tests was conducted without trees and with the model turned so that the approach wind formed an angle of 47° with the perpendicular to the long axis of the building. This is an angle at which flow visualization photographs showed strong vortex formation on the leading top corner of the building. Vortex formation on the leading corner occurs over a wide range of wind directions but visual observation showed the 47° wind produced the best defined vortex pair. Profiles were taken at a height z = 2.4" at locations numbered 1 through 7 above. Pitot-tube profiles were taken at additional locations downwind of Tower 5 until the mean velocity wake disappeared or the end of the test section was reached.

Vertical profiles of velocity and turbulence intensity were measured at all instrumented tower locations (including towers off the centerline) with the wind normal to the model face.

To determine the effect of H/δ on the decay of the mean velocity wake, the mean velocity wakes of models of scale 1:106 and 1:21.3 were examined with Pitot-tube traverses. The 1:50 scale model wake was examined with both hot-wire and Pitot-tube traverses. The three models, of scales 1:106, 1:50, and 1:21.3, are termed models 1, 2, and 3 respectively in this report.

All heights (z) reported are measured from the reference of the bottom of the shag pile of the carpet. All distances downstream (x) are measured from the line of intersection of the tunnel centerline with the plan of the rear face of the building. Rotation of the model was done about its center.

3. RESULTS AND DISCUSSION

3.1 Effect of the Upwind Trees on the Wake

The effect that upwind tree lines which occur at the field site may have on the wake characteristics was examined first. Figures 3a and 4a show vertical profiles of turbulence intensity and mean velocity taken with and without the treelines in the tunnel but with all other conditions the same. It can be seen that the trees cause a definite but small change in the wake strength. The effect of the trees is to give the flow approaching the building a higher turbulence level and a higher exponent in the power-law velocity profile (from 0.25 without the trees to .35 with trees). This change in the approach flow is shown in Figures 3b and 4b.

Since the effect of the trees was small and the results for the tests without the trees in the tunnel are more generally applicable all detailed measurements were made without the trees in place. All subsequent measurements shown in this report were made without trees in the tunnel.

3.2 Basic Wake Description

When the wind approaches normal to the long building face the simplest possible building wake structure is formed. The wake is symmetric about a vertical plane through the tunnel centerline. Strong, organized, standing-vortex patterns are not observed except for the familiar horseshoe vortex system. These vortices do not persist to form standing vortices in the far wake.

Figure 5 shows profiles of normalized velocity deficit at several downwind locations behind the building with the 0^{o} wind. The velocity deficit is simply the velocity at a point in the wake of the building subtracted from the velocity at the same location in the undisturbed boundary layer ($\Delta U = U_o - U$). The mean velocity wake is symmetrical about its centerline as expected. Considerable detail can be seen in the wake. The deficits are positive everywhere except near the building sides where the flow must accelerate to go around the building. The wake strength decreases smoothly downwind. At Tower 5 (x/H = 18.6) no mean velocity deficit is evident. Thus the mean velocity wake has decayed within 16-18 building heights downwind of the building. The wake widens slowly until it spans approximately five building widths at x/H = 12.8. It should be noted that Tower 2 is in the separation bubble behind the building. The hot wire anemometer is not designed to make accurate measurements in regions of high turbulence intensity such as separated flow regions. Thus the results presented at Tower 2 are not highly accurate but certainly demonstrate useful qualitative information. The error in measurement tends to show a higher mean velocity (lower velocity deficit) than really exists.

The nature of the turbulence intensity wake is shown in Figure 6. Again, the wake is symmetrical about its centerline. Of interest is the increase in turbulence intensity in the high shear regions at Towers 2, 3, and 3 1/2 near the sides of the building. These sharp peaks and gradients in turbulence intensity diffuse outward rapidly to give the smooth profile seen at Tower 4. Just as for the mean velocity wake, the turbulence wake spans approximately five building widths at Tower 4 1/2 and extends to approximately 16-18 building heights in the downwind direction.

The nature of the wake in a vertical plane is shown in Figures 7 and 8. The fine grid of measurements at Tower 3 1/2 was made to determine whether the wake structure changes significantly at different heights above the ground. The interesting result is that not only the basic nature of the wake but also the actual values of velocity deficit and turbulence intensity excess do not change at different heights until the top of the wake is approached. This means that a measurement at one height in the wake will be closely representative of measurements at several heights at the same downwind position. Two points should be noted from the figures. First, the wake narrows at greater heights above the ground. Second, at the lateral edge of the wake the velocity defect is stronger near the ground than it is at higher elevations but near the wake centerline the intermediate heights show the stronger defect . As already noted, these differences are quite small.

3.3 Effect of H/δ on the Wake Decay Rate

Lemberg (4) recognized that proper scaling of the building height relative to the boundary layer height may be necessary for proper wind tunnel modeling of building wakes. To examine this hypothesis, the mean velocity wake of the building at three different scales was studied. Figure 9 shows the results of measuring the mean velocity deficit along the centerline for these models at a height near $z/h = 0.9$. Field data taken behind a hangar by Colmer are shown for comparison.

The measurements show the important result that the decay rate (m) is independent of H/δ but that the magnitude or strength of the velocity deficit does depend on H/δ. Thus, to properly model a building wake the value of H/δ must be scaled for the model and the prototype. Figure 9 does suggest, since the decay rates are equal, that an empirical relation may be obtainable to scale the wake strengths if it is not possible to properly model the value of H/δ.

Some care must be taken in interpreting the measurements behind the large 1/21.3 scale model (Model 3). The model is so wide its wake impinged on the side walls of the wind tunnel at approximately $x/H = 10$. Beyond this point the wake was influenced by the tunnel walls and thus no longer represented a correct modeling of the desired flow situation. The magnitude of the interference effect is not known though it is anticipated that the influence on the flow near the tunnel centerline for moderate downstream distances was small.

The agreement between the wind-tunnel tests for model 1 and Colmer's field measurements is encouraging. The data agree despite a significant difference in H/δ. This difference may be compensated by the larger turbulence intensity in the wind-tunnel tests. Since the wake extent increases with increasing H/δ and probably decreases with increasing turbulence intensity, the deviations of the wind-tunnel model from the field data may have provided two essentially canceling effects. An alternate explanation may be that H/δ is not a significant factor in wake extent for small values of H/δ. The fact that the decay rates, m, are essentially the same for the two data sets is most significant. Further comparison with field data can be performed when data from the modeled site of Marshall Space Flight Center becomes available.

Wind-tunnel tests by Lemberg (4) on the wake of a cube showed a mean velocity wake decay rate (m) of -1.58. This is in very good agreement with the values of -1.55 and -1.85 measured in the present work in the wake of the block normal to the wind.

3.4 Wake of the Model Turned 47°

The wake assumes a completely different nature when the wind approaches at an angle of 47°. In this configuration flow visualization photographs show a pair of standing longitudinal vortices being generated at the leading corner of the roof (Figure 10). It appears that these vortices extend into the far wake of the building, since the vortex is an extremely stable flow pattern. The only mechanism available to dissipate the angular momentum of a vortex is viscous or turbulent stress acting to produce a moment about the vortex axis. Unless interactions (such as the Crow instability (13) that causes breakdown of aircraft vortex pairs) occur immediately, the vortex wake shed from the building will extend much farther downwind than the wake of the building that doesn't shed a standing vortex pattern. Comparison of Figures 5 and 11 and Figure 13 show this concept clearly. Even at 80 building heights downwind the mean velocity wake is apparent. This behavior is drastically different from the complete wake decay within 16-18 model heights downwind for the model at 0^{o}. Notice also that the wake shows a velocity excess at some lateral locations rather than a velocity deficit all across the wake. This velocity excess is the proportion of the wake that extends far downwind. The wake was followed as far downwind as the wind-tunnel test section length allowed with virtually no measurable change in the magnitude of this velocity excess. Of course, the measurements shown in this report are of longitudinal wind speeds. The vertical and lateral mean velocities associated with the vortices have not yet been measured.

A possible simple mechanism to account for the increase in longitudinal wind speeds can be identified by examining the direction of rotation of the vortices. When viewed looking downwind the right-hand vortex rotates counterclockwise while the left-hand vortex rotates in a clockwise direction. Thus, between the vortex pair, air is being swept downward toward the ground. High-speed air from the upper portion of the boundary layer is brought nearer to the ground and velocities near the ground are increased.

The turbulence-intensity wake also extends farther downwind when the model is oriented so that a vortex pair is generated, but not as dramatically as the mean velocity wake. Figure 12 shows profiles of longitudinal turbulence intensity at three downwind locations. At Tower 5 the turbulence intensity shows a deficit rather than an excess. However, examination of the root-mean-square of the wind speed fluctuations and Tower 5 shows that the rms is very nearly constant and variations in the turbulence intensity are due solely to variations of the mean wind speed.

Figures 13 and 14 show the decay of the mean velocity and turbulence intensity wakes along the centerline at $z/H = 0.94$. The persistence of the wake containing the vortex pair is quite evident. The turbulence intensity wake has two characteristic decay regions. The first region extends to approximately 10 building heights. In this region the decay is similar to that of the wake of the model at 0°. Beyond approximately 10 building heights the decay proceeds more slowly and is affected only slightly by the existence of the vortex pair.

The implications of these measurements are highly significant. They demonstrate that the wake is extremely persistent, but perhaps more importantly, the measurements and flow visualization show that the wake has a definite swirling character. The concentrated vorticity in the wake may pose a real danger to aircraft flying through the wake. Additional work to measure the magnitudes of the swirling velocities an aircraft may encounter is certainly warranted.

One difficulty arises concerning the modeling of the vortex wake at the 47° azimuth. Saffman (14) has indicated that the decay rate of of a turbulent line vortex is Reynolds-number dependent. He indicates that a variation in the decay rate by a factor of roughly three is noticed when the Reynolds number (based on the swirl velocity and the core diameter) is changed from 2×10^3 to 10^7. The Reynolds numbers of wind-tunnel tests may be on the order of one to two orders-of-magnitude less than field site Reynolds numbers. Because no data exists for structures in an atmospheric flow, an area for future investigation is evident. The need is to determine if a Reynolds number dependence exists in the range of Reynolds numbers likely to be encountered in situations of interest and what the dependence of the decay rate on the Reynolds number is. The formation of the vortex wake is not Reynolds-number dependent for a sharp-edged building but the vorticity decay rate may be Reynolds-number dependent.

4. CONCLUSIONS

Detailed measurements of longitudinal mean velocity and turbulence intensity have been made in the wake of a rectangular block model deeply submerged in a turbulent boundary layer. The approach velocity profile is similar to that of a natural wind over a moderately rough, lightly forested grass plain and was selected to closely model conditions at the 8-Tower planetary boundary-layer test site of the NASA George C. Marshall Space Flight Center.

Measurements were made with the wind approaching normal to the long face of the building (0° wind) and for the 47° wind. When the wind blows at 0° the wake is symmetrical and persists to approximately 16-18 building heights downwind of the model. The mean velocity and turbulence intensity wakes both decay in this distance. When the wind blows at 47° to the model the wake assumes a completely different character. Standing longitudinal vortices are formed in the wake and the result is a much slower wake decay rate. At 80 building heights downwind a velocity excess is still evident and has the same value as the excess at locations near the model. The turbulence wake decays more quickly than the mean velocity wake. At $x/H = 18$ the rms of the velocity fluctuations is essentially the same as in the undisturbed boundary-layer flow.

Measurements in the wake of three models of identical proportions but different scales showed that the mean velocity wake decay rate is independent of model scale. But the magnitude of the disturbance is, in a non-dimensional sense, greater for the larger model and hence its wake persists farther downwind in non-dimensional coordinates. To properly model the wake of a building the relative heights of the building and the boundary layer must be modeled to scale. Agreement was obtained between the field measurements in the wake of a hangar by Colmer and the present wind tunnel tests. More conclusive comparisons will be made with the NASA field site data.

The measurements have identified the region in the lee of an isolated building of simple shape where aircraft will operate in an altered wind environment. To assess the hazard to aircraft posed by the vortex wake of a building, measurements must be made of the swirling velocities that will be encountered in the vortices. In addition, field measurements should be made to verify the wind tunnel modeling of the vortex wake.

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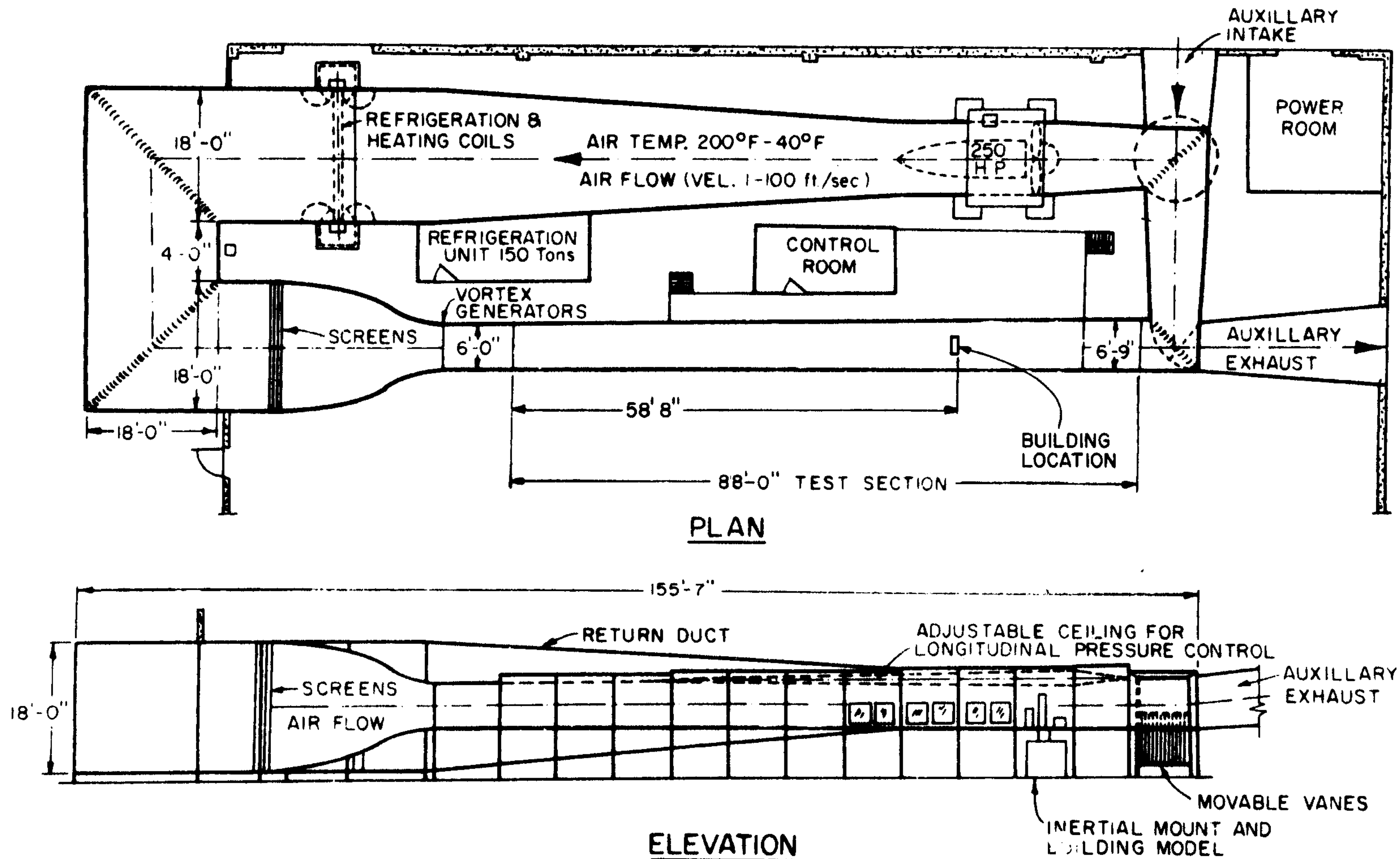

Figure 1. Meteorological Wind Tunnel Facility, Fluid Dynamics and Diffusion Laboratory, Colorado State University.

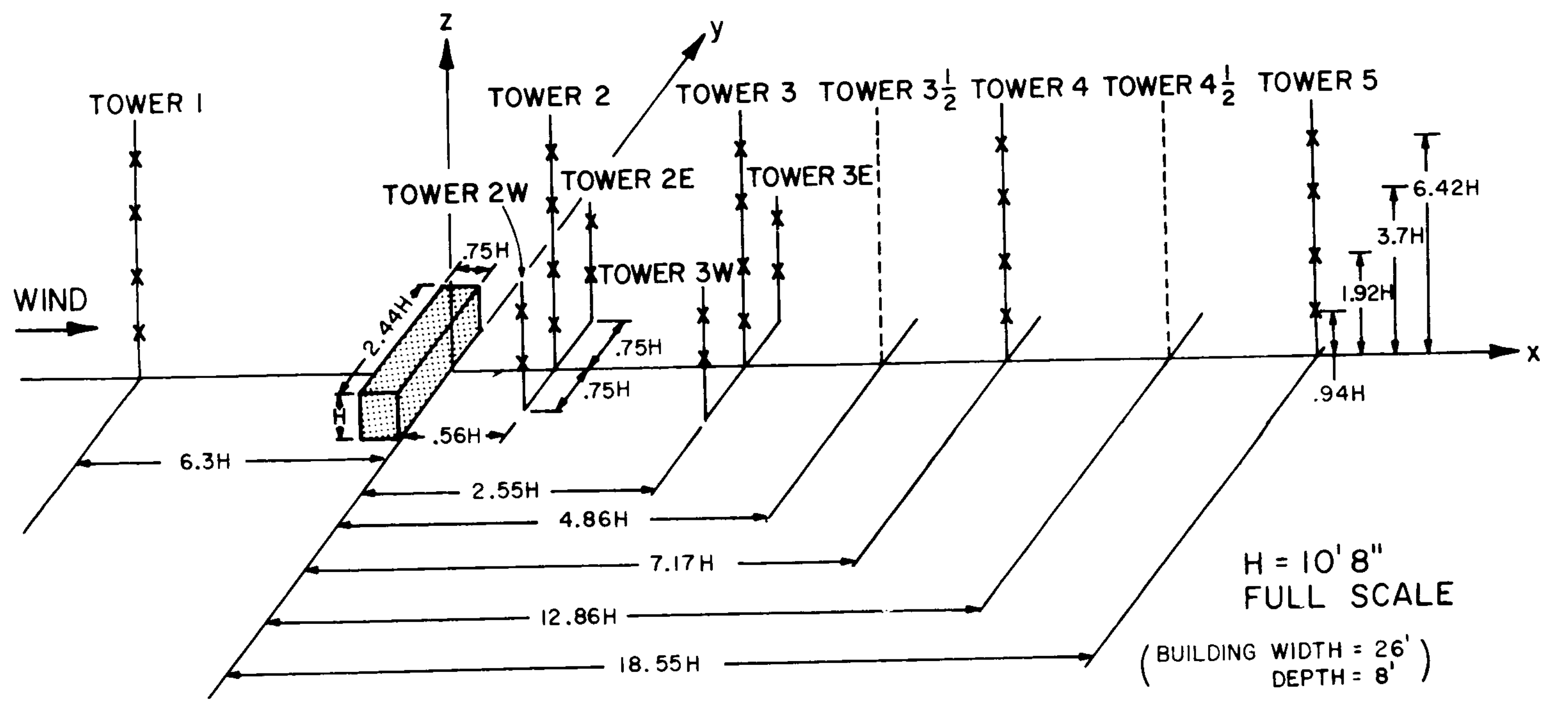

Figure 2(a). Schematic View of the NASA, George C. Marshall Space Flight Center Eight Tower Boundary-Layer Facility (Not to scale).

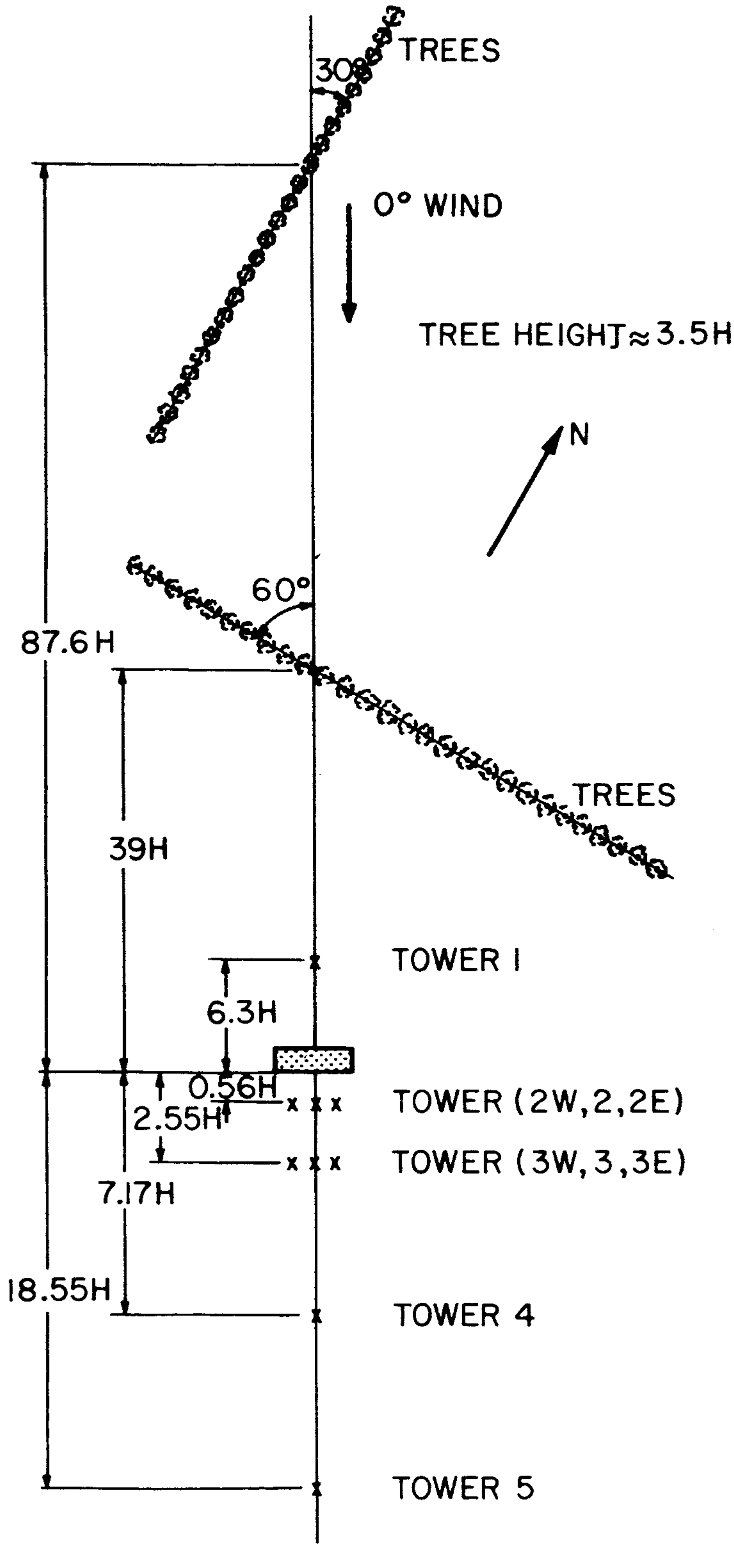

Figure 2(b). Schematic View of the NASA, George C. Marshall Space Flight Center Eight Tower Boundary-Layer Facility (Not to scale).

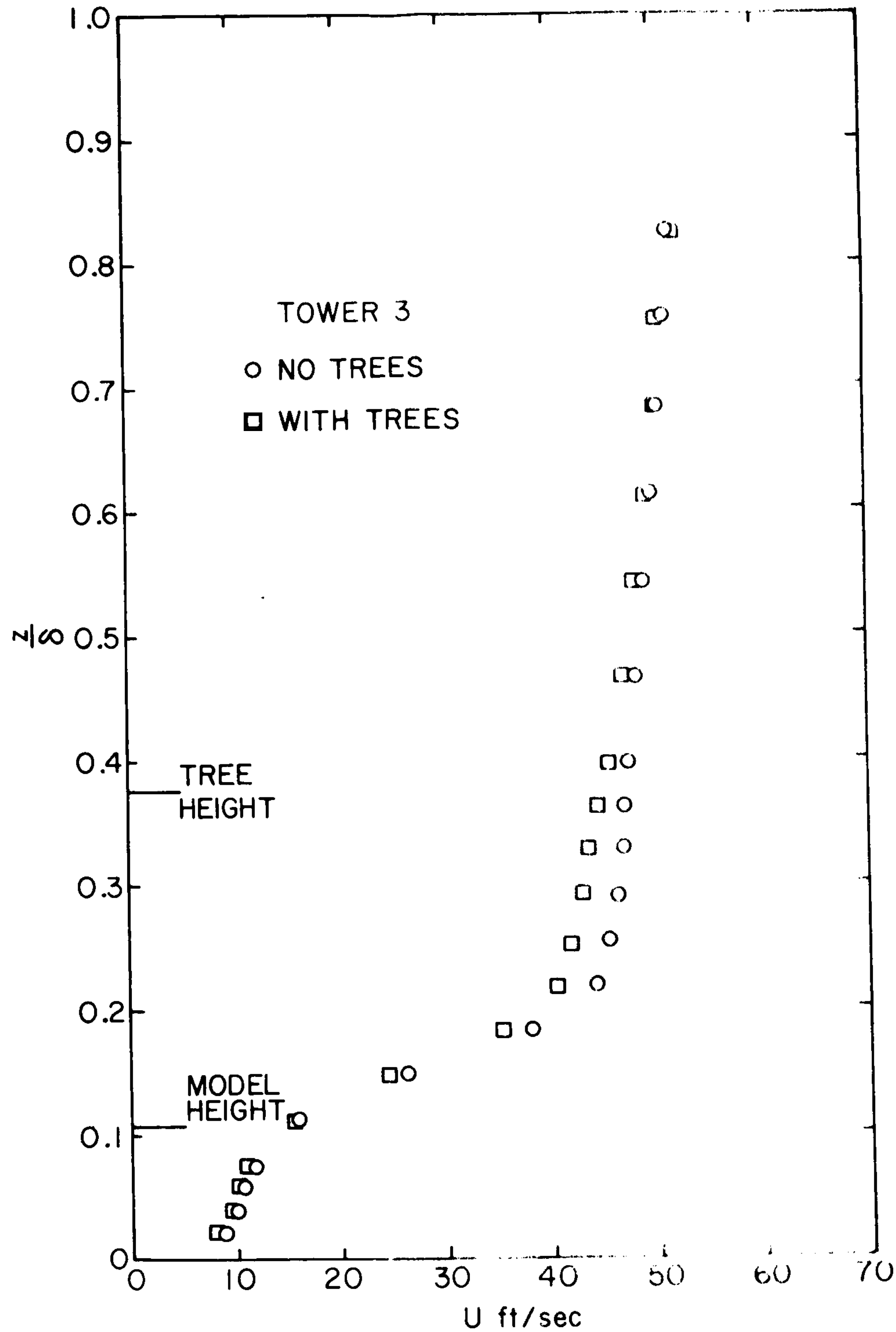

Figure 3(a). Vertical Profile of Longitudinal Mean Velocity Behind the Building Model (Tower 3)

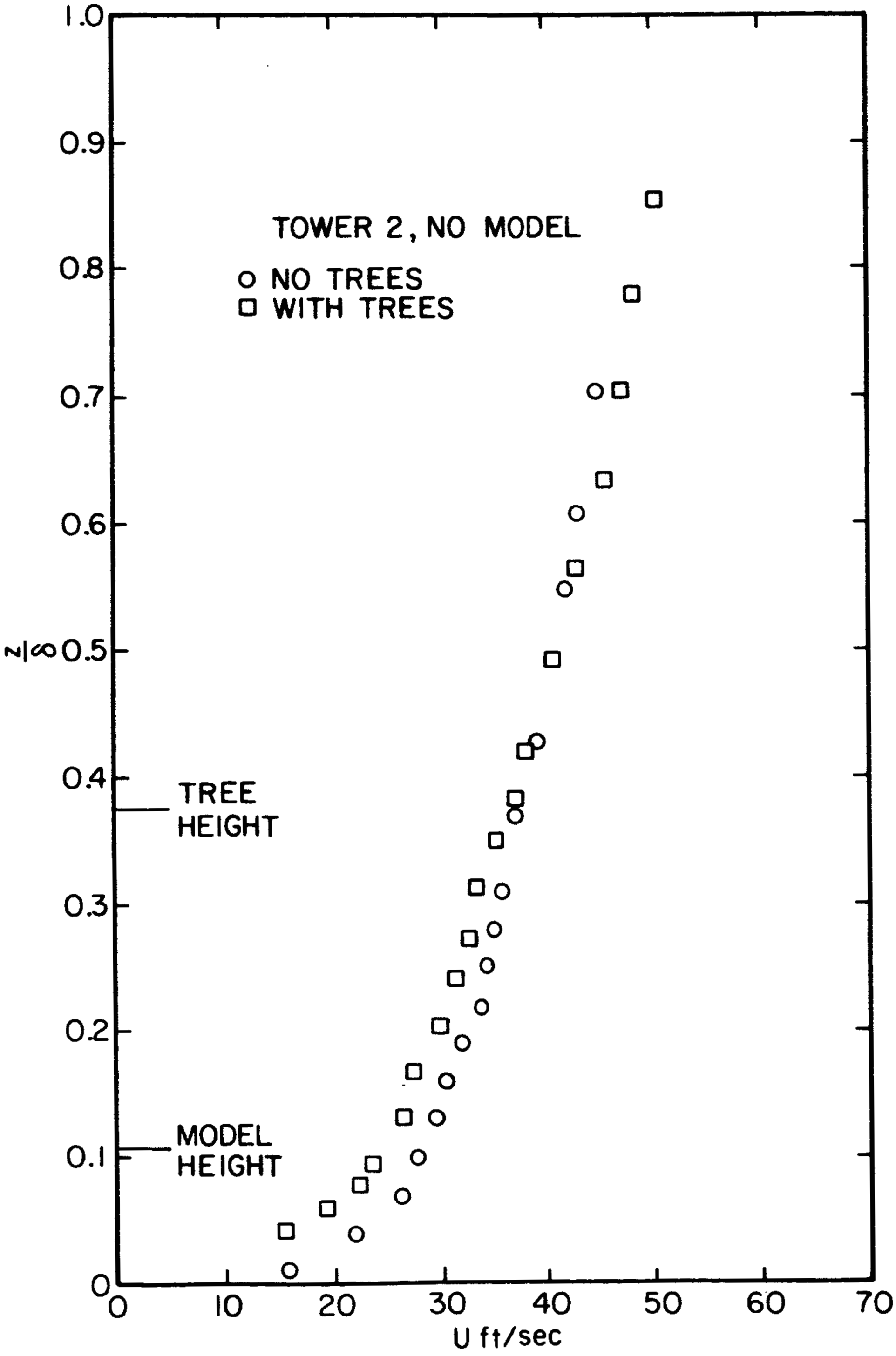

Figure 3(b). Vertical Profile of Longitudinal Mean Velocity in the Approach Flow.

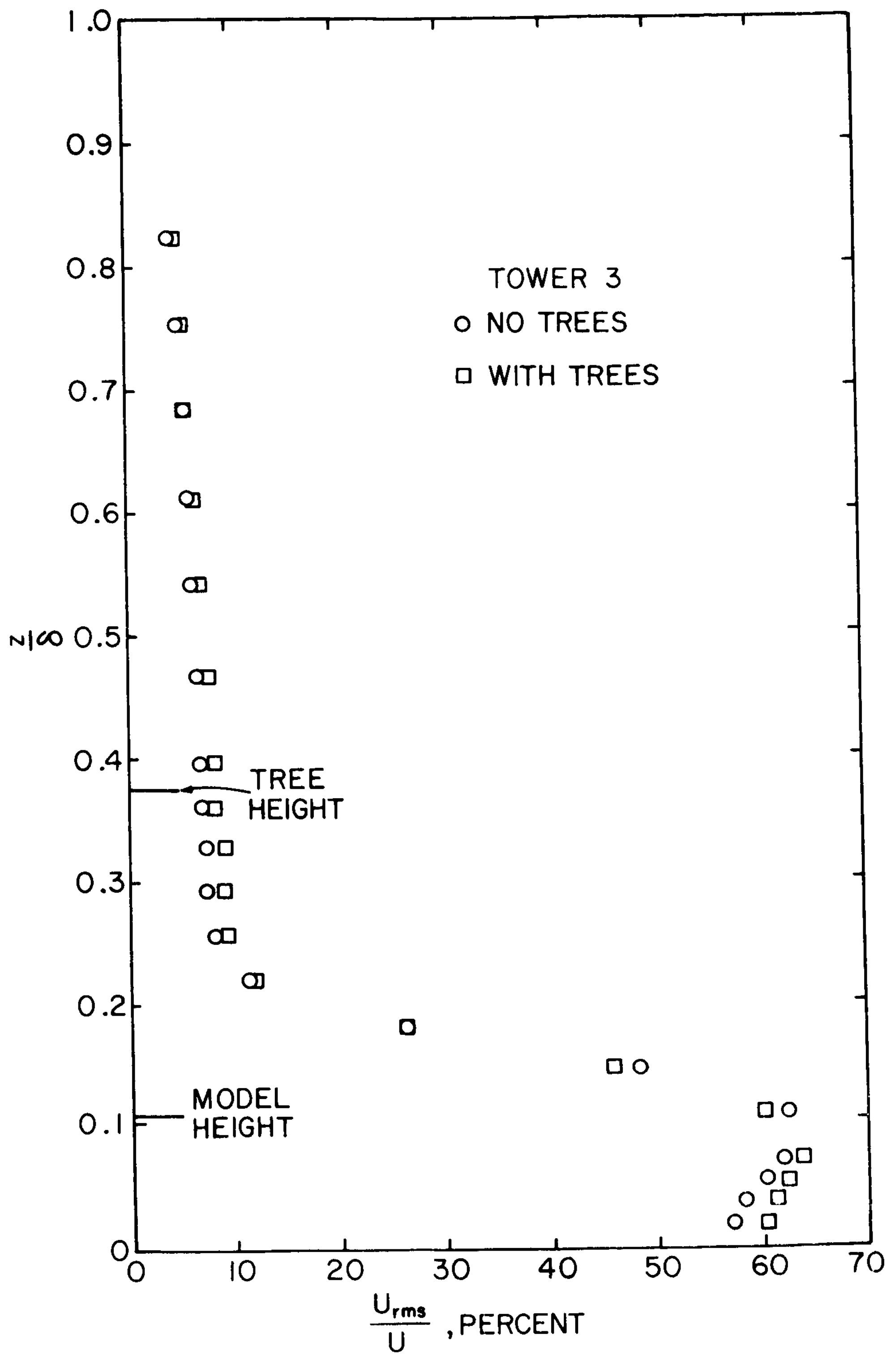

Figure 4(a). Vertical Profile of Longitudinal Turbulence Intensity Behind the Building Model (Tower 3).

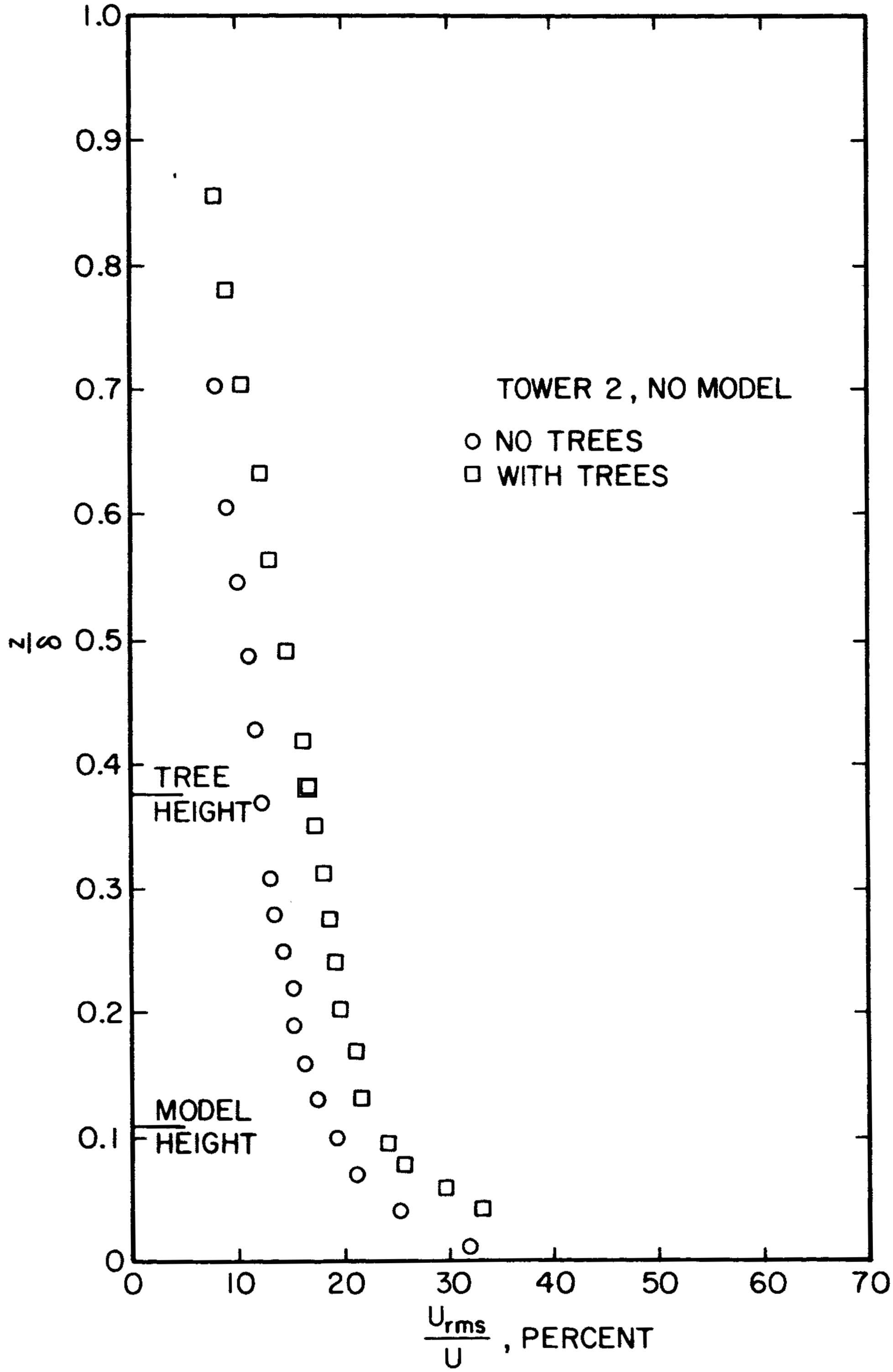

Figure 4(b). Vertical Profile of Longitudinal Turbulence Intensity in the Approach Flow.

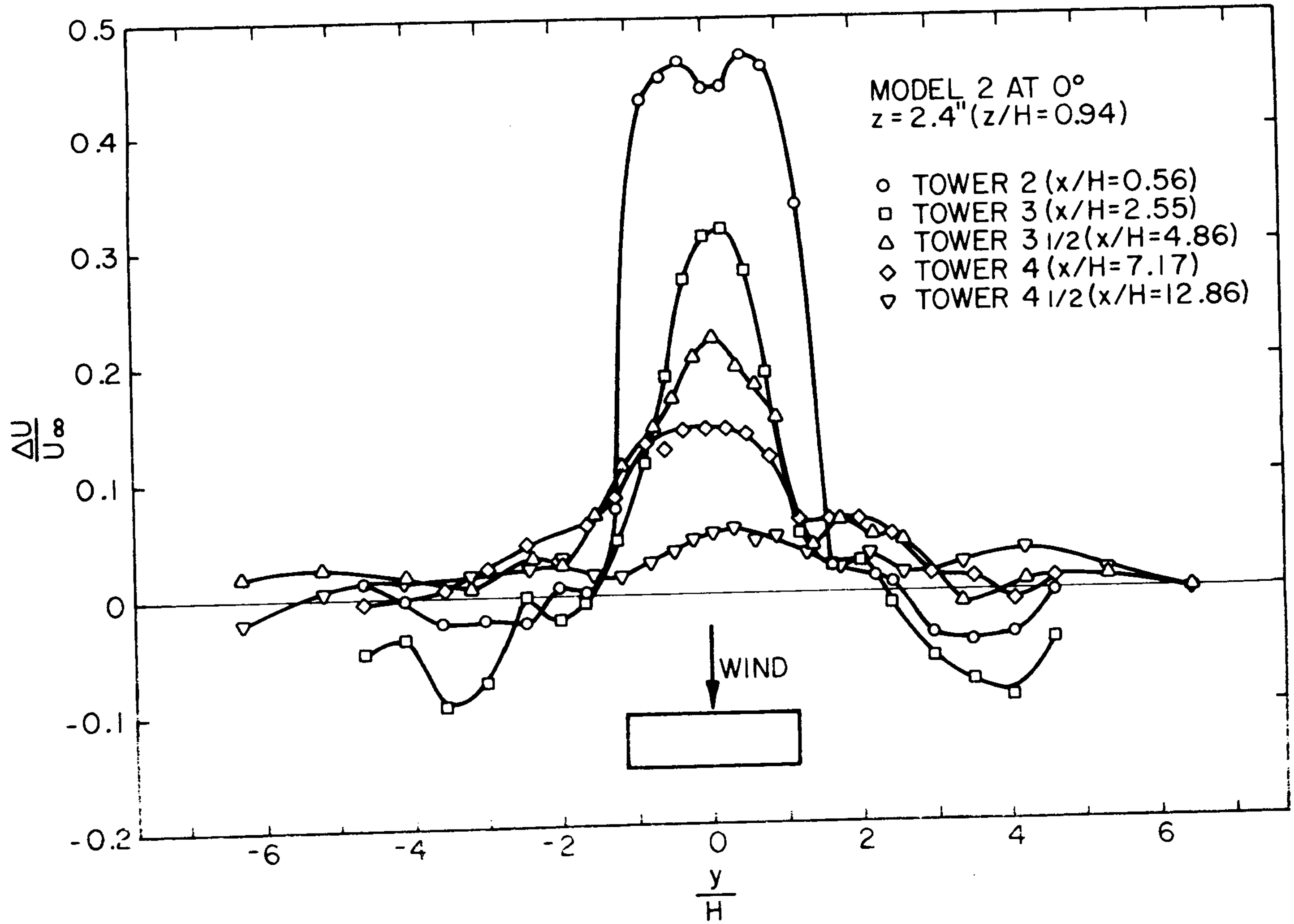

Figure 5. Lateral Profiles of Mean Velocity Deficit in the Wake of the Building at 0 Degrees.

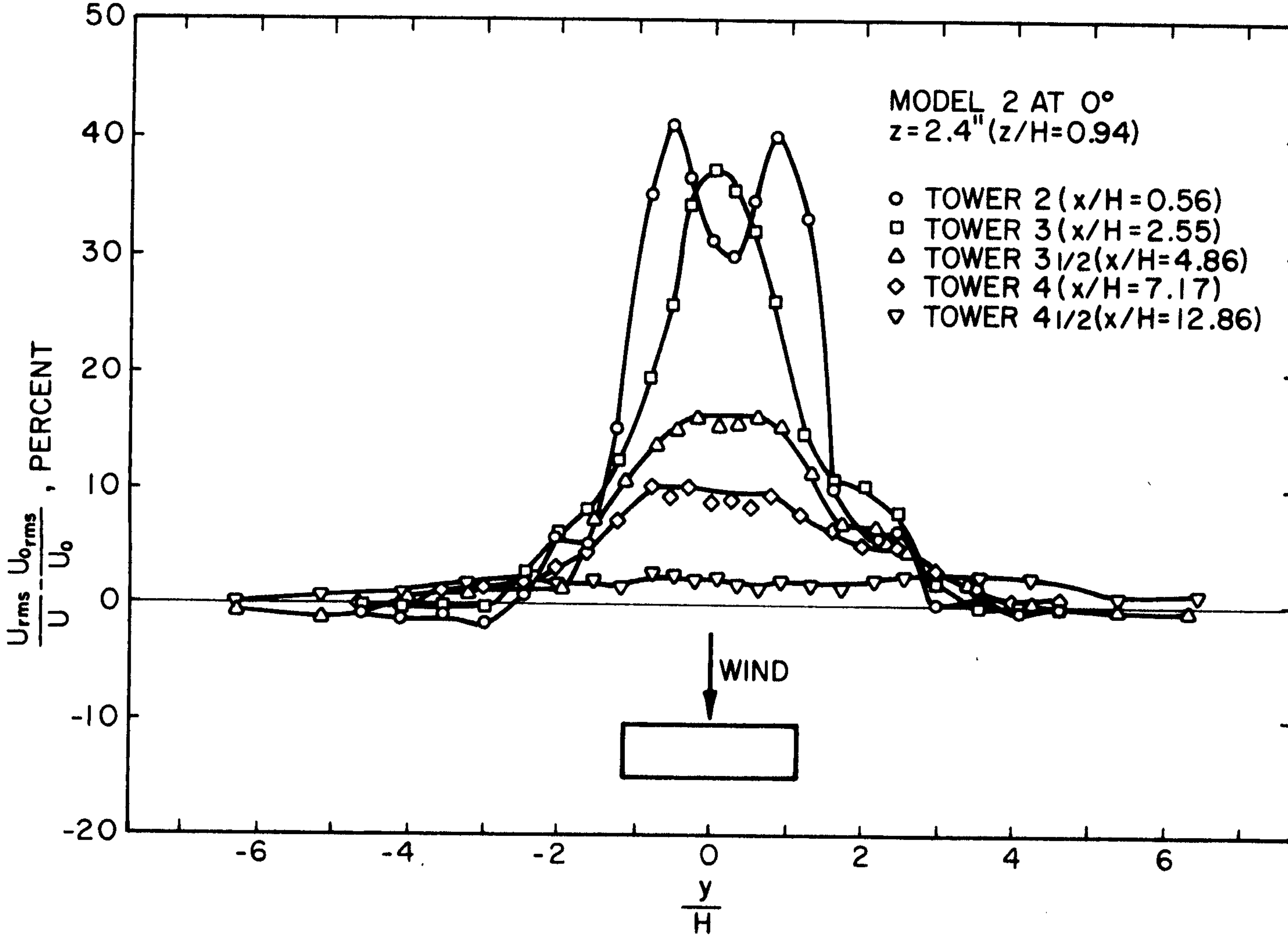

Figure 6. Lateral Profiles of Turbulence Intensity Excess in the Wake of the Building at 0 Degrees.

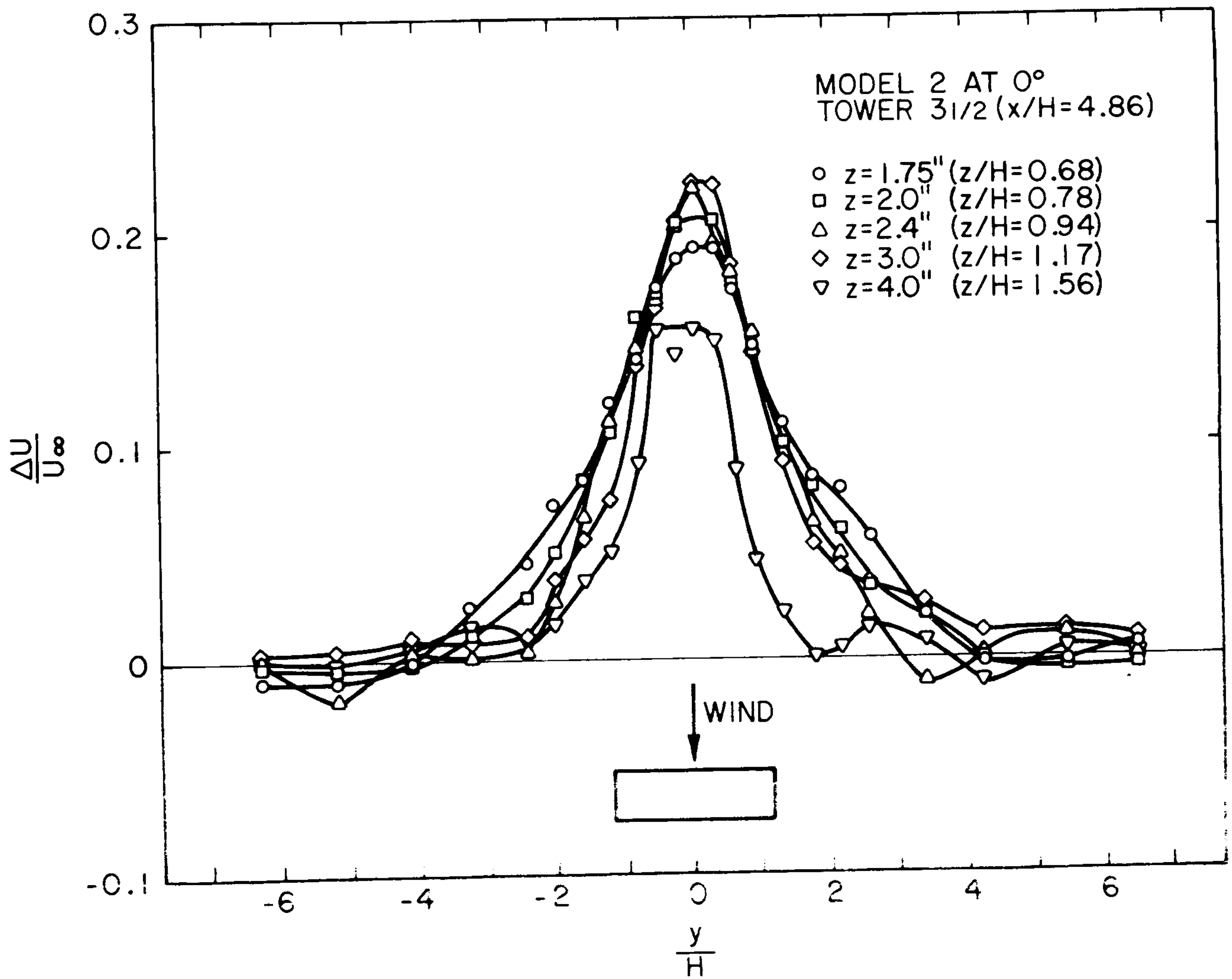

Figure 7. Lateral Profiles of Mean Velocity Deficit at Five Heights Above the Ground on Tower 3½.

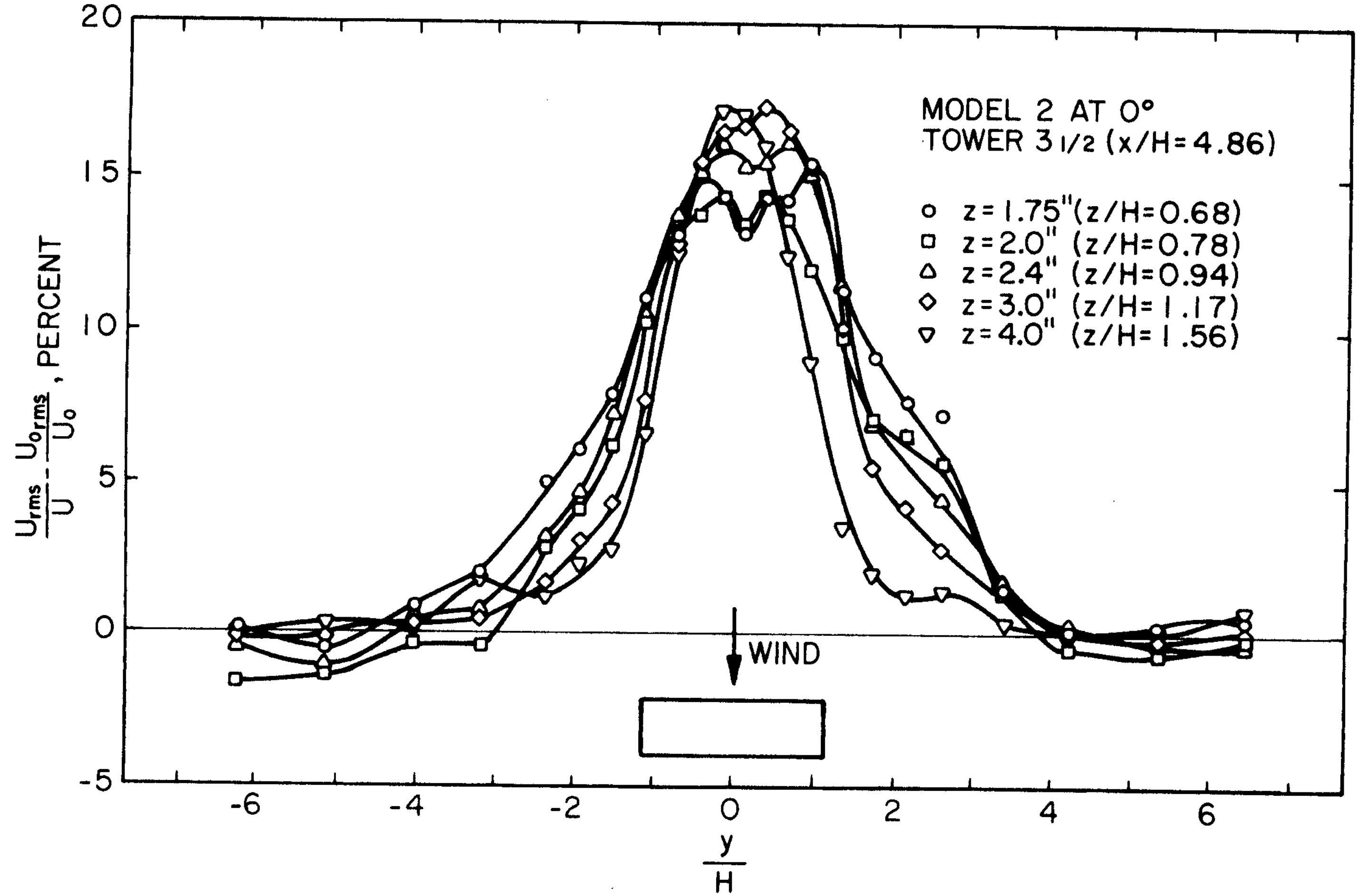

Figure 8. Lateral Profiles of Turbulence Intensity Excess of Five Heights Above the Ground on Tower 3½.

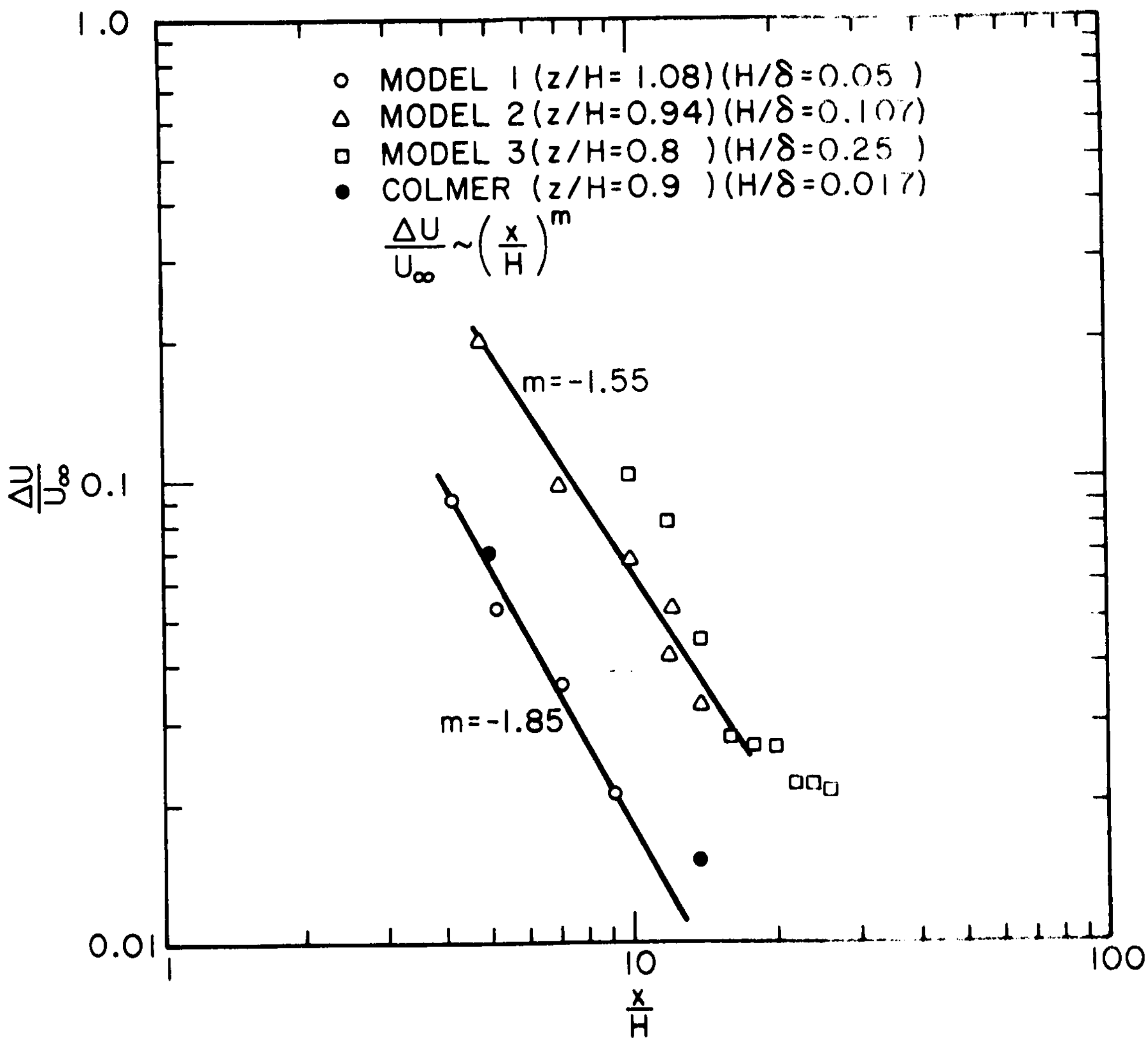

Figure 9. Decay of Mean Velocity Deficit Along the Wake Centerline for Values of H/S.

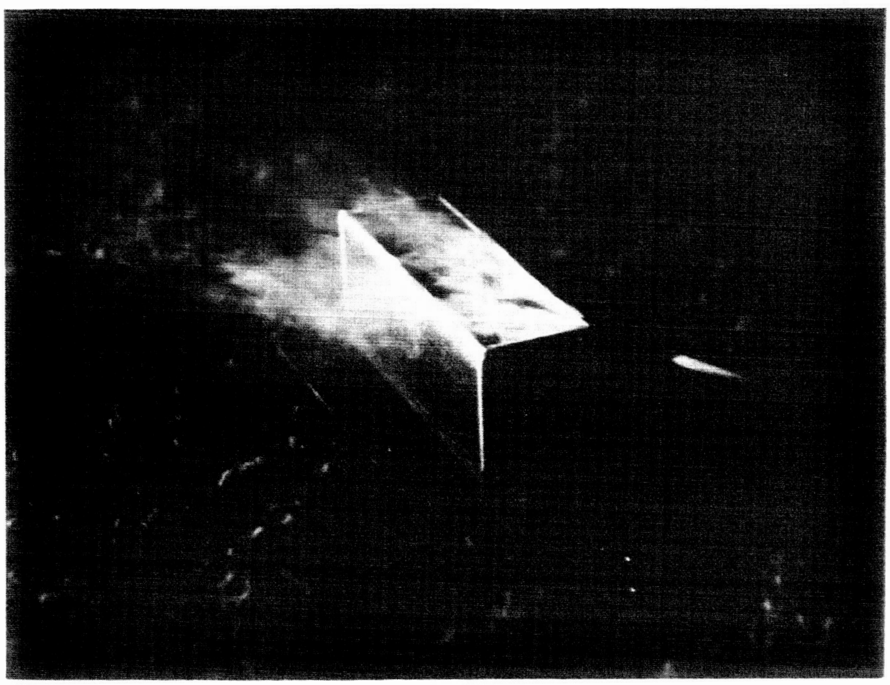

Figure 10. Flow Visualization of the Roof Corner Vortices with the Wind Approaching at 47 Degrees to the Building Face.

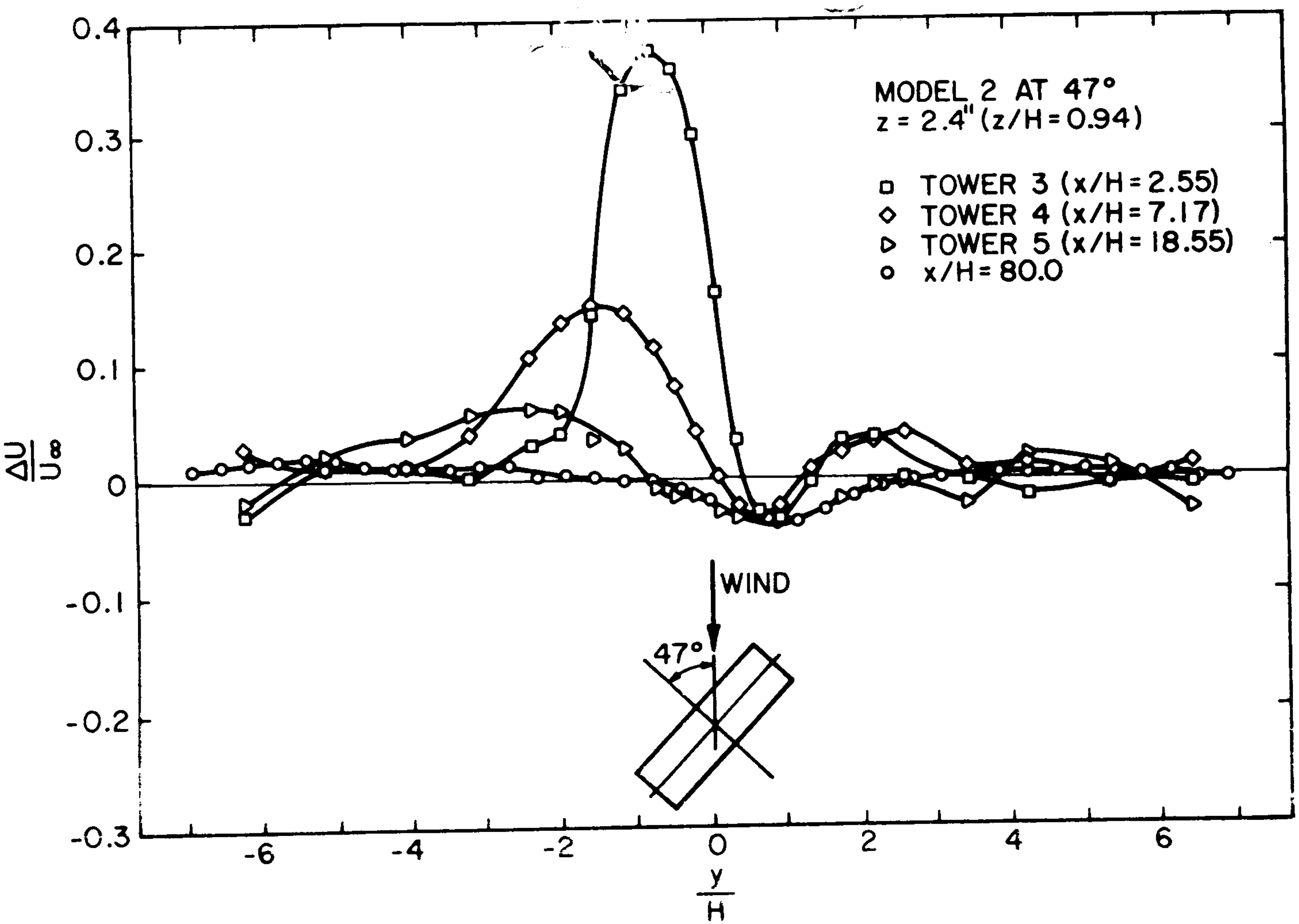

Figure 11. Lateral Profiles of Mean Velocity Deficit in the Wake of the Building at 47 Degrees.

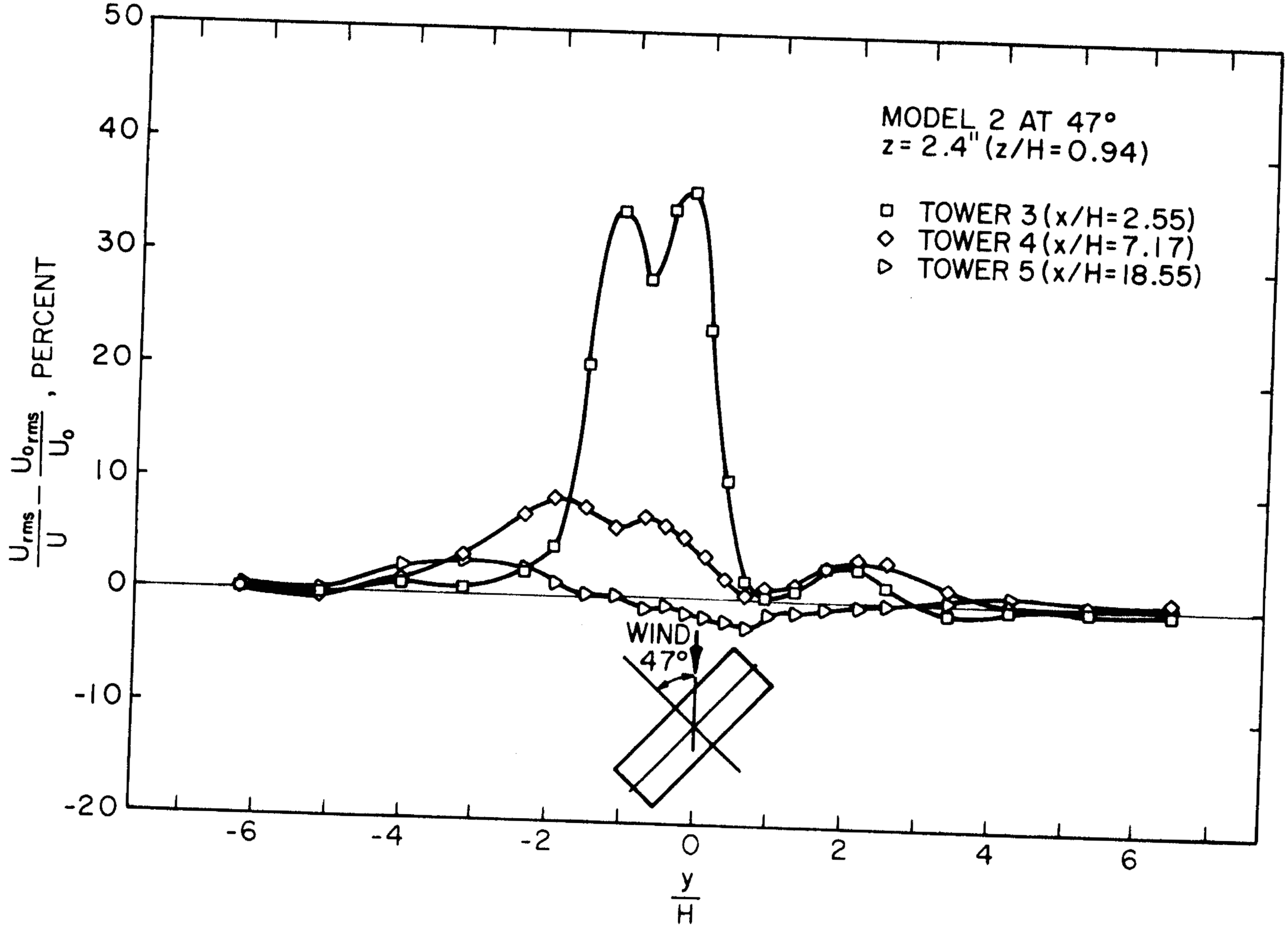

Figure 12. Lateral Profiles of Turbulence Intensity Excess in the Wake of the Building at 47 Degrees.

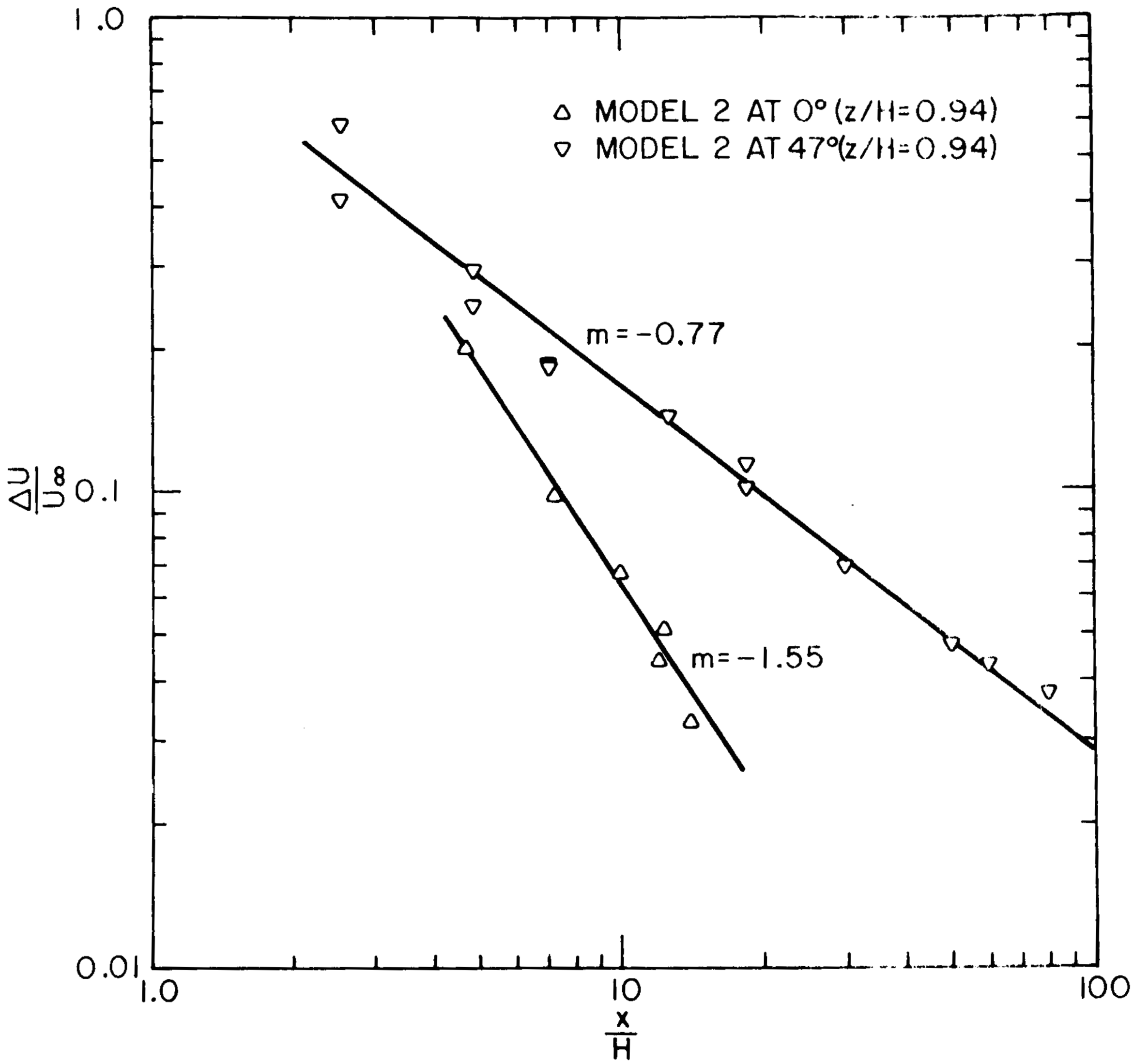

Figure 13. Decay of the Maximum Mean Velocity Difference Across a Lateral Profile with Downwind Distance for Two Wind Directions.

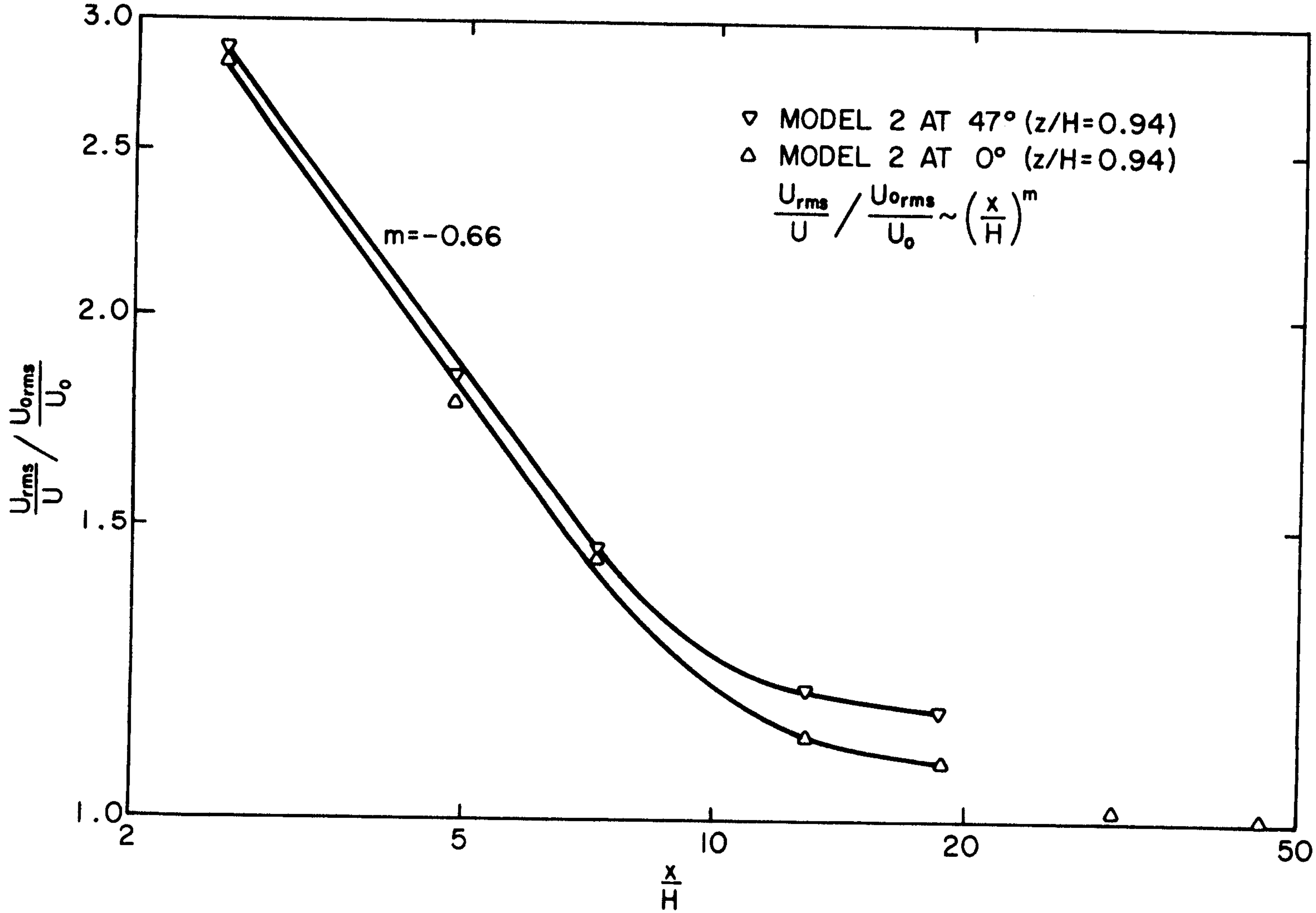

Figure 14. Decay of the Ratio Between Maximum Turbulence Intensity in the Wake and Turbulence Intensity at the Same Location in the Undisturbed Flow for Two Wind Directions.

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