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FLOW ESTABLISHMENT IN AN OPEN CHANNEL

A THESIS

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James Martin Wallace, Jr.

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Approved:

Chairman

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SUMMARY

The object of this work was to study flow establishment in an open channel. The study was conducted in a tiltable, rectangular, steel flume 3.5 feet wide and 80 feet long.

The study of flow establishment was accomplished by examining the depth, the developing velocity profiles, and the turbulence characteristics of the flow. The depth of flow was measured systematically along the channel to determine where uniform depth was achieved. The longevity of eddies generated by the entrance geometry was studied by comparing the developing velocity profiles.

A single roughness element was placed in the channel. This constituted a new entrance condition. The developing velocity profiles downstream from the element were studied, as was the turbulence intensity.

In the clear test channel, the results were as follows: (1) Uniform depth, as measured by a point gage, was established approximately 35 feet from the entrance. (2) The velocity distribution, as measured by a pitot tube, was established approximately 50 feet from the entrance. (3) Velocity fluctuations of the order of 25 per cent of the mean velocity were observed 70 feet from the entrance.

With the roughness element in the flow, the results were as follows: (1) The roughness element affected the velocity distribution and the turbulence intensity of a supercritical flow approximately 350 roughness heights downstream. (2) The roughness element affected the velocity

distribution of a subcritical flow approximately 750 roughness heights downstream.

CHAPTER I

INTRODUCTION

Description of the Problem

A major assumption often made in experimental studies in fluid mechanics is that flow patterns are established. However, few systematic studies of flow establishment in open channels have been made. This lack of information encouraged the study reported herein, which was an investigation of flow establishment in an open channel.

Uniform flow in open channels is assumed established when the depth of the flow does not vary from station to station. This criterion however, does not reveal much about fluid motion within the flow. For studies of the mechanics within the flow, the longitudinal development of velocity profiles is a more sensitive criterion. Therefore, a more adequate flow establishment criterion is that both depth and mean velocity distribution do not vary from station to station. When diffusion processes are considered, the eddy viscosity as related to variations of turbulence characteristics is important. The criterion for flow establishment, then, is that depth, mean velocity distribution, and turbulence characteristics (i.e., intensity and scale of turbulence) are constant from station to station. Finally, in the study of discrete particle transport, flow can be considered established when the rate of particle entrainment and deposition are in equilibrium, in addition to the constancy of depth, velocity distribution, and turbulence characteristics.

The following criteria, then, are measures of the establishment of uniform flow in open channels. They are ranked in order of increasing sensitivity (i.e., in order of distance necessary for the criteria to be satisfied).

1. Constancy of depth from station to station.
2. Constancy of the mean velocity distribution from station to station.
3. Constancy of turbulence intensity and scale from station to station.
4. Equilibrium of the rate of entrainment and deposition of discrete particles.

Purpose and Scope of the Investigation

The principal purpose of this study was to determine where flow is established in an open channel for which entrance conditions give rise to large scale eddy formation. The point of establishment of uniform depth was determined and the longevity of entrance-created vorticity was investigated by comparing the mean velocity profiles of the developing flows. Only a limited investigation of turbulence characteristics was carried out. No study of discrete particle motion was undertaken.

A second and related purpose of this investigation was the study of the flow downstream from a single roughness element. The roughness element created a new entrance condition and the vortices induced by the roughness produced secondary motion in the flow. The effect of the roughness element on the velocity profiles of various turbulent flows

was studied and compared with the clear channel velocity profiles of the same flow conditions. The nature of the turbulence downstream from the roughness element was also studied and compared with the turbulence in the clear channel.

It is hoped that this study will contribute to the present knowledge in this field and that it will enhance the state of the art.

Review of the Literature

The work of J. M. Robertson and T. J. Mueller (1) is a notable exception to the scarcity of studies of open channel flow establishment. They studied the flow patterns downstream from a two-dimensional, step-type roughness and concluded that:

1. At 40 roughness heights downstream the turbulent boundary layer was re-established and the mean velocity profiles were free of any distortions introduced by the roughness.

2. The turbulence characteristics appeared to have returned to initial values in 40 roughness heights.

Little additional work of this type has been done however, though it has long been known that regions of unestablished flow exist. Even the classical work of H. Bazin (2) suggests developing flow regimes. V. A. Vanoni (3) measured the sediment and velocity distributions in a 60 foot long laboratory channel and indicated a region of unestablished velocity distribution. This fact notwithstanding, many studies of flow in open channels assume established flow. The description of the mean velocity distribution for fully developed turbulent flow is an example. In 1938 G. Keulegan (4) applied the formulas describing velocity distri-

bution in pipes to turbulent flow in open channels. Keulegan assumed that the average effect of secondary currents and the free surface was a small quantity which could be merged into a term called the "surface characteristic." Thus, he developed an analogous formula for the velocity distribution in open channel flow.

H. Tracy and C. Lester (5) performed measurements to determine the effect of the free surface on flow patterns and to determine the mean velocity distributions. Again, these studies were based on the assumption that flow was established.

The secondary currents mentioned by Keulegan were observed by A. Gibson (6) in 1909. Of late, much interest in these currents has been shown. H. Einstein and H. Li (7) and J. Delleur (8) have made analytical studies of these secondary currents. Delleur also performed measurements to verify his analysis. Both of these investigations state that uniform flow in prismatic open channels have superimposed on the main flow, a secondary flow which is helical in character. Delleur's channel had a horizontal bottom and it was relatively short. Uniform flow was very likely not present in his study. This secondary motion was observed to be similar to that in pipe bends and curbed open channels which is due to centrifugal effects. For flow in straight channels, however, these investigations assumed that there were no centrifugal effects and that the explanation of secondary currents was basically different. This is essentially an assumption that flow is established in the straight channel because entrance effects can be considered centrifugal effects.

There are many studies of flow establishment in pipes. Examples are analytical studies made by T. Boussinesq (9) in 1891 and L. Schiller

(10) in 1922 which, combined with the experimental studies of Nikuradse, showed that the velocity profile in the unestablished flow region of a pipe varied over a length of approximately

$$L = 0.03 \text{ diameter} \times R_d$$

where L is the length and R_d is the Reynolds number. Measurements made by H. Kirsten (11) in 1927 showed that the inlet length for turbulent flow was about 50 to 100 pipe diameters. Nikuradse found that the velocity profiles had fully developed in 25 to 40 pipe diameters.

Because of the energy-dissipating effects of rough boundaries, these boundaries have been studied in connection with engineering designs. For example, the aeronautics industry has been concerned with the effects of roughnesses, such as that of rivets, because of the drag effects.

K. Wieghardt (12) and W. Tillman (13) extensively studied the effect of the drag by a single roughness element. H. Schlichting (14) measured the velocity field behind a row of spheres placed on a boundary and showed that the highest velocities occur directly behind the spheres and the lowest velocities occur behind the free gaps between the spheres. His measurements were made ten sphere diameters downstream from the row of spheres. This effect he called a "negative wake" and he determined that ". . . the effect of the wake behind the obstacle is not only nullified at a certain distance from it, but becomes negative." Schlichting explained this phenomenon by connecting it with ". . . the existence of secondary flows similar to those which exist in rectangular ducts or

open channels." W. Jacobs (15) carried out a more detailed study of this phenomenon. The existence of this negative wake also was confirmed by D. Williams and A. Brown (16), who showed that the local coefficient of drag behind a row of rivets on an aerofoil is less than that behind the space between the rows.

Energy dissipation and drag phenomena are related to the nature of the turbulence intensity and turbulence decay at various points downstream from a roughness element. Some work has been done in investigating the decay of isotropic turbulence. For example, G. Batchelor and A. Townsend (17) have made experimental and analytical studies of isotropic turbulence produced by square-mesh grid. After discussing the fact that where inertial forces were predominant, the decay law was

$$u' = \text{constant} \times t^{-1}$$

they showed that where viscous forces were predominant, the decay law takes the form of

$$u' = \text{constant} \times t^{-5/2}$$

where u' represents the turbulent velocity component in the stream-wise direction and t is time. Their measurements confirmed this latter law which can be derived by neglecting the inertial terms in the Navier-Stokes equations.

Measurements of wall-generated turbulence in a boundary layer have been made by several investigators. S. Corrsin and A. Kistler (18),

using a wall of a wind-tunnel roughened by corrugated paper, measured a relative turbulence intensity of 0.06 per cent in a flow with a free stream velocity of 1,120 cm/sec.

The present study of flow patterns downstream from a single roughness element was similar to that of Robertson and Mueller but dealt with a three-dimensional flow condition. It was also similar to the study of spheres in a flow made by Schlichting, Jacobs, and others, except that in this study a short cylinder was used.

CHAPTER II

DESCRIPTION OF EQUIPMENT

General Arrangement

This experimental investigation was carried out in the Hydraulics Laboratory, School of Civil Engineering, Georgia Institute of Technology. The data were taken in an existing variable-slope flume with particular entrance conditions. The flow was also disturbed by a single roughness element placed on the floor of the experimental flume. Dynamic pressure was measured using a pitot tube and turbulence measurements were made using a pressure transducer fitted with a pitot tube.

The Flume

A rectangular, variable-slope, steel flume was used for the tests. The flume was 3.5 feet wide, 18 inches deep, and 80 feet long. It was principally supported by two longitudinal, variable-depth, built-up steel beams. The two steel beams were supported by a fixed pivot at their midpoints and at their ends by pairs of screw jacks. The flume was tilted by using an electric motor which drove the jacks through two torque tubes. The slope of the flume was registered by a mechanical counter.

Water was pumped to a constant head tank and then supplied through either a 12-inch or a 6-inch line into the flume and recirculated through floor channels back to the pumps. Electrically operated valves controlled the flow. A butterfly valve was used in the 12-inch line and a

gate valve was used in the 6-inch line.

The water surface profile and depth of flow were controlled by an adjustable sluice-gate at the flume entrance and a tailgate at its downstream end. These were adjusted electrically and their positions were registered by a dial.

The Entrance

The 12-inch and the 6-inch supply lines emptied vertically into a head bay. The flow moved from this bay over a vertical weir, through a wire mesh, into the flume. Across the upper end of the flume were placed vertical straightening vanes set 2.5 inches apart. A sketch of the flume and appurtenances is shown in Figure 1.

The Roughness Element

The flow was disturbed by a single roughness element. This element was a short cylinder 0.653 inches long and 0.992 inches in diameter. A small permanent magnet was located inside a piece of plexi-glass tubing which was covered with a thin brass plate. The roughness element could thus be attached to the steel floor of the flume.

Depth Measurements

The depth of the flow was measured by an electrical point gage whose support was a carriage which rolled along rails at the top of the flume walls. The point gage was supported so that it could be moved transversely across the carriage. Depth measurements could be made at any longitudinal or transverse position in the flume. The point gage could be positioned vertically to the nearest 0.1 mm and transversely

to the nearest 0.1 inch. The longitudinal position of the carriage was established by a steel tape which was attached to the top of the flume wall. It could be read to the nearest 0.01 foot.

Mean Velocity Measurements

At various positions in the flow cross sections, average dynamic pressure measurements were made using a pitot tube of 0.028 inches I.D. The pitot tube was connected by tygon tubing to a manometer which could be read to the 0.001 inch. The pitot tube was attached to a carriage which rolled along rails at the top of the flume sidewalls like the point gage carriage. The pitot tube could be positioned vertically and horizontally with respect to the flume to the nearest 0.001 inch.

Turbulence Measurements

To determine the longitudinal turbulent velocity component at various points in the flow, a special measuring device was assembled. A pitot tube was connected to a pressure transducer which in turn was connected to a recorder. A continuum of water was maintained from the diaphragm of the transducer to the open end of the pitot tube. Pressure flucturations at a point could then be transmitted by the water to the transducer diaphragm. The transducer was a Statham transducer with a maximum sensitivity of ± 0.15 psi. The attached recorder was a Sanborn 2-channel Recorder Model 297.

Propeller and Dye Studies

A small zero pitch propeller was built and used to investigate the nature of the secondary motion in the channel. It would turn only when

inside a longitudinal vortex.

Dye traces were also used to study flow patterns.

CHAPTER III

EXPERIMENTAL PROCEDURE

Tests in Clear Channel

The clear channel flows were the flows unobstructed by the roughness element. Depth and mean velocity were measured in a subcritical flow described below. Turbulence was measured in a supercritical flow also described below.

Depth Measurements

A subcritical flow was established with a flume bottom slope of $1{,}100 \times 10^{-6}$ ft/ft and a flowrate of 1.01 cfs. For these flow conditions, the Reynolds number based on the hydraulic radius was 24,800 and the Fronde number based on the depth was 0.63. Point gage measurements were made at five foot intervals along the flume between stations five and 75 in order to determine the water surface profile and the region of uniform flow depth. Measurements were made at three points across the flow at every station and the average value was used to determine the depth. Thus, point gage measurements were made 0.875, 1.750, and 2.625 feet from the sidewall. Three sets of these readings were made for different tailgate settings. Typical data are shown in Table 1. Water surface profiles determined from these tests are shown in Figure 2.

Depth measurements were only approximate when surface waves were present. An attempt was made to measure a mean value between the peaks and valley of the waves.

Mean Velocity Measurements

A survey of velocities was made by means of pitot tube measurements at four cross sections along the flume. These sections were located at 10, 25, 50, and 75 feet from the flume entrance. Points in every section were chosen to give a representative picture of the velocity distributions. For that reason more points were chosen near the boundaries where the velocity gradient was high. Typical data are shown in Table 2.

The velocity head at a point in the flow was found to be the average height of the column of water in the manometer above the mean water surface in the flume. This column fluctuated due to turbulence and the average height was determined visually. The velocity head was found by applying the Bernoulli equation

$$v^2/2g + p/\delta + z = H$$

to the open channel flow where v is the velocity, g the acceleration of gravity, p the pressure, δ the specific weight of water, and z the elevation of the water surface. At the water surface, p/δ equals zero, z equals the elevation of the water surface, and

$$v^2/2g = H-z$$

where H is the total head of the flow at the measured point and is measured as the elevation of the water in the manometer. Since

$$v = \sqrt{2g(H-z)}$$

the measured velocity head was used to determine the velocity at a point.

Turbulence Measurements

A supercritical flow was established with a slope of 11,000 x 10^{-6} ft/ft and a flowrate of 1.04 cfs. For these flow conditions, the Reynolds number based on the hydraulic radius was 26,620 and the Froude number based on the depth was 2.05.

The turbulence intensity was investigated by means of the pitot tube transducer-recorder as described in Chapter II. This system was calibrated statically by measuring the deflection recorded by the recorder stylus due to a change in vertical position of the pitot tube in quiescent water.

The turbulence measuring device was centered in the channel 70 feet from the entrance at 0.469 and 0.475 inches above the flume floor to record instantaneous dynamic pressure fluctuations. A sample record is shown in Figure 3.

Tests with Cylindrical Roughness

These flows were disturbed by the cylindrical roughness described in Chapter II. Mean velocity measurements were made in a subcritical flow. Mean velocity and turbulence measurements were made in a supercritical flow.

Mean Velocity Measurements

For subcritical flow (slope 1,100 x 10^{-6} ft/ft and flowrate 1.01 cfs) the mean velocity was measured at various points downstream from

the roughness element. In this study, the pitot tube carriage was fixed at station 70. The roughness element was centered in the channel to eliminate sidewall effects. The roughness element was moved to positions 0.25, 2.00, 10.00, 20.00, and 40.00 feet upstream from the measuring station. Dynamic pressure was measured systematically in the region shown in Figure 7. Typical data are shown in Table 3.

For supercritical flow, (slope 11,000 x 10^{-6} ft/ft and flowrate 1.04 cfs) the mean velocity was measured similarly downstream from the roughness element. The measuring station was again established at a position 70 feet from the flume entrance. The roughness element was centered in the channel and dynamic pressure measurements were taken for roughness positions of 5, 10, 15, and 20 feet upstream from the measuring station. The dynamic pressure measurements were made at vertical positions of 0.211 and 0.711 inches above the flume floor and horizontally in the region shown in Figure 12.

For both subcritical and supercritical flow, measurements were made in the half channel only, on the assumption that the flow pattern was symmetrical about the centerline of the flume. For supercritical flow, measurements were taken slightly to the right of the centerline to verify this assumption.

Turbulence Measurements

The turbulence measuring instrument was located at station 70 and centered in the channel. Instantaneous dynamic pressure was measured for various upstream positions of the roughness element.

Propeller and Dye Studies

The propeller described in Chapter II was aligned with the flow

in the wake behind the roughness element to determine the vorticity pattern.

Dye was introduced in the flow upstream from the roughness element and flow patterns around and over the roughness were observed.

CHAPTER IV

ANALYSIS AND DISCUSSION OF RESULTS

Tests in Clear Channel

Depth Measurements

The water surface profiles for the subcritical flow used in these tests are shown in Figure 6. Uniform depth was obtained approximately 35 feet from the flume entrance.

Mean Velocity Measurements

Velocity traverses were made at various sections of the flume as described in Chapter III. Isovels for four cross sections of the developing flow are seen in Figures 4 and 5. It is seen that the mean velocity distribution is reasonably free of entrance effects at approximately 50 feet from the entrance. The isovel pattern at 50 and 70 feet are very similar.

The severe distortions in the isovels of the developing flows can be explained by the entrance conditions. As the water enters the flume from the head tank, secondary motion is created by the change in flow direction similar to flow around an elbow.

Figure 6 shows the average velocity in any vertical section plotted against the distance from the sidewall for the four cross sections. These plots show the effect of the wall on the developing flow. Near the entrance the velocities and the velocity gradient was high in the region near the wall. As the flow moves downstream, the wall shear gradually

retards the flow in the wall region.

Turbulence Measurements

The turbulence measurements in the clear channel as seen on Figure 13 show that at 70 feet from the entrance, the longitudinal turbulent velocity fluctuation is of the order of 25 per cent of the mean velocity for the supercritical flow tested. This indicates that the entrance effect on the turbulence intensity persisted throughout the length of the channel since this intensity is much higher than ordinary wall turbulence observed by Corrsin and Kistler and others to be about 0.10 per cent.

Tests with Cylindrical Roughness

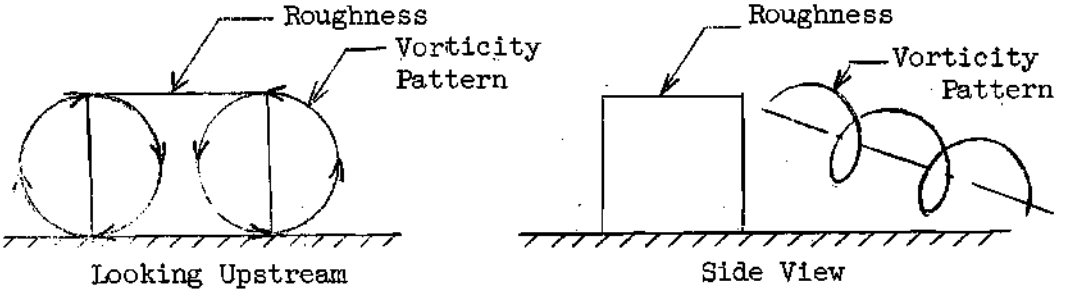
Mean Velocity Measurements

Figures 7 through 11 show the disturbed isovels of the subcritical flow developing downstream from the roughness element. Superimposed on these isovels are the isovels of the clear channel flow to illustrate the effect of the roughness element on the flow. It is seen from these figures that the isovel distortions in subcritical flow have damped out in about 740 roughness heights downstream.

It was found that the effects of the roughness element did not persist as long in supercritical flow. The isovels of the developing supercritical flow are shown in Figure 12. It is seen that the roughness element distorts the isovels for approximately 350 roughness element downstream at which point the distortions appear to have damped out. Since the turbulence level is higher in supercritical flow, there is a greater mechanism for destroying and assimilating the eddies shed from the roughness and this probably accounts for the relatively shorter

distance needed to re-establish the supercritical flow.

The shape of the distorted isovels was of great interest. For both the subcritical and the supercritical flows, the greatest velocities were found to be directly behind the roughness element and lowest velocities at some distance to either side as seen in Figures 7 through 11 and in Figure 12. This "negative wake effect" was similar to that seen by Schlichting and Jacobs. Using the small zero pitch propeller, it was observed that a vortex pattern existed behind the roughness element in both the subcritical and the supercritical cases. The pattern is sketched below.



The longitudinal vorticity pattern illustrated in the sketch may serve to explain the character of the isovel distortion. It is seen from the sketch that high momentum fluid which has been accelerated around the roughness is being transported into the region behind the roughness and that low momentum fluid behind the roughness is being transported outside. The effect of this motion is to increase the velocities behind the element and decrease the velocities to either side. This effect, accord-

ing to Schlichting, is similar to the effect of the secondary motion in straight, rectangular ducts where it was suggested that there is secondary motion toward the corners of the conduit and away from the walls.

Turbulence Measurements

In this discussion, turbulence fluctuations are those computed from the instantaneous dynamic pressure records, hence only the longitudinal turbulent velocity component. The instantaneous turbulent velocity components at various points were found by calculating the root-mean-square value from the recorder charts. These values were calculated by reading the recorder stylus deflection from the mean at 0.25 sec. intervals. The average deflection was computed and the root-mean-square value of the longitudinal turbulent velocity component was found from this average. The time scale was shifted and it was found that the root-mean-square value did not change significantly. Figure 13 is a dimensionless plot of the turbulence intensity as a function of the distance downstream from the roughness element at two positions above the flume floor. It is seen that the turbulence intensity level decreases below the level for the clear channel flow when the roughness element is introduced into the flow, and then gradually increases with distance downstream from the roughness, approaching the clear channel intensity. This increase in intensity with distance from the roughness is exactly opposite to the decay function observed by Batchelor and Townsend from isotropic turbulence. The explanation of this observation is that the turbulence intensity level in the clear channel was apparently higher than that generated behind the roughness. Consequently, as the flow pattern was re-established, the turbulence intensity increased.

The effect of the roughness element on the turbulence intensity persisted for approximately 350 roughness heights downstream, which was the same distance as found in the mean velocity tests.

CHAPTER V

CONCLUSIONS

The criteria, in increasing order of sensitivity, for flow establishment in an open channel are:

1. Constancy of depth from station to station.

2. Constancy of the mean velocity distribution from station to station.

3. Constancy of turbulence intensity and scale from station to station.

4. Equilibrium of the rate of entrainment and deposition of discrete particles.

In the clear channel, the first two criteria were tested in subcritical flow. The first criterion, uniform depth, was established approximately 35 feet from the entrance. The second criterion, constant velocity distribution, was established approximately 50 feet from the entrance. The third criterion, establishment of turbulence intensity, was tested in supercritical flow. Turbulence intensity equilibrium was never established throughout the length of the channel.

In the flow disturbed by the cylindrical roughness, the second criterion was tested in subcritical flow and the second and third criteria were tested in supercritical flow. It was found that the roughness element affects the velocity distribution of the subcritical flow approximately 750 roughness heights downstream. The roughness element

affects the velocity distribution and the turbulence intensity of the supercritical flow approximately 350 roughness heights downstream, thus meeting the second and third establishment criteria at the same point.

It is thus seen that flow was established in the clear channel if only depth and mean velocity distribution are considered, but it was not established if turbulence intensity is considered.

In the flow downstream from the cylindrical roughness, it took approximately twice the length to establish subcritical flow than it did to establish supercritical flow.

The fourth criterion (the rate of entrainment and deposition of discrete particles) was not investigated in this research.

A P P E N D I X

Table 1. Point Gage Measurements

Channel Position (feet)	0.875 Point Gage Reading (cm)	1.750 Point Gage Reading (cm)	2.625 Point Gage Reading (cm)
75	9.70	9.73	9.69
70	9.71	9.70	9.68
65	9.71	9.70	9.69
60	9.71	9.70	9.71
55	9.72	9.70	9.69
50	9.70	9.67	9.68
45	9.69	9.71	9.69
40	9.64	9.68	9.66
35	9.67	9.67	9.64
30	9.70	9.70	9.65
25	9.64	9.68	9.61
20	9.65	9.64	9.62
15	9.69	9.67	9.51
10	9.61	9.76	9.48
5	9.68	9.76	9.53

Table 2. Pitot Tube Measurements at Station 10

Pitot Tube Horizontal Location (in.)	Pitot Tube Vertical Location (in.)	Manometer Reading (in.)
2.300	1.800	9.157
	2.000	9.183
	2.300	9.194
	2.600	9.216
	2.900	9.230
	3.200	9.250
	3.500	9.256
	3.700	9.245
2.500	1.800	9.185
	2.000	9.271
	2.300	9.325
	2.600	9.324
	2.900	9.336
	3.200	9.351
	3.500	9.362
	3.700	9.345

Table 3. Pitot Tube Measurements Two Feet Downstream from Roughness

Pitot Tube Horizontal Location (in.)	Pitot Tube Vertical Location (in.)	Manometer Reading (in.)
22.075	1.750	8.676
	1.800	8.704
	1.900	8.777
	2.000	8.819
	2.100	8.812
	2.200	8.845
	2.300	8.845
	2.900	8.920
	3.500	9.011
21.575	1.750	8.615
	1.800	8.681
	1.900	8.735
	2.000	8.759
	2.100	8.759
	2.200	8.778
	2.300	8.797
	2.900	8.923
	3.500	9.010

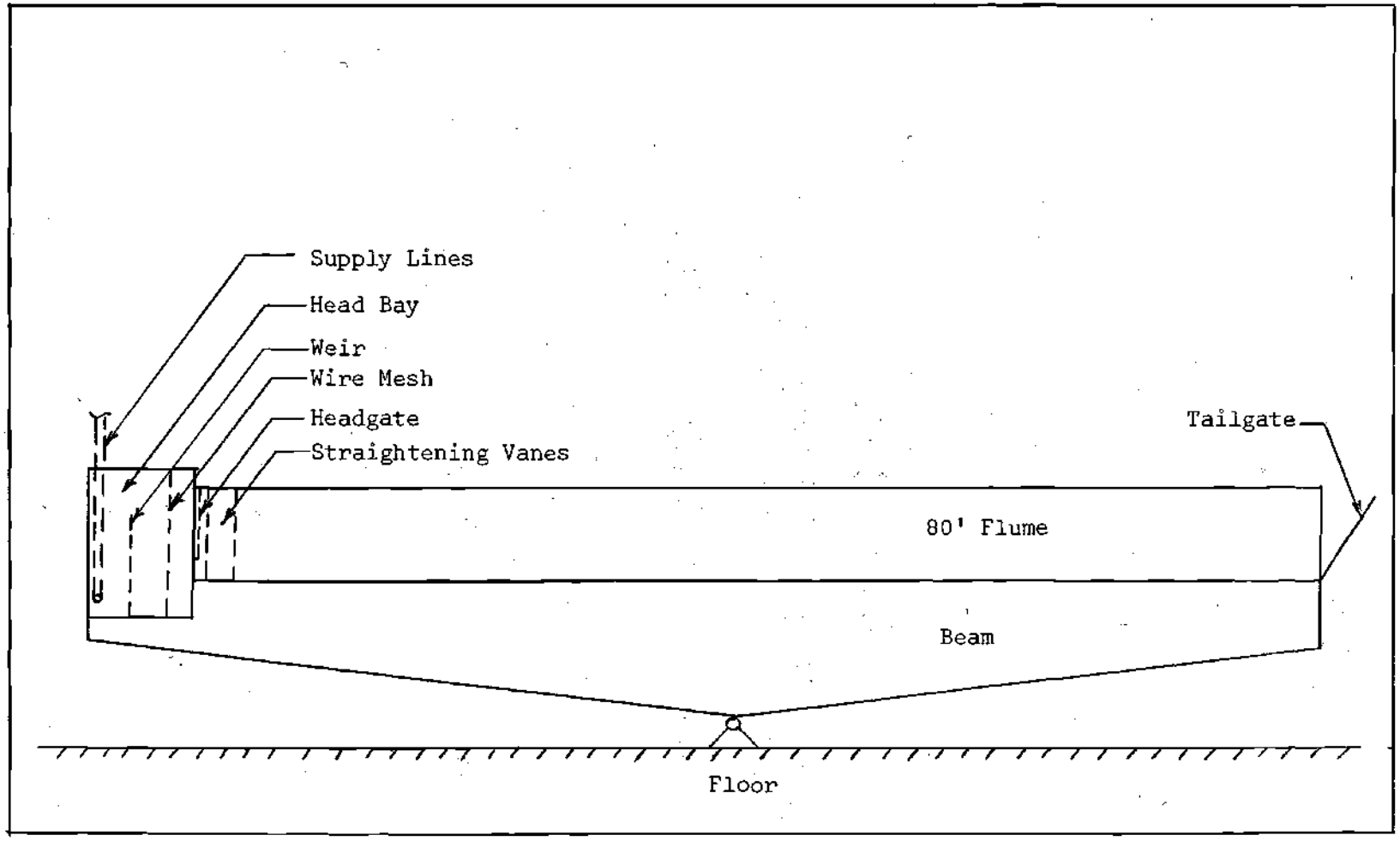


Figure 1. Sketch of Flume and Appurtenances

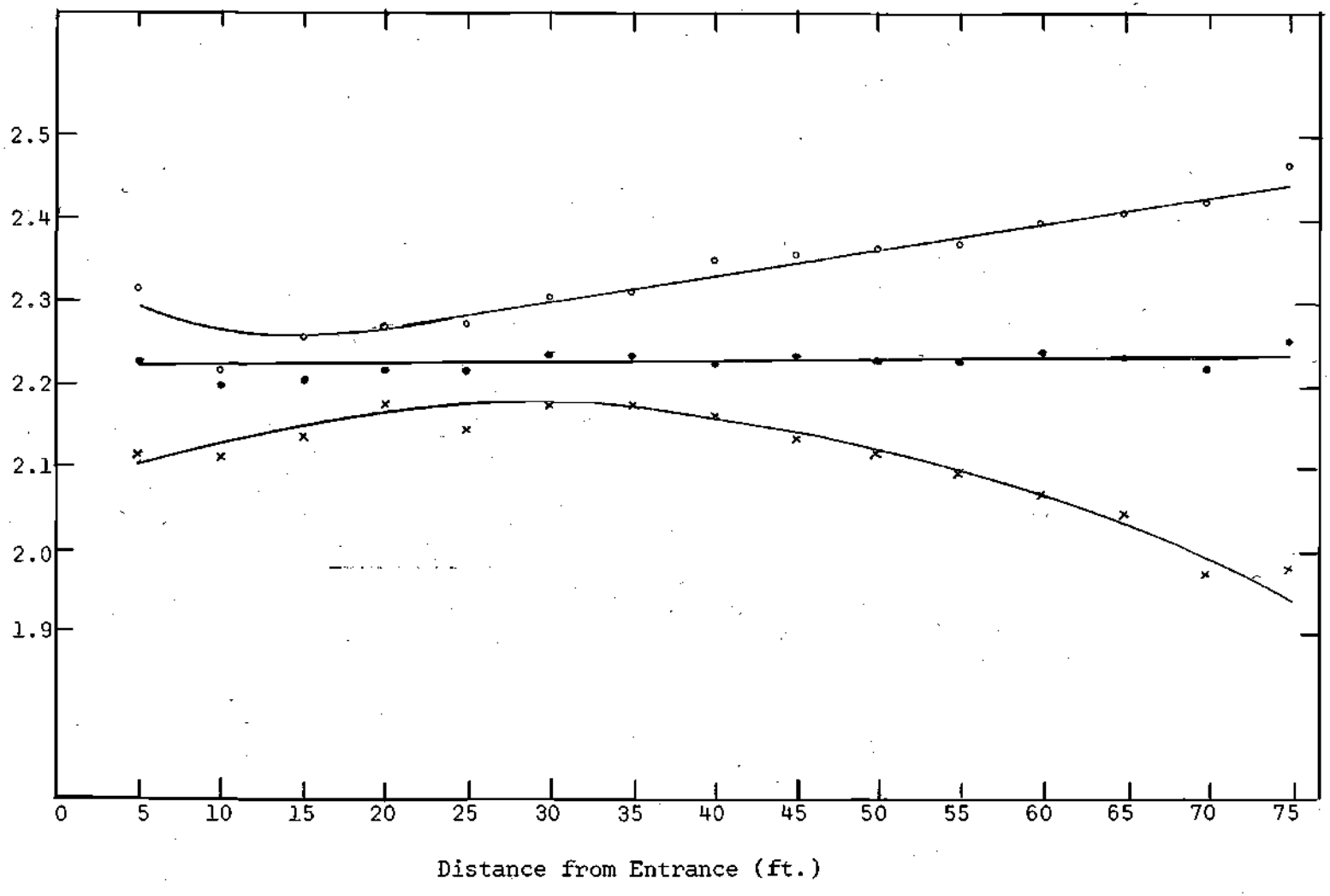


Figure 2. Water Surface Profiles

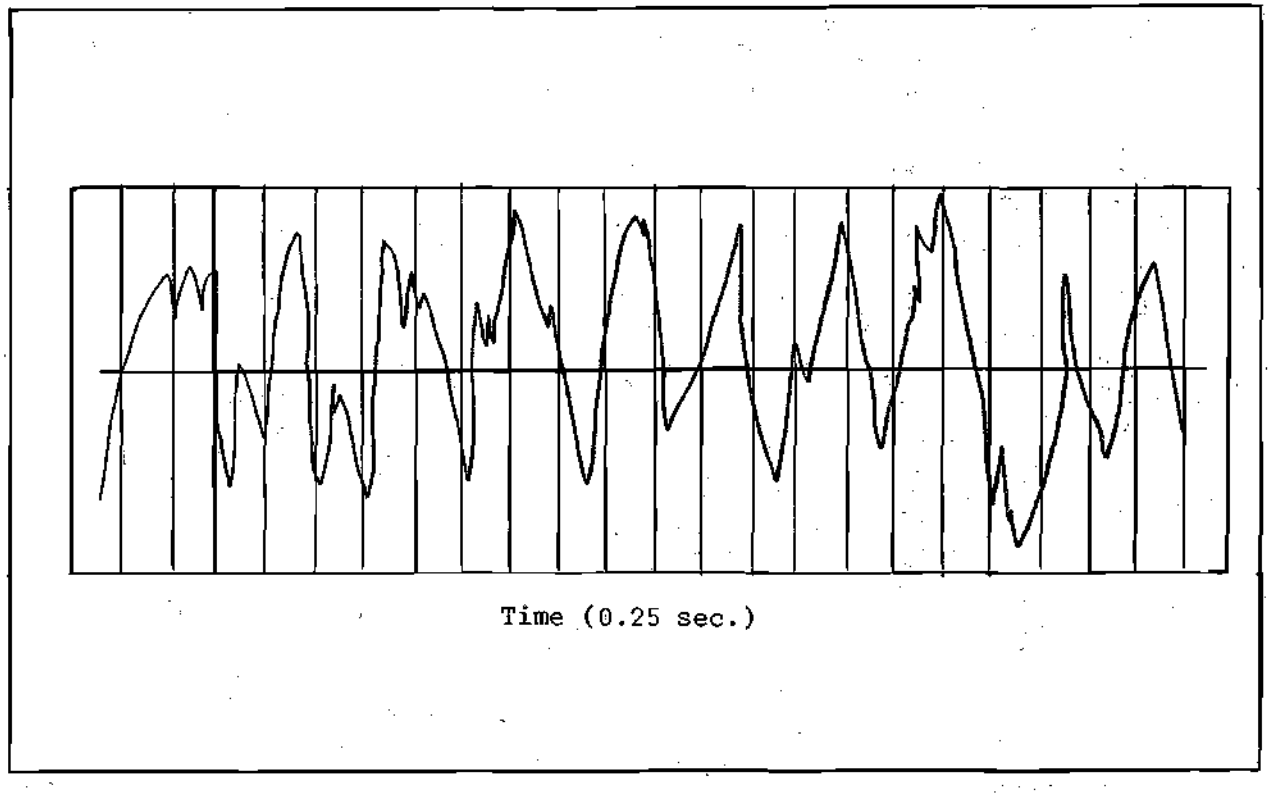


Figure 3. Sketch of Instantaneous Dynamic Pressure Record

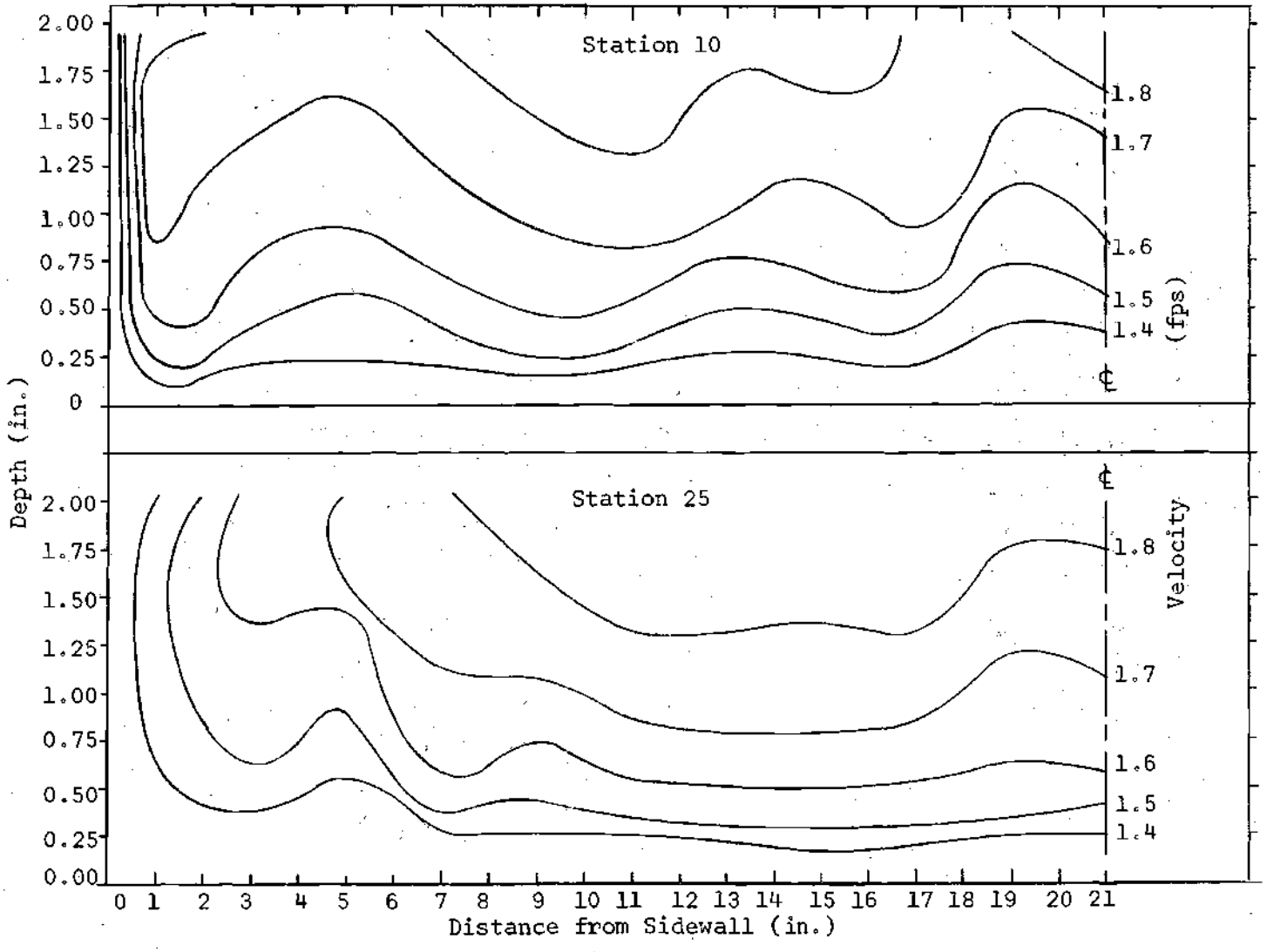


Figure 4. Clear Channel Isovels

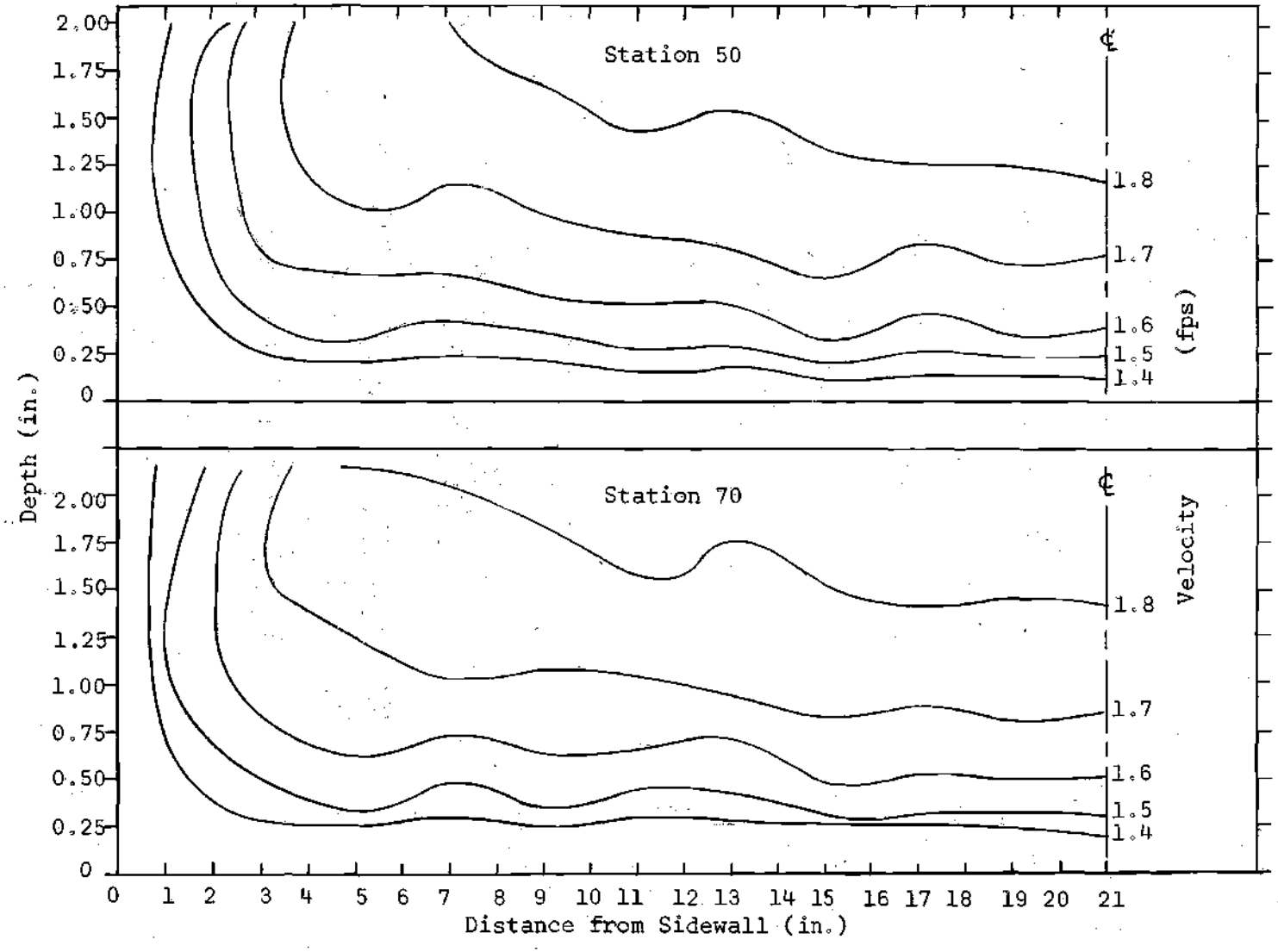


Figure 5. Clear Channel Isovels

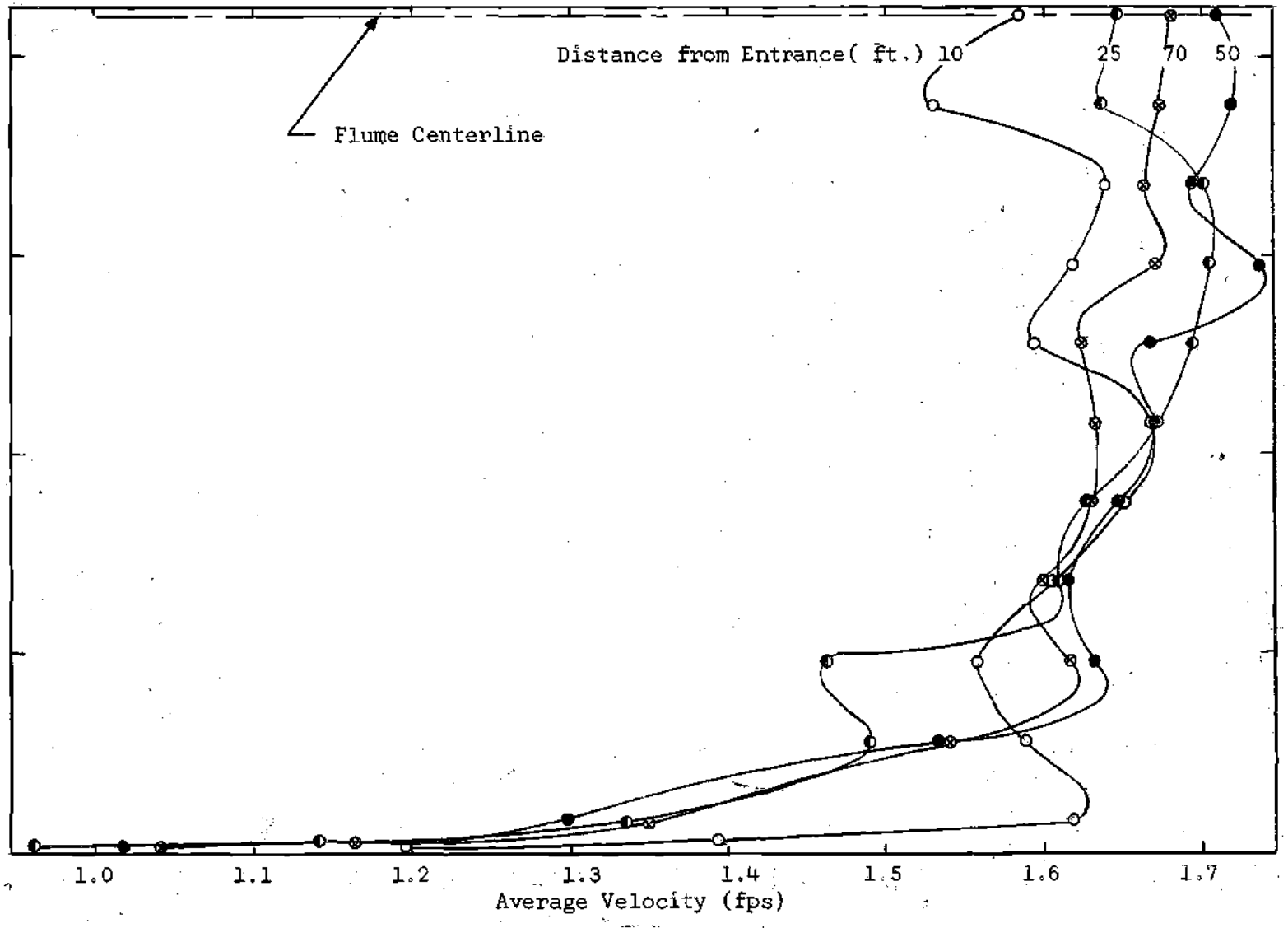


Figure 6. Velocity Distribution in Developing Flow

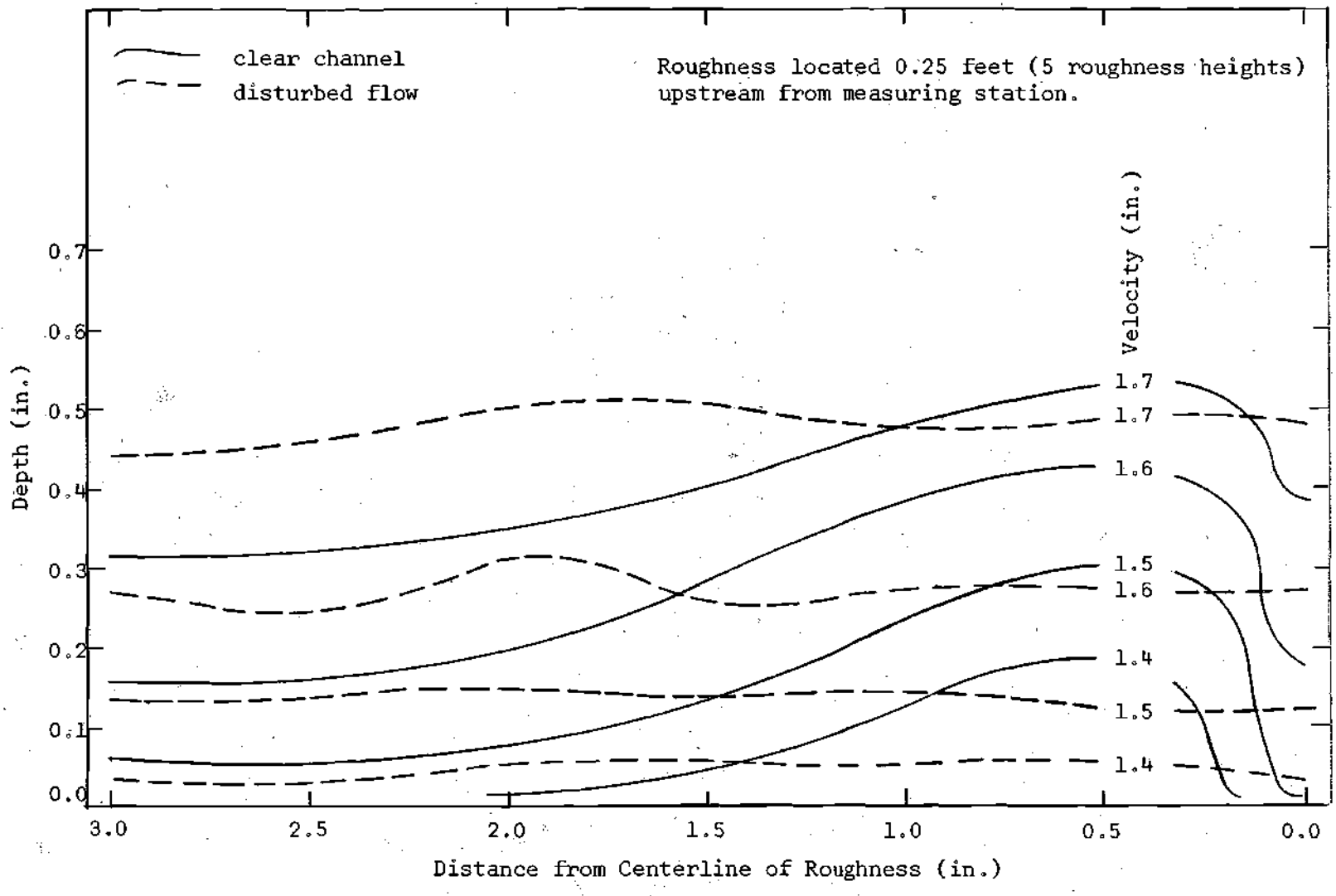


Figure 7. Cylindrical Roughness Test Isovels for Subcritical Flow

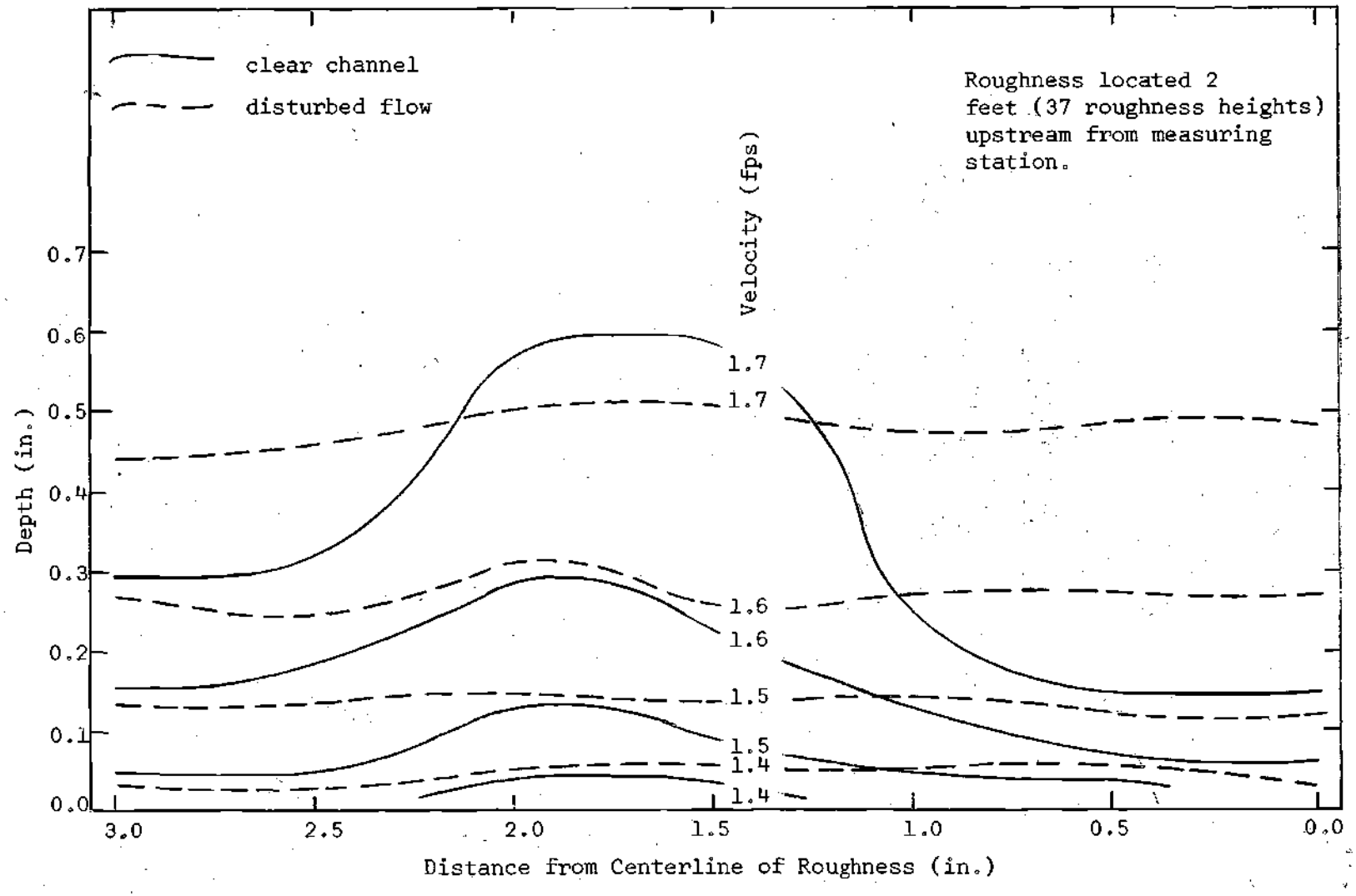


Figure 8. Cylindrical Roughness Test Isovels for Subcritical Flow

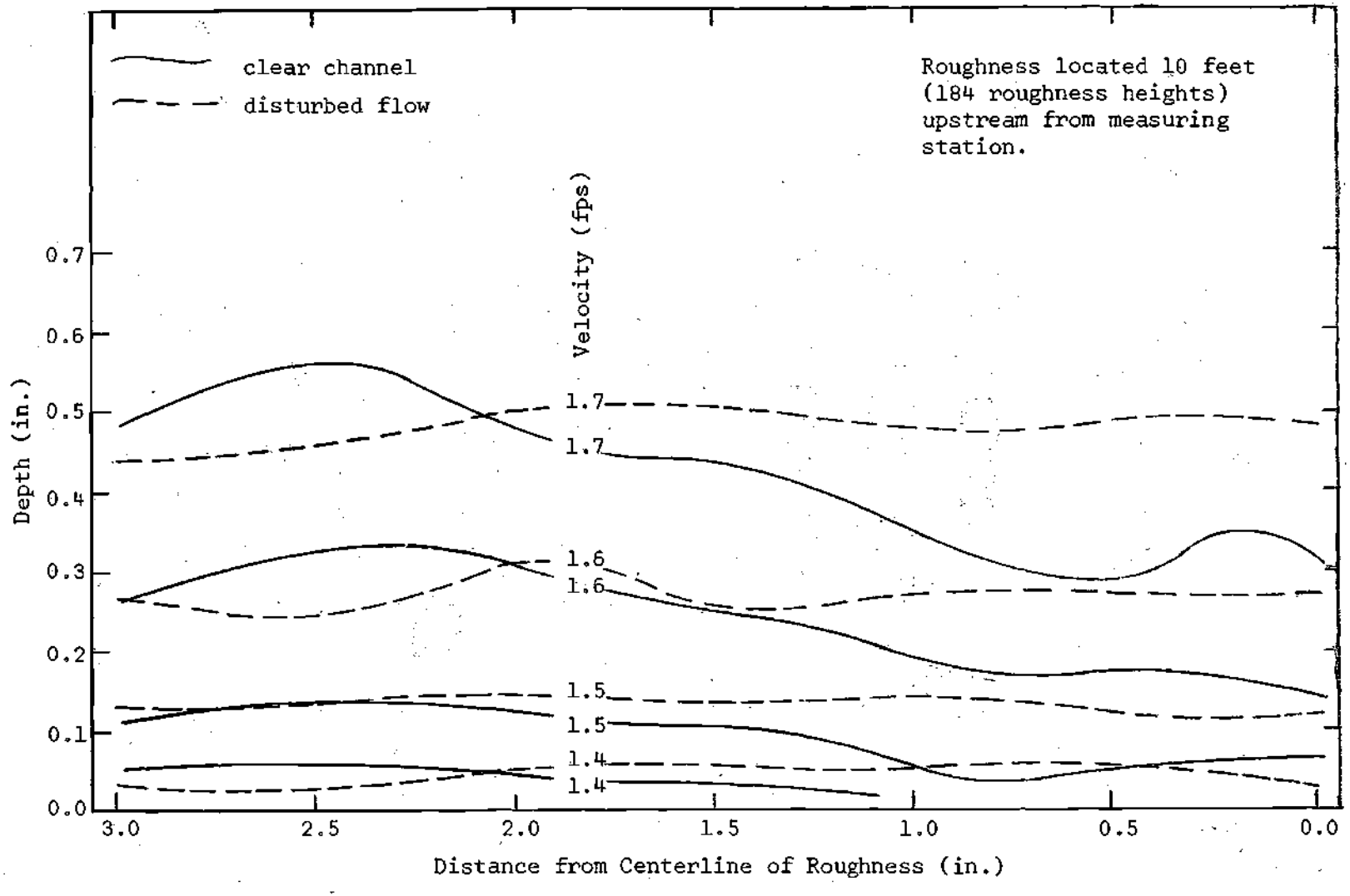


Figure 9. Cylindrical Roughness Test Isovels for Subcritical Flow

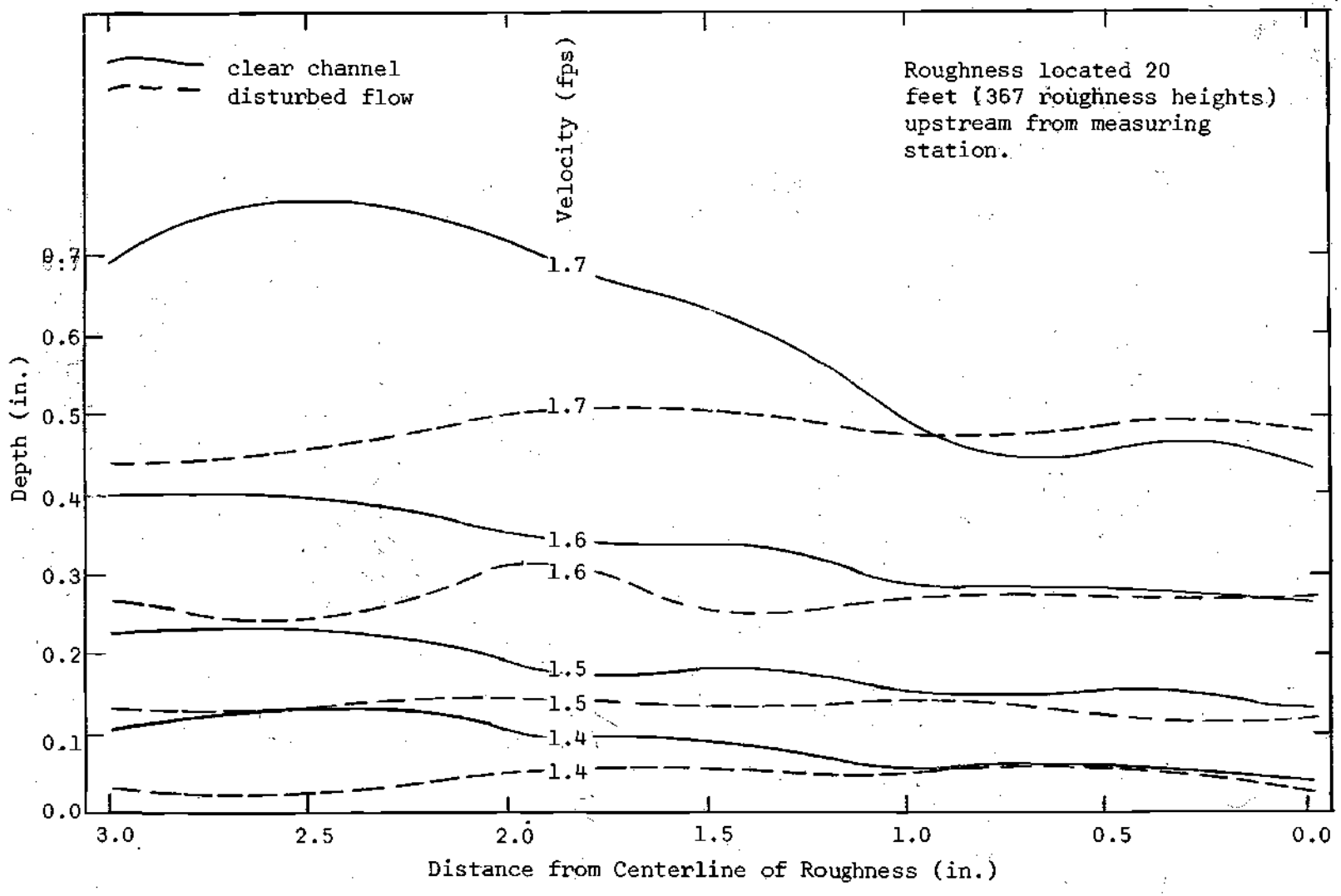


Figure 10. Cylindrical Roughness Test Isovels for Subcritical Flow

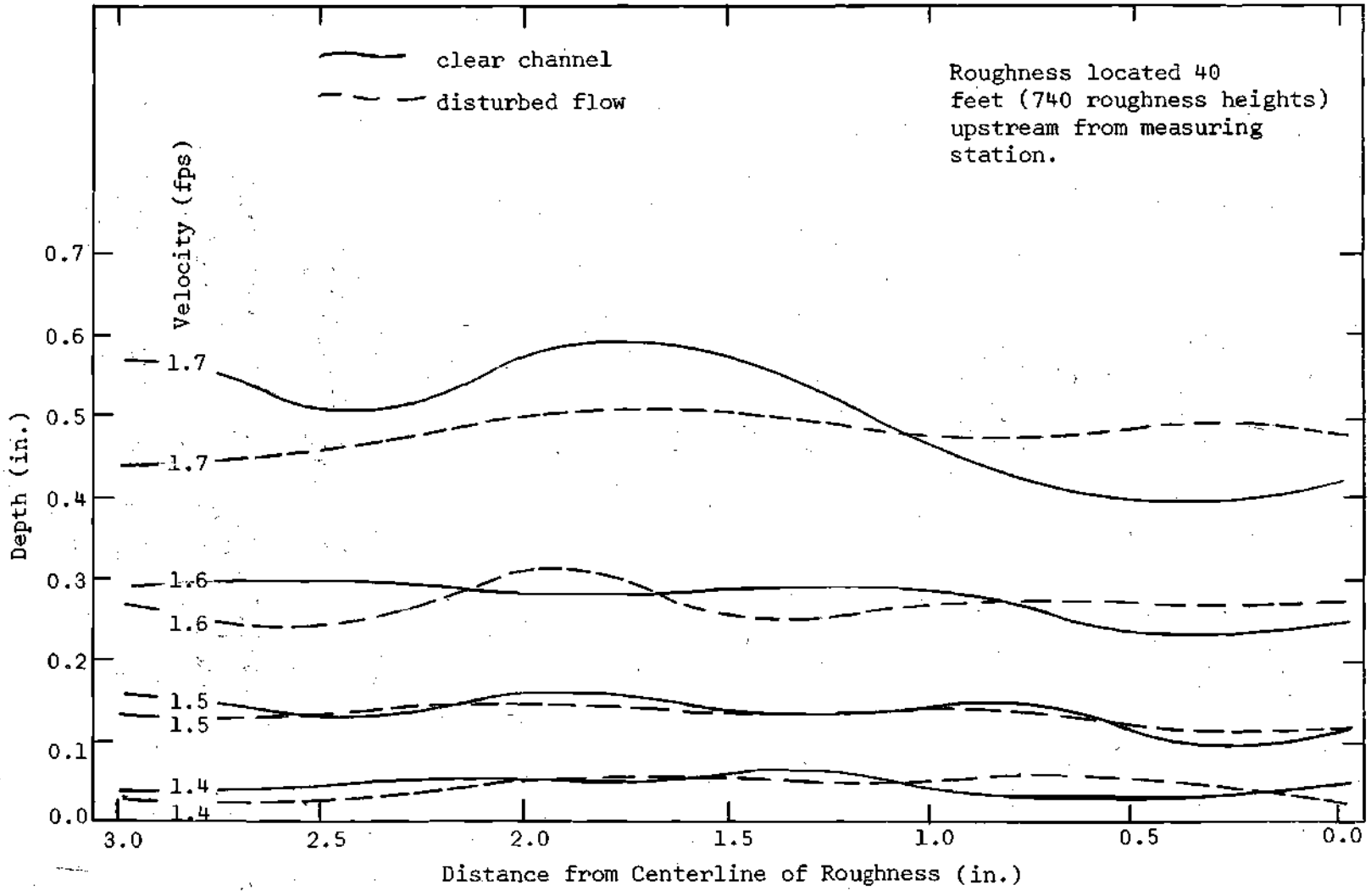


Figure 11. Cylindrical Roughness Test Isovels for Subcritical Flow

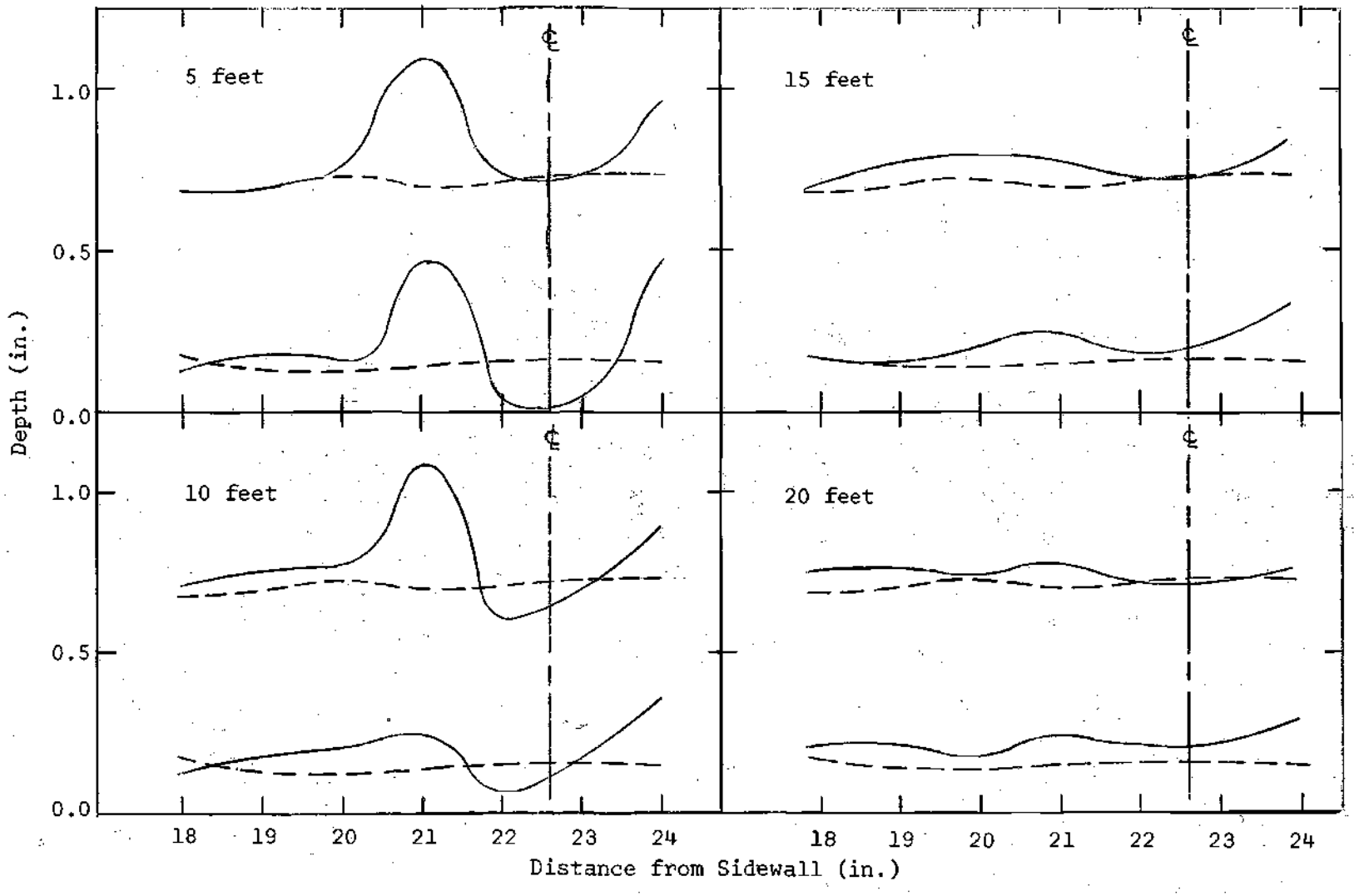


Figure 12. Cylindrical Roughness Test Isovels for Subcritical Flow

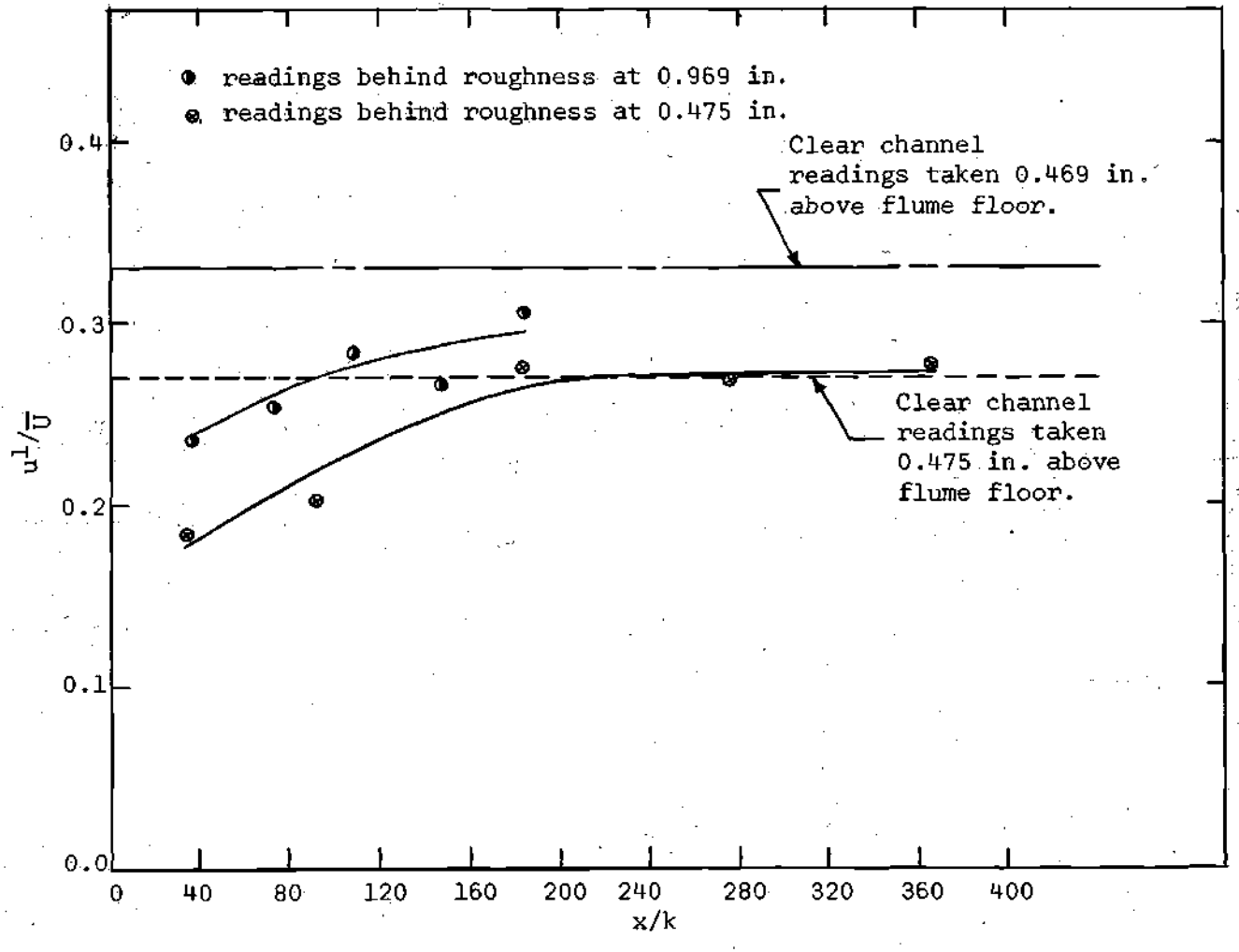


Figure 13. Turbulence Intensity

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