NASA Contractor Report 3565

Wind Tunnel Measurements of Three-Dimensional Wakes of Buildings

Earl Logan, Jr., and Shu Ho Lin

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NOMENCLATURE

C_f	Friction coefficient
E	Output voltage
G	Equilibrium shape factor
H	Height of model
S	slope of the calibration curve
U	Longitudinal mean velocity in m/s
U_{eff}	Effective cooling velocity
u	Instantaneous longitudinal fluctuation
U_N, U_B	Normal velocity components
U_T	Tangential velocity component
U_1	Free stream mean velocity
U^*	Friction velocity
$\overline{uv}$	Component of Reynolds shear stress
u'	RMS value of longitudinal turbulence intensity
V	Vertical mean velocity in m/s
v	Instantaneous vertical fluctuation
v'	RMS value of vertical turbulence intensity
W	Lateral mean velocity in m/s
w	Instantaneous lateral fluctuation
w'	RMS value of lateral turbulence intensity
X	Longitudinal coordinate
Y	Distance from floor and wind tunnel
Z	Lateral coordinate

Greek Alphabet

δ	Boundary layer thickness
	Kinematic viscosity

θ	**Momentum thickness**
α	**Wire angle**
ψ	**Probe rotation angle**

CHAPTER 1

INTRODUCTION

Low-level wind conditions around airports which can be hazardous to aircraft have been identified by Fichtl, Camp and Frost (1977). Wakes from bluff bodies, such as buildings, can produce such conditions. STOL vehicles landing or taking off over buildings, fences or other obstacles, can be affected adversely by wake flows. Research which can enable prediction of the wind environment encountered by aircraft is currently needed.

The NASA Marshall Space Flight Center has developed a program to meet this need. Early work was reported by Frost and Shahabi (1977) and by Frost, et. al. (1977). The initial work involved the use of instrumented wind towers located in an open field in the wake of a simulated block building 3.2-m high by 26.8-m long. Wind and turbulence profiles were determined from readings of anemometers located at heights of 3, 6.2, 12 and 20.88 m above the ground.

Field measurements have been compared with wind tunnel profiles in the wake of a 1/50-scale model of the 3.2 x 2.4 x 26.8-m building. The results of the model study were reported by Woo, Peterka and Cermak (1977), and a comparison of data was presented by Logan and Camp (1978).

It was found that field measurements of velocity and turbulence in the wake of the block building 3.2m high and 26.8m long show an apparent increase in momentum flow above the upwind value. Work by Logan and Chang (1980) in a pipe flow showed that the effect can be explained by an additional obstacle located some distance upstream of the model.

Lateral spreading of wakes from three-dimensional models has been studied by Woo, Peterka and Cermak (1977). For more than one building, placed side by side or one behind another, existing data could be used to predict wake behavior, provided the spacing between buildings is very large. For smaller spacings, interference effects must be present, and single model results would not be valid.

As part of a basic study of the effect of building spacing on wake flow, Logan and Barber (1980) studied centerline wake flow behind the gap between two long models of rectangular cross-section. The present work is part of a program to extend this work through the use of flow visualization and hot-wire measurements of all three velocity components at off-centerline stations in the wake behind the gap between two buildings.

The wind tunnel and models used in the present experiments are the same as described by Logan and Barber (1980). Models are glued to the bottom of a wind tunnel with a gap centered on the wind tunnel centerline. The model arrangement is depicted schematically in Fig. 1.

Definition of the separation region behind the models has been attempted through a flow visualization technique. This is discussed in Chapter 2 of the present report. Instrumentation and measurement techniques for measurement of velocity components in the wake of the gap flow are discussed in Chapter 3.

CHAPTER 2

FLOW VISUALIZATION

1. Introduction

In the flow shown in Fig. 1, the flow direction is mainly longitudinal (X direction). The presence of the surface-mounted obstacle requires that a vertical component (y direction) will also exist. Also a lateral (z direction) component of velocity must exist near the gap. It is desirable to use tracers to allow visualization of flow direction. The present chapter describes efforts made to accomplish this end.

Although smoke filaments are useful in describing wind tunnel flows about sting-mounted models, this technique would not be as useful when applied to surface mounted obstacles located in a relatively thick boundary layer. It is thought that smoke filaments are dispersed too quickly to show mean flow direction. For this reason smoke has not been employed to date in the present work. Instead the surface flow was studied using the oil-film technique.

2. Oil-film Technique

A mixture of oil and pigment spread on a surface can reveal flow direction. Oil viscosity is varied to suit tunnel speed, low viscosity fluid being used for low speeds. Oil is blown in the direction of surface stream-lines, but streaking occurs because of inhomogeneities of film thickness, with thicker ridges protecting downstream oil from being blown, and the unblown oil contains pigment which is visible as streaks. The streaks are photographed and correspond to surface streamlines of the air flow.

Since a kerosene and titanium dioxide mixture has been used successfully by Perry, Schofield and Joubert (1969), kerosene was selected for use in the

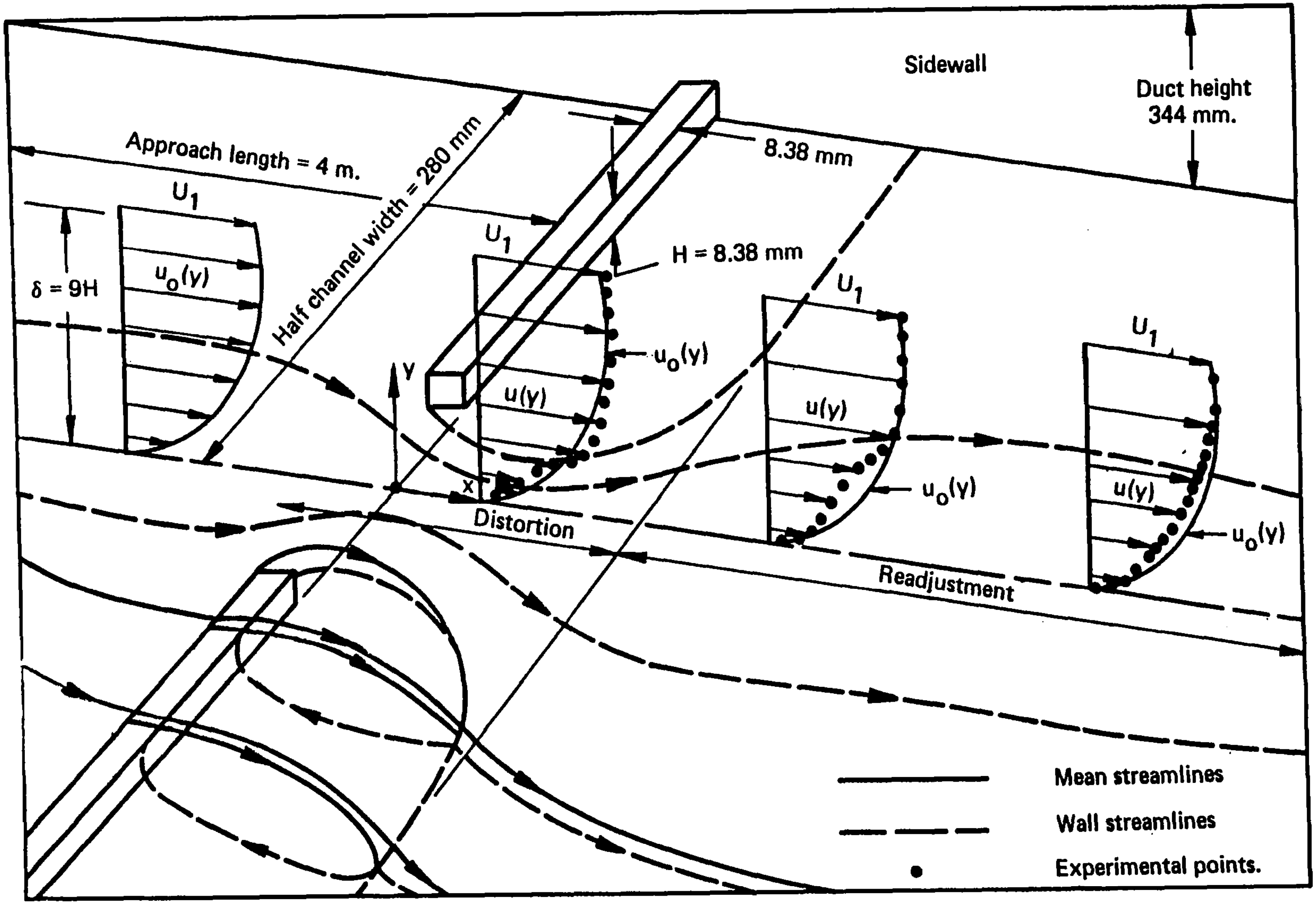


FIG. 1 SCHEMATIC VIEW OF EXPERIMENTAL FLOW

present work. However, no success has been achieved with this oil film. The reason may be that the tunnel speed is extremely low for the viscosity of the kerosene and removal of the film by surface forces was not achieved.

A mixture of isopropyl alcohol and charcoal was found to be useful in the low-speed flow, provided that photographs were taken during the first 15 seconds of tunnel operation. Since the roof of the wind tunnel is clear Plexiglas, this procedure was feasible. The arrangement used is depicted in Fig. 2.

Photographs were obtained for the two-dimensional (no-gap case) and for ratios of gap to obstacle height of 0.5, 1.0, 2.0, 5.0 and 10.0. A wide variety of streamline patterns was thus obtained. A photograph of the flow pattern obtained for the largest gap is shown in Fig. 3. Sketches of the photographically obtained surface flow patterns are presented in Figs. 4-9 for all gap sizes used.

For the two-dimensional (no-gap) case, a region of reattachment is clearly observed. It is parallel to the model and 8-9H downstream of it, as is indicated in Fig. 4. This finding is in good agreement with the position of reattachment obtained from extrapolating the C_f vs X curve given by Logan and Barber (1980) to $C_f = 0$. The C_f graph indicates that reattachment occurs at X = 8.8H.

The effect of the gap is to eliminate the separation zone in the wake of the gap. Separation zones appear on either side of the gap and regions of reattachment tend to curve towards the ends of the models. Thus, in Fig. 9, reattachment occurs at about 9H at a distance 7H from the end of the model, and the distance is gradually decreased to about 3H downstream from the end of the model. The same shape of reattachment line is observed for smaller gaps in

Figs. 7 and 8. The streamline pattern for gap sizes less than 2H may be more like that shown in Fig. 6.

The streamline pattern indicated in Fig. 6 for a gap size of 1.0H shows complete blockage of throughflow through the gap. The vortex structure on either side of the gap (points A and B) apparenty blocks the lower portion of the gap and extends the reattachment line between points C and D. The distance between C and D is about 5H, and reattachment occurs between X=6H and X=7H. It is noted in Fig. 5 that the jet feeding the gap vortex (A and B) becomes asymmetric for very small gap sizes. The asymmetry may be explained by considering the entrainment of ambient fluid from the vortices at either side of the gap. Unequal crosswise velocities or unequal rates of entrainment could lead to jet deflection. Experiments to observe the effect of small differences in model height on the two sides of the gap showed that jet deflection in the opposite sense could be effected by modifying the height of one model and not the other.

Disregarding the jet deflection, the surface flows may be classified as three types:

i) The no-gap flow (Gap=0) having a straight reattachment line at about 8.5 element heights downstream of the back side of the model.

ii) The small-gap flow (Gap < 2H) with recirculation near the gap and a curved, segmented reattachment line.

iii) The large-gap flow (Gap > 2H) having throughflow near the centerline and two curved reattachment lines at either side.

3. Dye Technique

A water channel having a width of 61cm and a length of 10m was used to study the wake behind a gap. Water flowing at a depth of about 23cm was used with models made of 19mm high square bar. The Reynolds number, based on

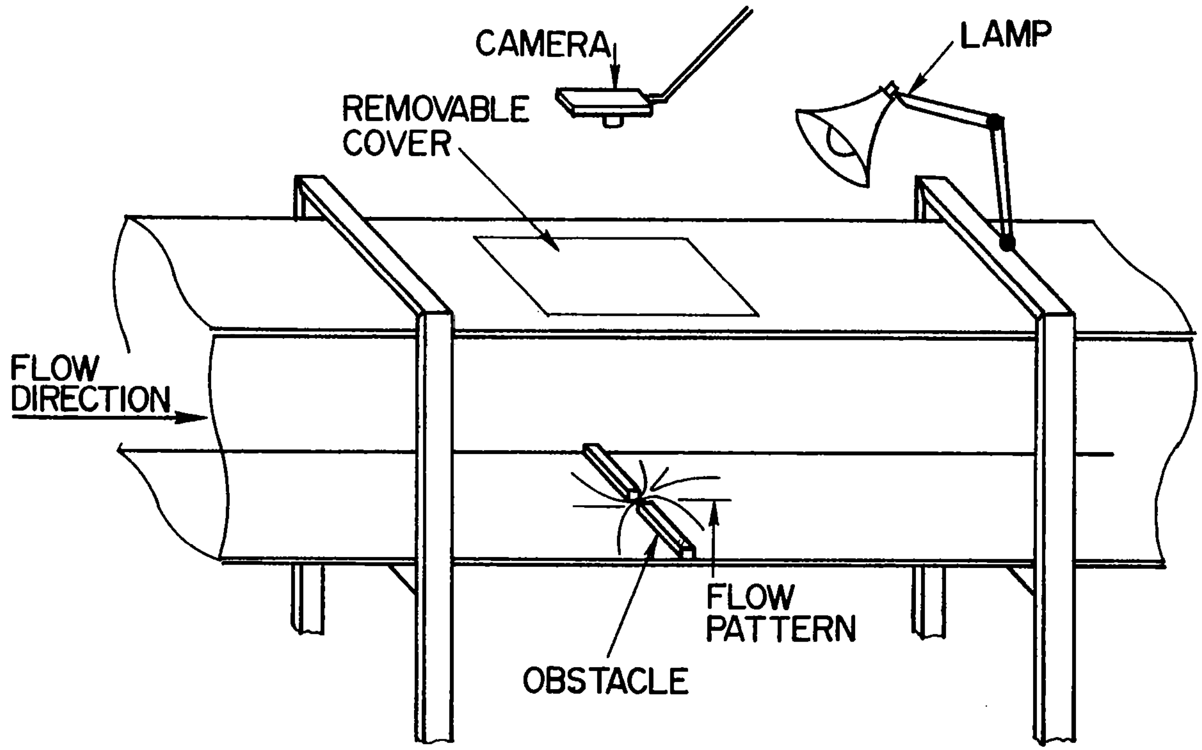


Fig. 2 Flow Visualization Arrangement

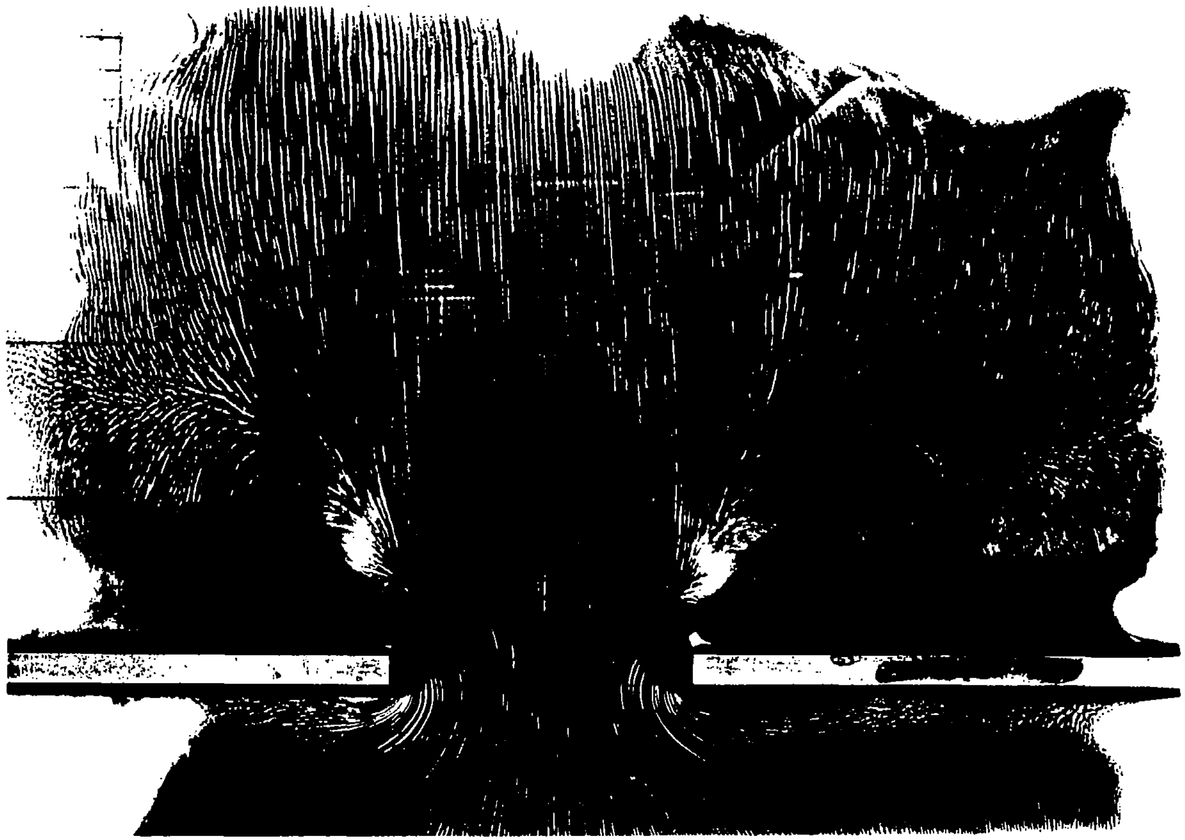


Fig. 3 Photograph of Streak Pattern

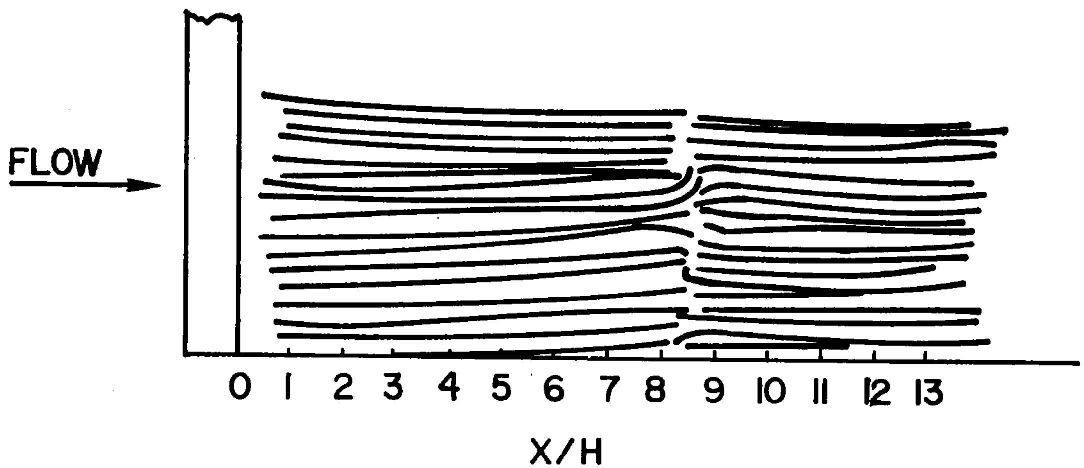


Fig. 4 Streamlines with No Gap

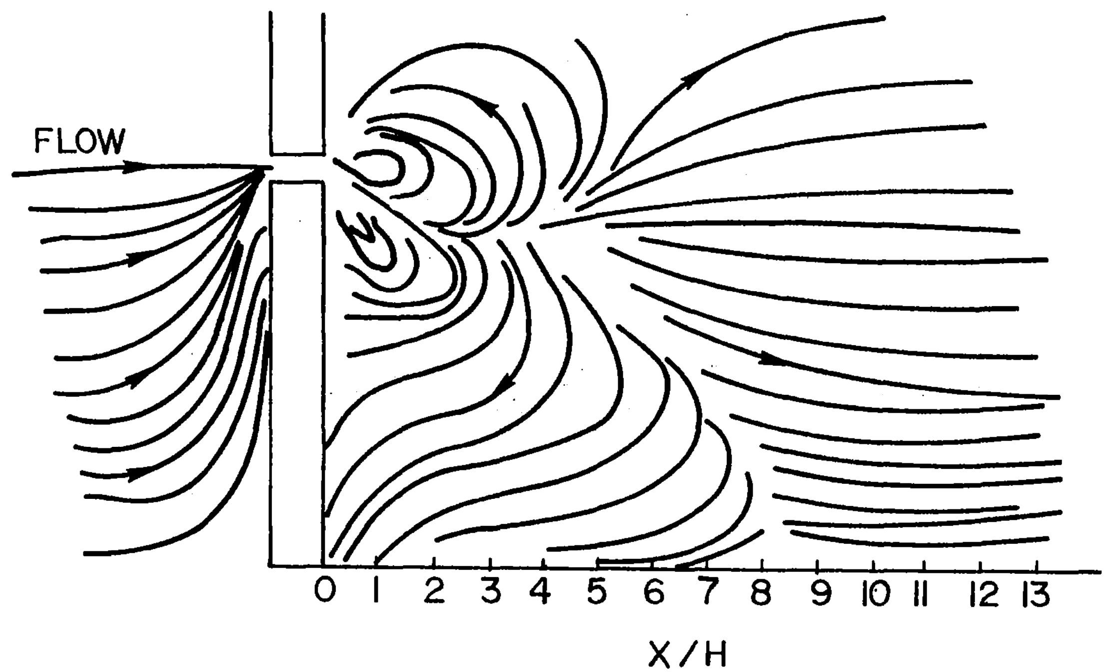


Fig. 5 Streamlines for Gap = 0.5H

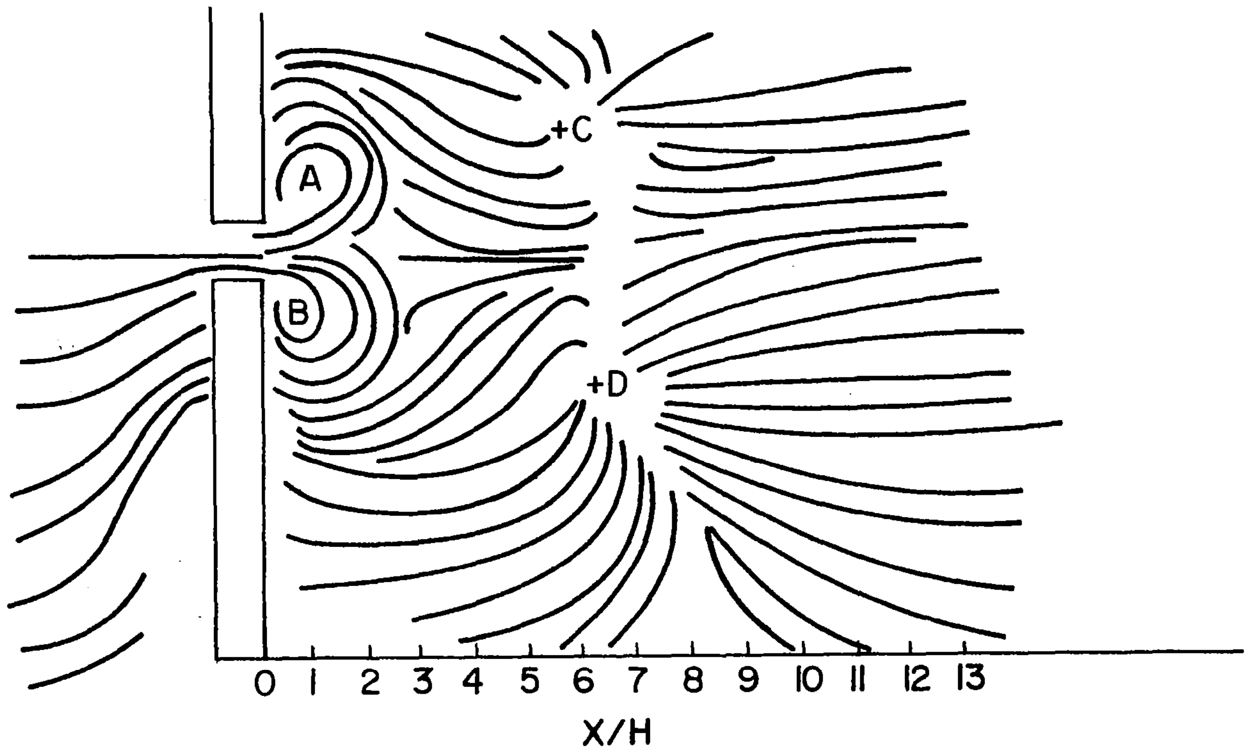


Fig. 6 Streamlines for Gap = 1.0H

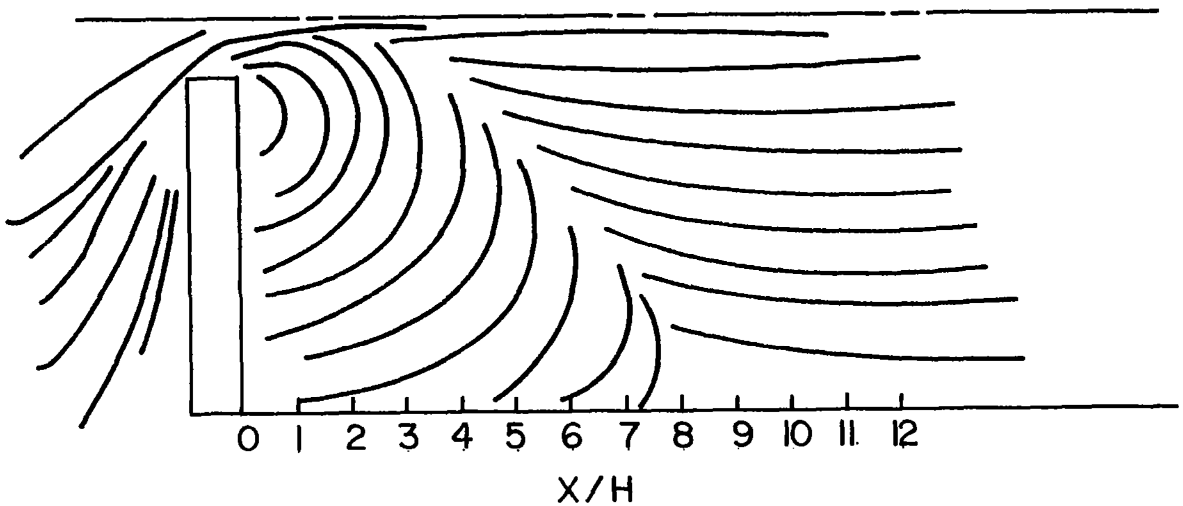


Fig. 7 Streamlines for Gap = 2.0H

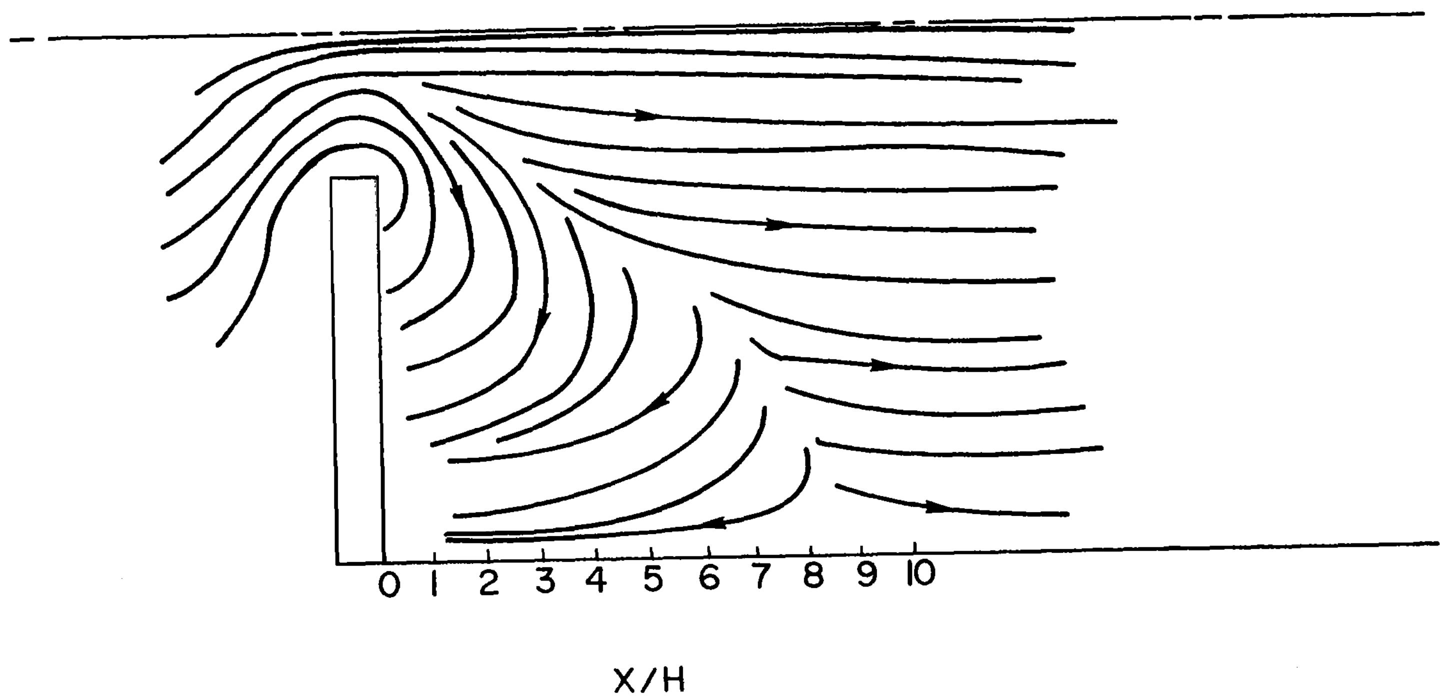


Fig. 8 Streamlines for Gap = 5.0H

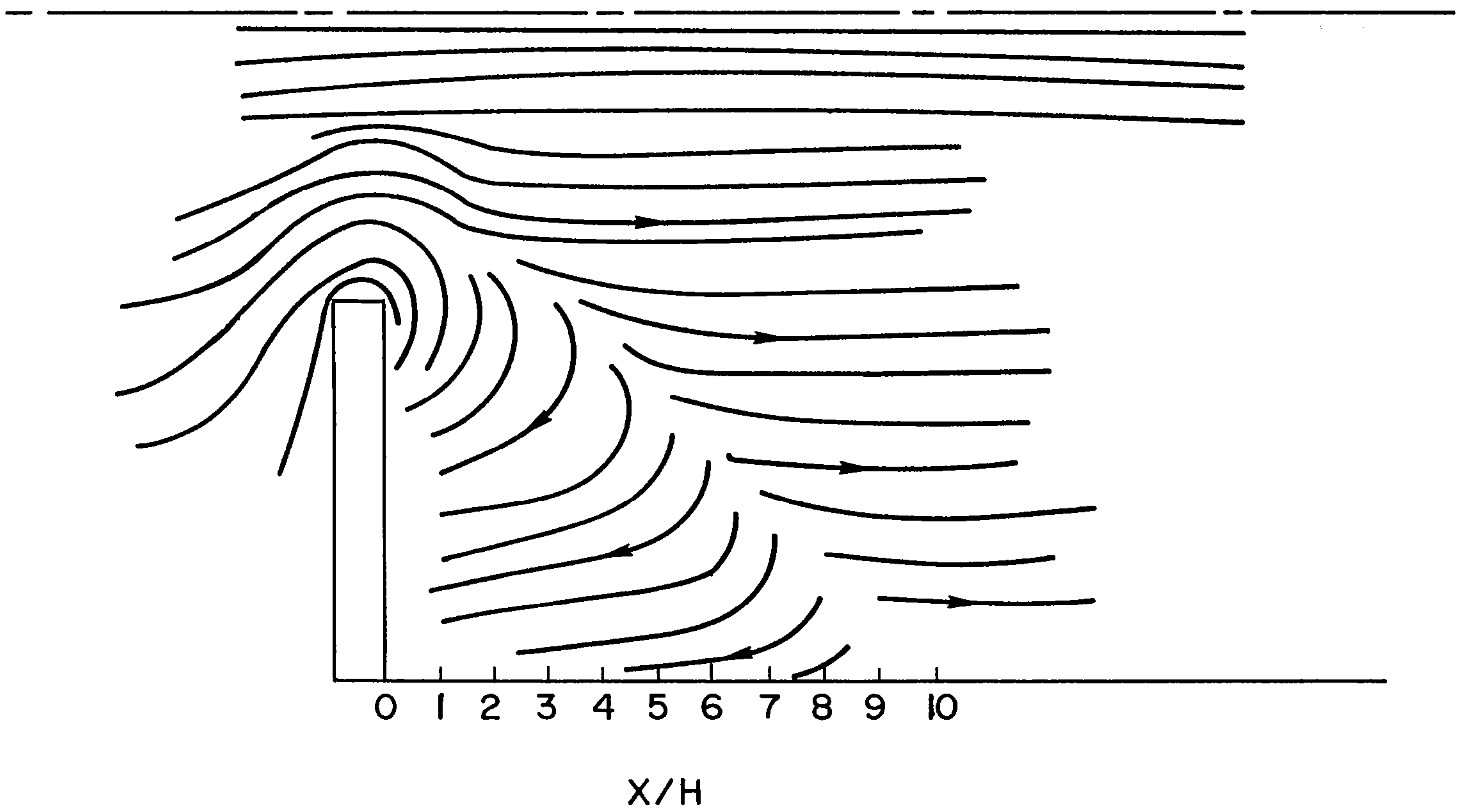


Fig. 9 Streamlines for Gap = 10.0H

maximum velocity (12 cm/s) and model height, was roughly the same as in the wind tunnel.

Attempts to find streamlines in the wake were unsuccessful, as the turbulence in the flow quickly mixed the dye emitted from a hypodermic needle. It was noted that dye injected at some point could be followed a short distance, especially near the surface. The surface of the water tunnel floor was scribed with a grid of lines 1.0H apart. Dye was injected at nodal points and the direction noted by placing an arrow on a drawing. Typical results are shown in Figs. 10 and 11.

The arrows of Figs. 10 and 11 show that surface flow follows a qualitatively similar pattern to that inferred from the streaks photographed on the wind tunnel floor. There are some obvious differences, e.g., the location of the reattachment zone appears to lie a little nearer to the back face of the models than in the wind tunnel flow. The dye study was useful to confirm the existence of the separation zones on both sides of the models, even though dimensions were slightly different for the air and water cases.

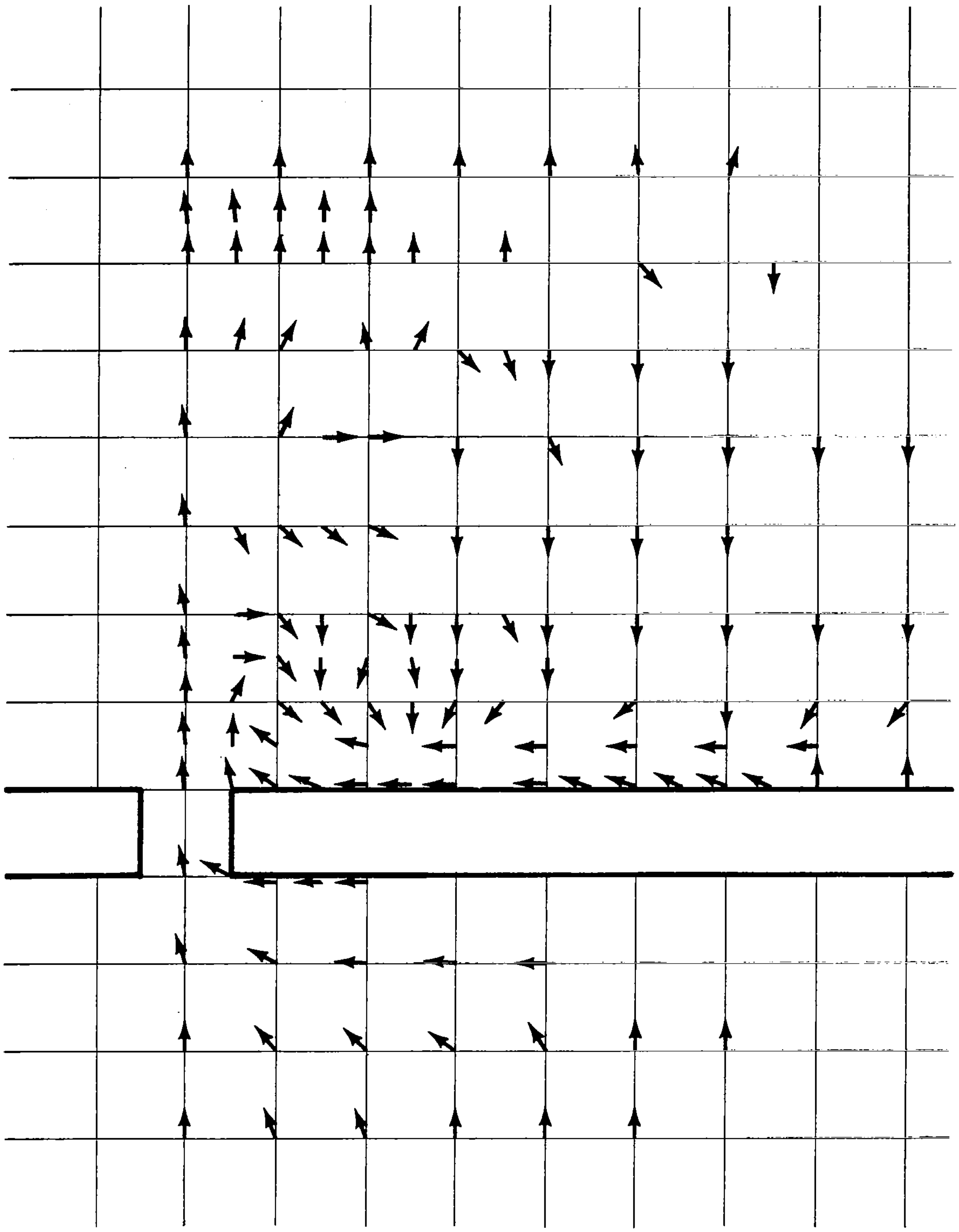


Fig. 10 Surface Flow Directions in Water Flow for Gap = 1.0H

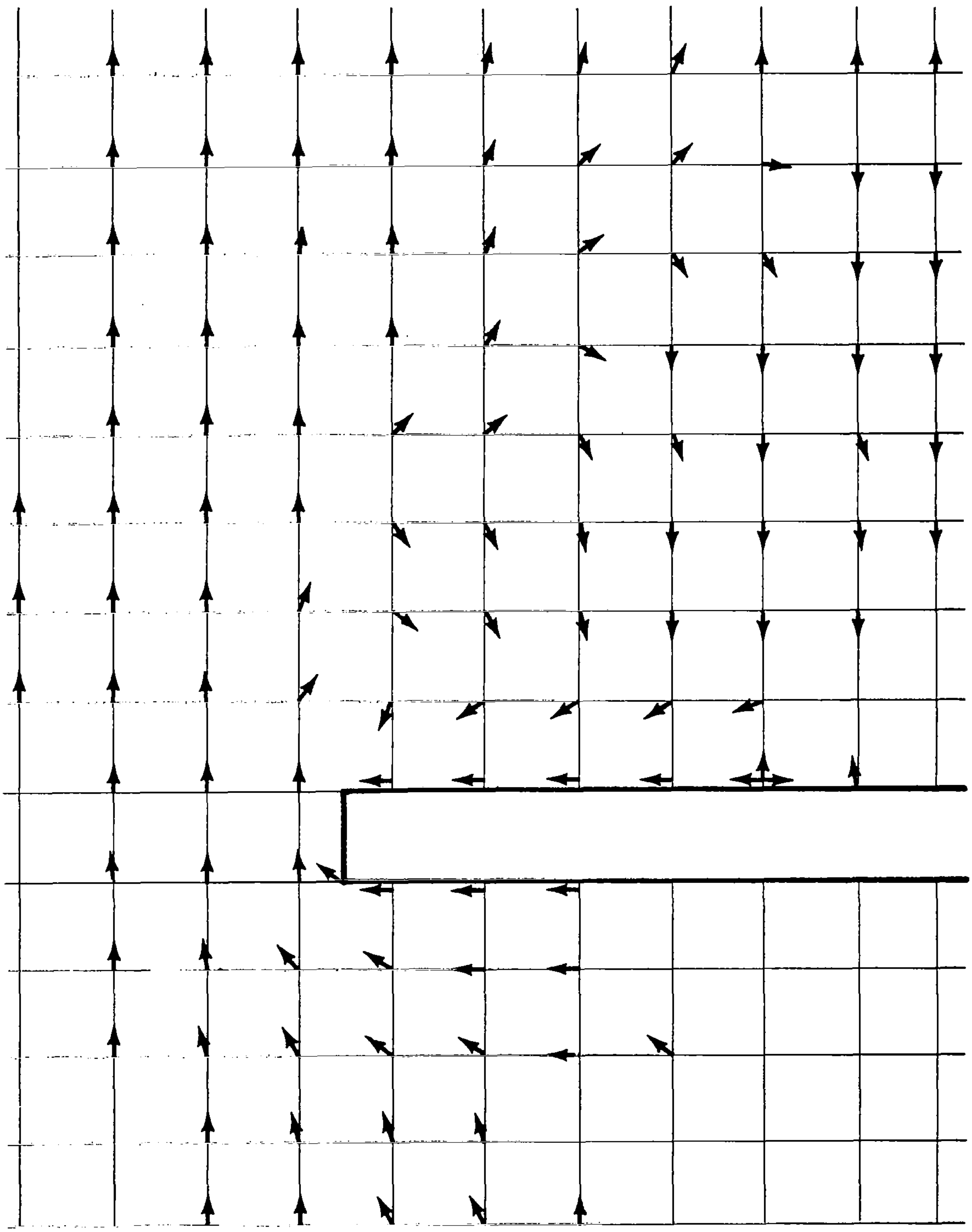


Fig. 11 Surface Flow Directions in Water Flow for Gap = 5.0H

CHAPTER 3

HOT-WIRE ANEMOMETRY

1. Flow Field

According to the measurement of Logan and Barber (1980) significant deviations from the undistrubed boundary layer velocity profile occur between X/H=0 and X/H=250, as shown from the variation of the Clauser parameter G. The thickness δ_i of the disturbed layer attains full boundary layer height δ in the same region. The region of interest can then be designated as $0 < X/H < 250$ and $0 < y/H < 10$. Lateral variations in velocity and turbulence will also occur in this region. Flow visualization studies (Chapter 2) indicate that the width of the disturbed region is 10 to 15H on either side of the centerline, and it is expected to collapse inward with downstream distance. Thus the region of primary interest has been defined, and measurements for this wake should be three-dimensional.

2. Hot-wire Theory

The recent development by Acrivlellis (1978) was selected as a suitable technique for determining all components of the velocity and turbulence fields in the wake behind the gap. The method uses data from a single normal wire probe (α=0 deg) and a slanted-wire probe (α=45 deg). Figure 12 shows the slanted probe and notation used.

The hot-wire shown in Fig. 12 is heated by an electric current within it and is cooled by air flow around it. Traditionally the cooling velocity U_{eff} is defined in terms of a tangential velocity component U_T and two normal components, U_N and U_B, as

$$U_{eff}^2 = U_N^2 + k^2U_T^2 + h^2\ U_B^2 \qquad (1)$$

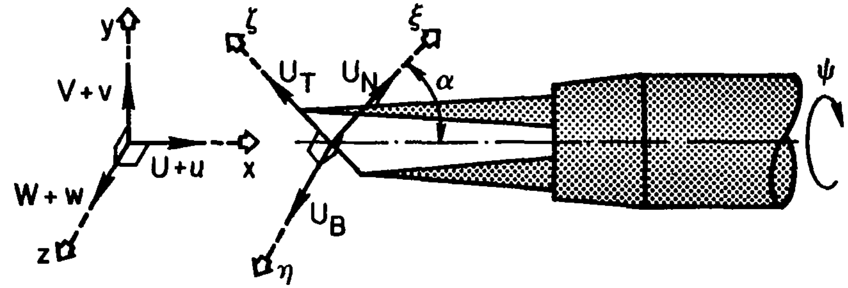


Fig. 12 Hot-wire Probe

where k and h are sensitivity coefficients. The effective velocity U_{eff} is related to the output voltage E of the anemometer by the linear equation

$$E = S\, U_{eff} \tag{2}$$

The value of U_N, U_T and U_B depends on the wire angle α and the probe angle ψ. Thus

$$U_N = (U + u)\cos\alpha + [(V + v)\cos\psi - (W + w)\sin\psi]\sin\alpha \tag{3}$$

$$U_T = -(U + u)\sin\alpha + [(V + v)\cos\psi - (W + w)\sin\psi]\cos\alpha \tag{4}$$

$$U_B = (V + v)\sin\psi + (W + w)\cos\psi \tag{5}$$

Substitution of (3), (4) and (5) into (1), and then substitution of (1) into (2) leads to a relationship between E and the velocity components. Squaring and averaging yields the basic equation

$$\begin{aligned}\overline{E^2} = S^2[&(U^2 + \overline{u^2})(\cos^2\alpha + k^2\sin^2\alpha)\\
&+ (V^2 + \overline{v^2})(\cos^2\psi\sin^2\alpha + k^2\cos^2\psi\cos^2\alpha + h^2\sin^2\psi)\\
&+ (W^2 + \overline{w^2})(\sin^2\psi\sin^2\alpha + k^2\sin^2\psi\cos^2\alpha + h^2\cos^2\psi)\\
&+ (UV + \overline{uv})(1-k^2)\cos\psi\sin 2\alpha\\
&- (UW + \overline{uw})(1-k^2)\sin\psi\sin 2\alpha\\
&- (VW + \overline{vw})(\sin^2\alpha + k^2\cos^2\alpha - h^2)\sin 2\psi]\end{aligned} \tag{6}$$

Noting that

$$\overline{E^2} = \overline{E}^2 + \overline{e^2} \tag{7}$$

and that

$$\overline{E} = S\overline{U}_{eff} \tag{8}$$

where

$$\overline{U}_{eff} = (\overline{U}_N^2 + k^2\overline{U}_T^2 + h^2\,\overline{U}_B^2)^{1/2} \tag{9}$$

with

$$\overline{U}_N = U\cos\alpha + [V\cos\psi - W\sin\psi]\sin\alpha \tag{10}$$

$$\overline{U}_T = -U\sin\alpha + [V\cos\psi - W\sin\psi]\cos\alpha \tag{11}$$

and

$$\overline{U}_B = V\sin\psi + W\cos\psi \tag{12}$$

If we solve (7) for $\overline{e^2}$ and substitute (10), (11) and (12) into (9), and (9) into (8), and (8) into (7), then we obtain

$$\begin{aligned}\overline{e^2} = S^2[&\overline{u^2}(\cos^2\alpha + k^2\sin^2\alpha) + \overline{v^2}(\cos^2\psi\sin^2\alpha + k^2\cos^2\psi\cos^2\alpha + h^2\sin^2\psi) \\ &+ \overline{w^2}(\sin^2\psi\sin^2\alpha + k^2\sin^2\psi\cos^2\alpha + h^2\cos^2\psi) \\ &+ \overline{uv}(1-k^2)\cos\psi\sin2\alpha - \overline{uw}(1-k^2)\sin\psi\sin2\alpha \\ &- \overline{vw}(\sin^2\alpha + k^2\cos^2\alpha - h^2)\sin2\psi)]\end{aligned} \tag{13}$$

Table 1 lists selections of ψ, or angular positions of the probe, made by Acrivlellis (1978).

Table 1

Position No.	Probe Angle	DC Output Voltage
1	0 deg	$\overline{E}_1$
2	90 deg	$\overline{E}_2$
3	180 deg	$\overline{E}_3$
4	270 deg	$\overline{E}_4$
5	45 deg	$\overline{E}_5$
6	-45 deg	$\overline{E}_6$

A different voltage reading is obtained for each probe angle. If we substitute the angles and readings into (6) and (13), then we can obtain

$$X_3U^2 + X_4\ V^2 + h^2\ W^2 = Z_1 \tag{14}$$

$$X_3U^2 + h^2\ V^2 + X_4\ W^2 = Z_2 \tag{15}$$

$$X_3U^2 + X_5\ V^2 + X_5\ W^2 = Z_3 \tag{16}$$

$$UW = \frac{\overline{E}_4{}^2 - \overline{E}_2{}^2}{2S^2\ X_1} = Y_2 \tag{17}$$

$$UV = \frac{\overline{E}_1^2 - \overline{E}_3^2}{2S^2\ X_1} = Y_1 \tag{18}$$

$$VW = \frac{(\overline{E}_6^2 - \overline{E}_5^2)\ (2)^{1/2} + \overline{E}_2^2 - \overline{E}_4^2}{2\ (2)^{1/2}\ S^2(X_4 - h^2)} = Y_4 \tag{19}$$

where

$$X_1 = (1-k^2)\sin^2\alpha \tag{20}$$

$$X_3 = \cos^2\alpha + k^2\sin^2\alpha \tag{21}$$

$$X_4 = \sin^2\alpha + k^2\cos^2\alpha \tag{22}$$

and

$$X_5 = \frac{X_4 + h^2}{2} \tag{23}$$

The wire angle α found in the equations is around 45 degrees for the slant hot-wire. The coefficient k is calculated from

$$k^2 = .0505 - .00016U \tag{24}$$

based on extensive testing by Kjellstrom and Hedberg (1970), and the coefficient h is in the range of 1.0 to 1.1. These coefficients were also determined experimentally by Jorgensen (1971). The factor S is set at 0.1 on the linearizer during calibration.

Mean velocities are obtained by solution of (14), (15) and (16). Reynolds stresses are easily determined from RMS values of turbulence fluctuations measured at the wire in each of the six positions, viz., e_1, e_2, e_3, e_4, e_5 and e_6, corresponding to positions in Table 1. Thus

$$\overline{uv} = \frac{\overline{e_1^2} - \overline{e_3^2}}{2S^2\ X_1} \tag{25}$$

$$\overline{uw} = \frac{\overline{e_4^2} - \overline{e_2^2}}{2S^2\ X_1} \tag{26}$$

$$\overline{vw} = \frac{(\overline{e_6^2} - \overline{e_5^2})\ (2)^{1/2} + \overline{e_2^2} - \overline{e_4^2}}{2\ (2)^{1/2}\ S^2(X_4 - h^2)} \tag{27}$$

3. Hot-wire Measurements

Measurements were taken at the locations indicated in Fig. 13. At each of the 24 stations a velocity profile was determined in the entire boundary layer. This includes, however, all three velocity components, U, V and W, as well as Reynolds stress components. Stations were selected in the wake region where three-dimensional effects were most likely to occur. The data taken at each measuring point were E_1, E_2, E_3, E_4, E_5, E_6, e_1, e_2, e_3, e_4, e_5 and e_6.

Measurements have been taken for small and large gaps and for the no-gap case. Data in processed form are presented in the Appendix in Tables A1-A4. Graphical presentation is made in the next chapter. Values of U, V and W are in meters-per-second units. Signs of V and W may be positive or negative and have been determined through the use of (17) and (18).

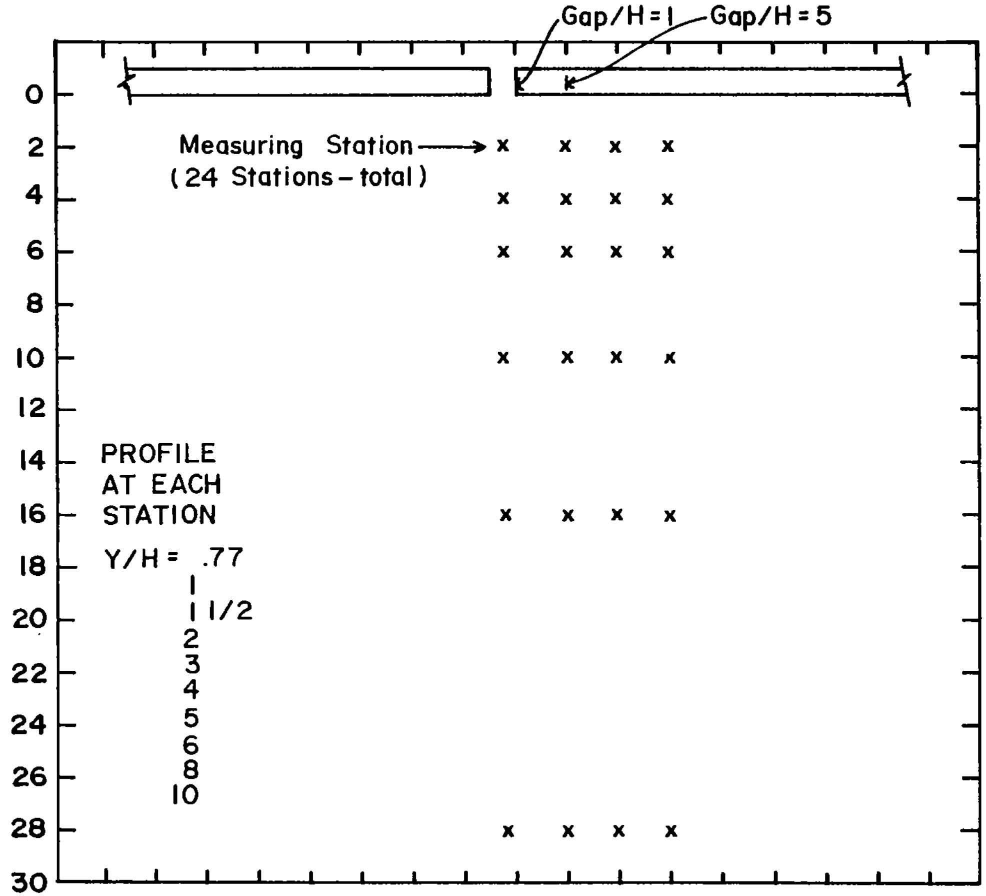


Fig. 13 Location of Measuring Stations

CHAPTER 4

DISCUSSION OF RESULTS

1. Two-dimensional Results

Figure 14 shows a comparison of centerline profiles of longitudinal velocity U (in m/s units) for the two-dimensional obstacle with no gap. Also shown for comparison is a profile with no obstacle in the test section. Clearly the immediate flow response to the obstacle ($x/H = 2$ profile) is a reduction in flow velocity near the surface ($y/H < 1.5$) and an increase in velocity farther from the surface ($y/H > 1.5$). A large increase in velocity gradient dU/dy occurs just behind the obstacle up to $y/H \approx 2$. As x/H increases the severity of this velocity gradient diminishes, and the affected region enlarges, e.g., at $x/H = 28$ region extends to $y/H \approx 4$. Simultaneously the disturbance is affecting a wider region and decaying near the surface. Thus the profile shape is approaching that of a no-obstacle profile as x/H increases.

This centerline behavior was studied in greater detail by Logan and Barber (1980) for the case of two-dimensional obstacles and obstacles with gaps as well. The off-centerline profiles were not obtained in their study but are presented herein.

2. Wakes From Small Gaps

Figure 15 displays velocity profiles on the centerline in the wake behind an obstacle with a small (1H) gap. While the recovery, exhibited by the profile taken at $x/H = 28$, is very close to that shown in Fig. 14 for the 2-dimensional obstacle, the initial disturbance, as shown in the profile at $x/H = 2$, is not as severe. The small gap has a clear effect in the near wake. The response of the flow to the small gap is qualitatively similar to that for no gap.

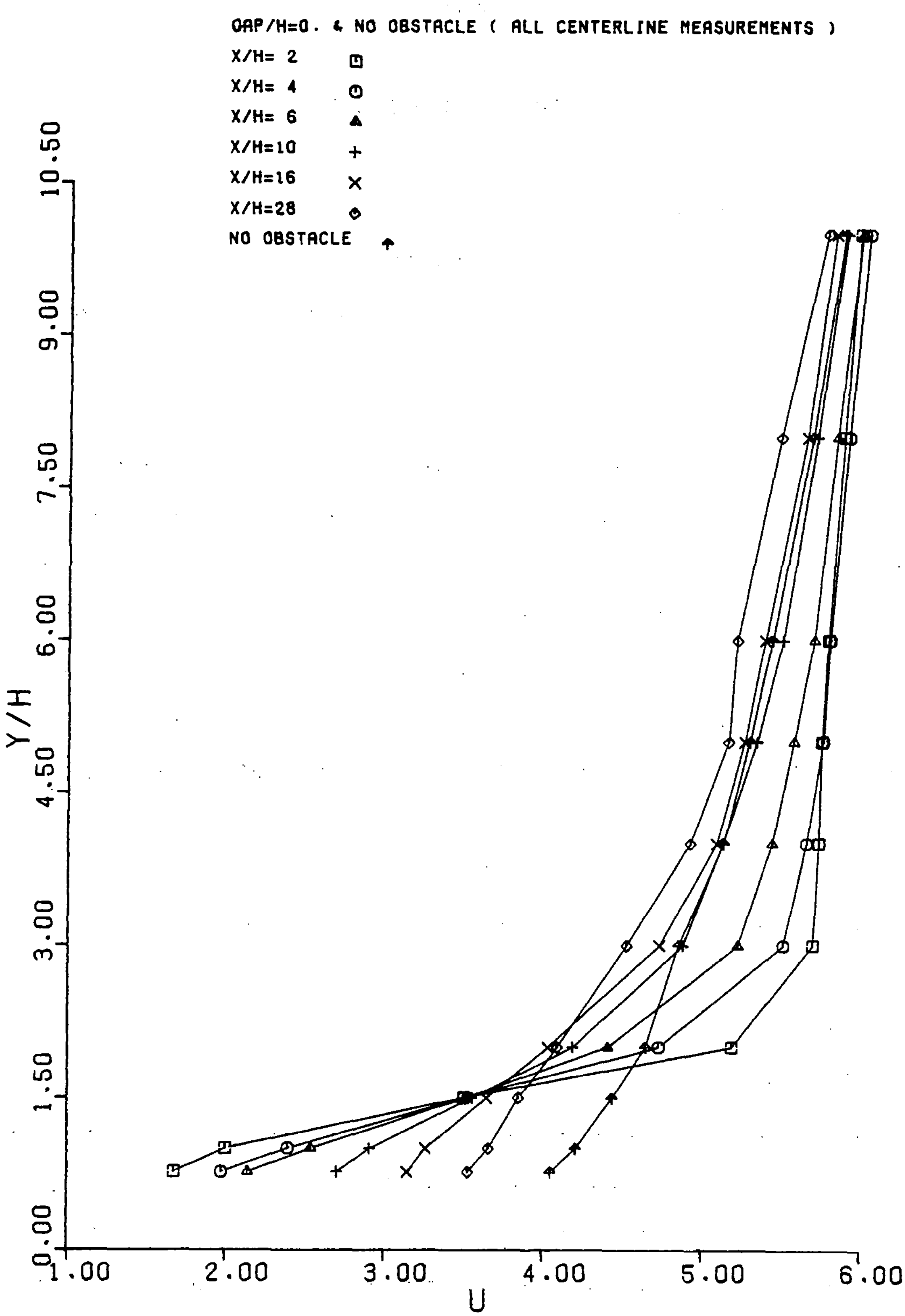


Fig. 14 Comparison of Longitudinal Velocities in the Wake of a Single Continuous Obstacle with the Undisturbed Flow

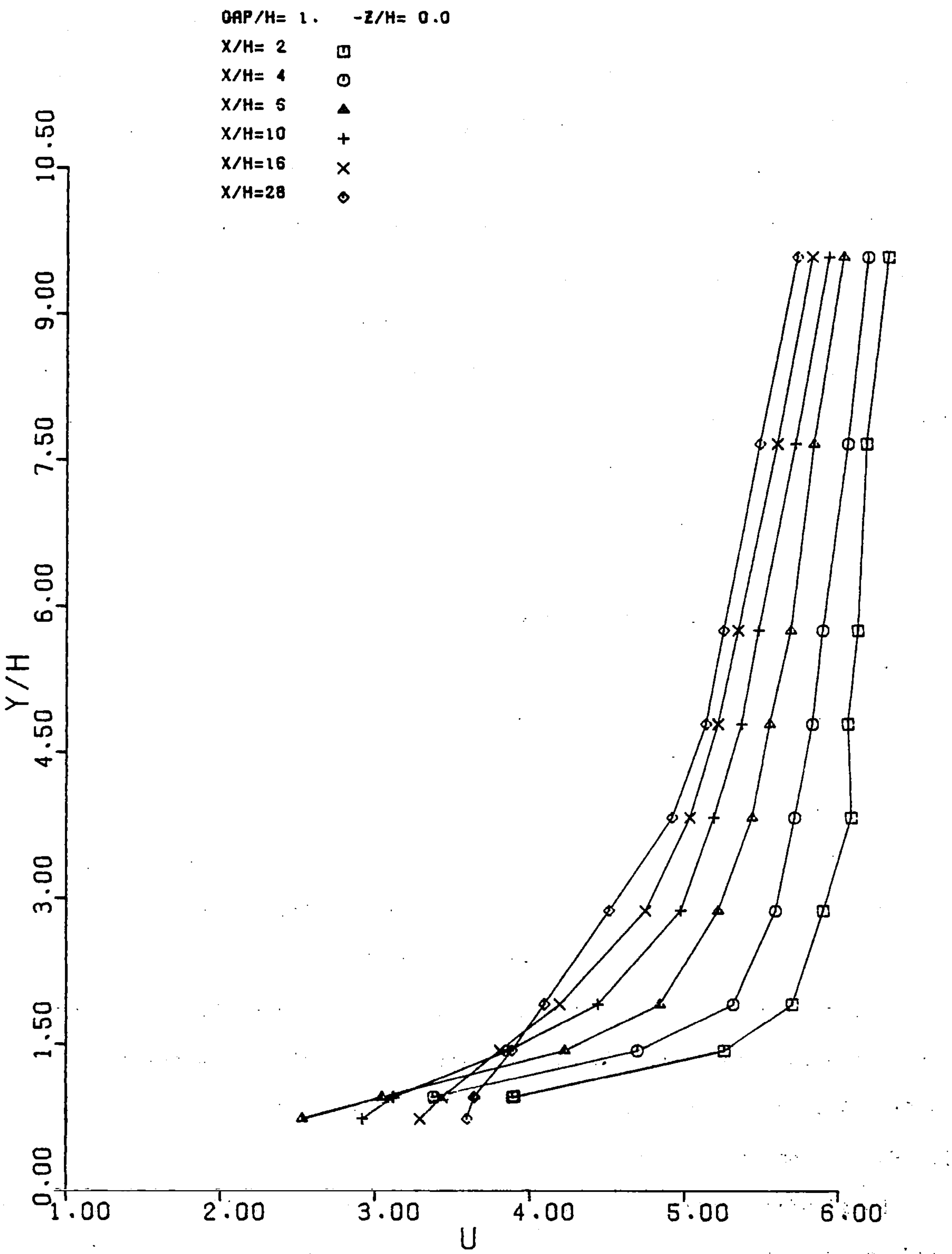


Fig. 15 Centerline Profiles for Small Gap

The off-centerline profiles are shown in Figs. 16-18. The origin of the coordinate system is taken at the centerline of the gap. Thus the ends of the obstacles are at $Z = \pm 0.5H$ and measurements were taken at $Z = -2.5H$, $-4.5H$ and $-6.5H$. Since the wakes are behind the obstacle for these locations, they appear similar to each other and to those shown in Fig. 14.

Differences can be more easily observed in the comparisons made in Figs. 19-24. It is seen that profiles taken on lines farther from the gap are disturbed more by the obstacle and are slower to relax. Thus some three-dimensionality appears to exist in the wake flow behind the small gap. Vertical and lateral components are shown in Figs. 25-32. These profiles indicate cross flow (W-component) away from the centerline in the near-wall region and towards the centerline farther from the wall. However, these vortical motions die out at farther-downstream locations. The V-components are generally negative (downward) except close to the element where strong upflow exists.

The lateral variation in the longitudinal velocity U, as indicated in Figs. 20-22, is significant (approximately 10 percent), since it could result in significant spanwise variation in lift (nearly 20 percent). It is noted that the large variation extends upward for at least 10 obstacle heights.

Figure 26 shows the possibility of large updrafts, equal to nearly 10 percent of the wind velocity, extending upward to at least 10 obstacle heights. This is also variable in the lateral direction. Equally strong downdrafts occur very near the obstacle height ($y/H < 3$). Likewise crosswinds, as shown in Fig. 30, are confined to lower elevations ($y/H < 4$).

3. Wakes from Large Gaps

Longitudinal velocities are compared in Figs. 33-38. The gap clearly produces a lateral variation in U at a given elevation (approximately 14

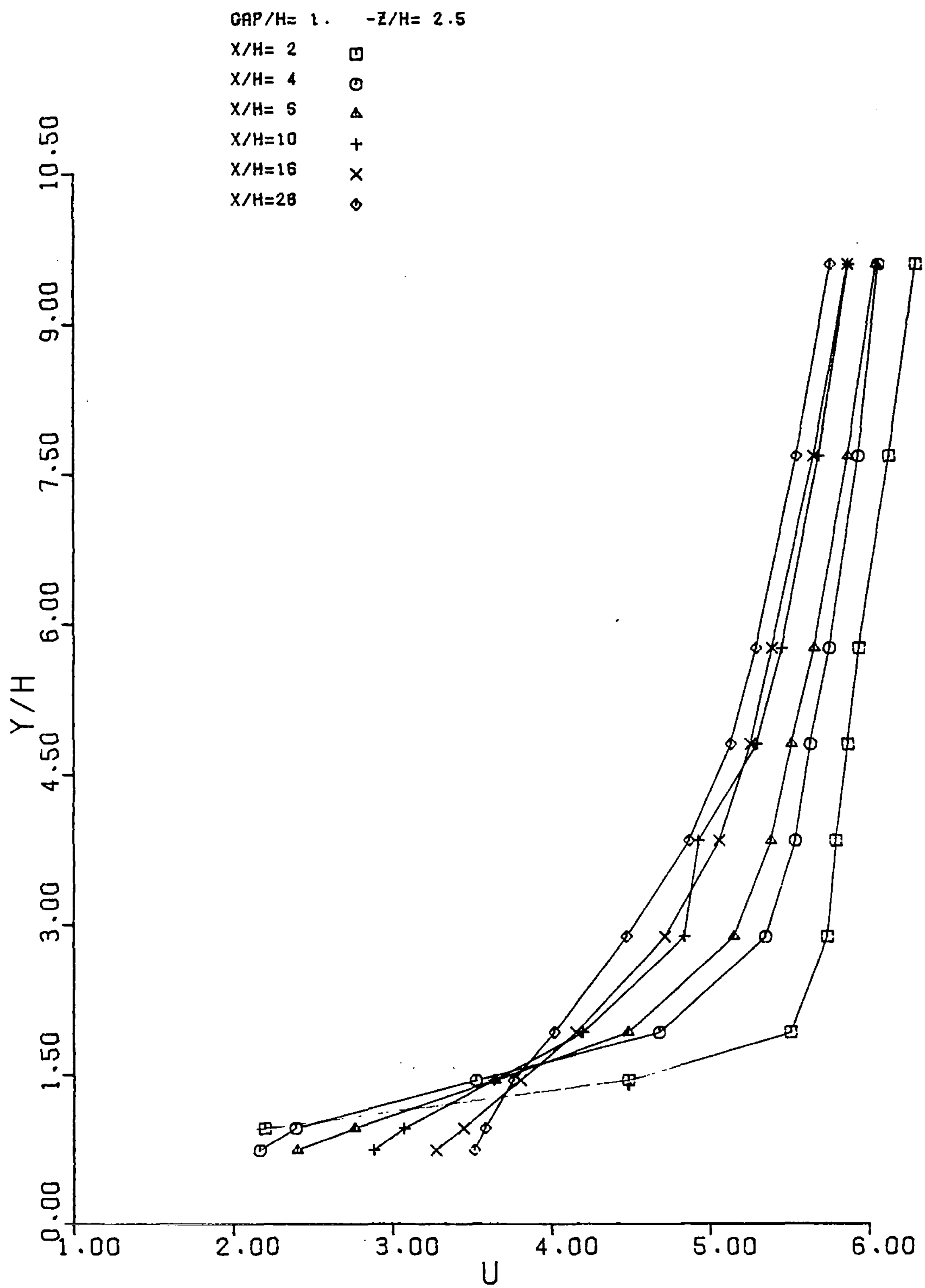


Fig. 16 Off-centerline Velocity Profiles for Small Gap at Z = - 2.5H

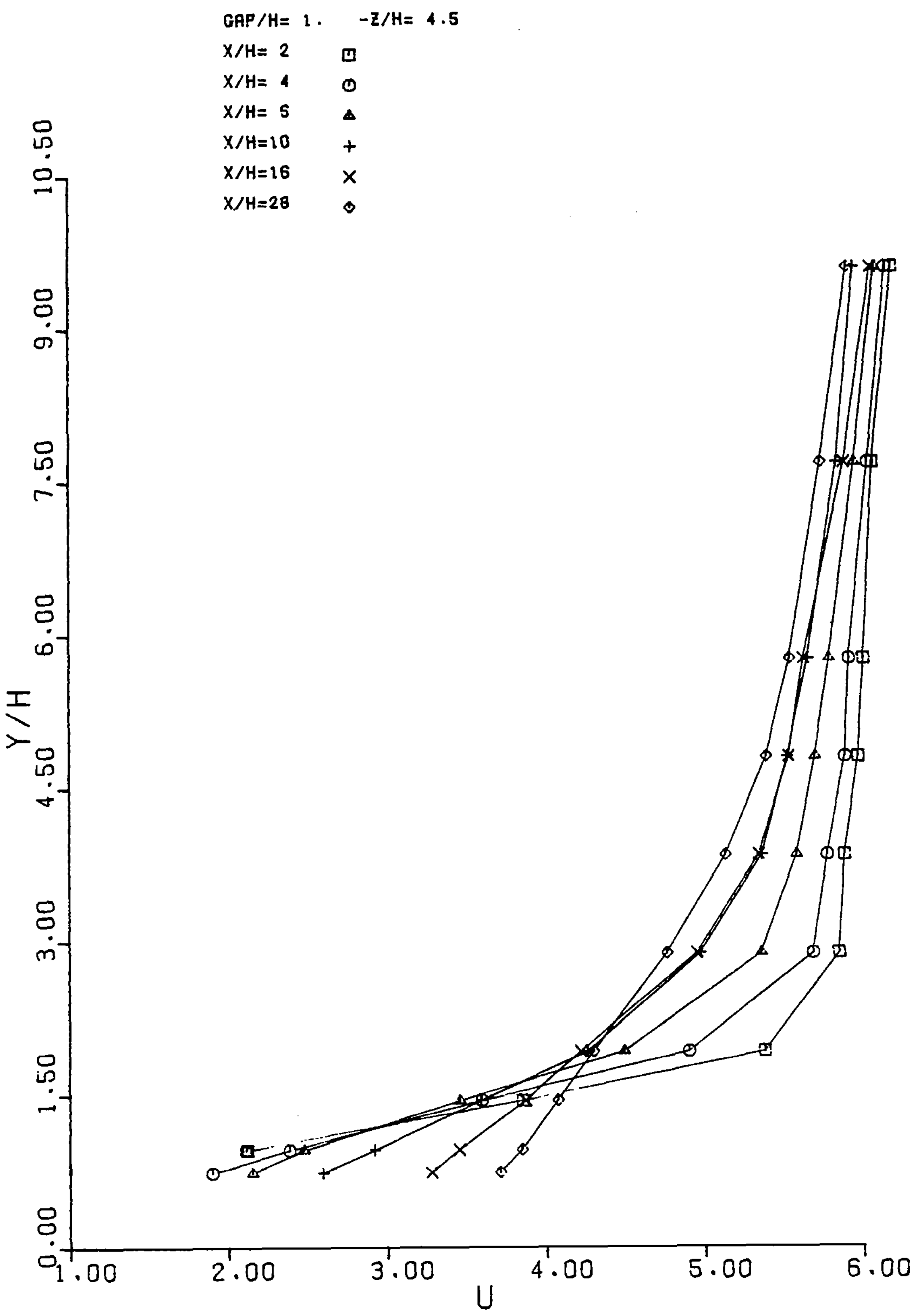


Fig. 17 Off-centerline Velocity Profiles for Small Gap at Z = - 4.5H

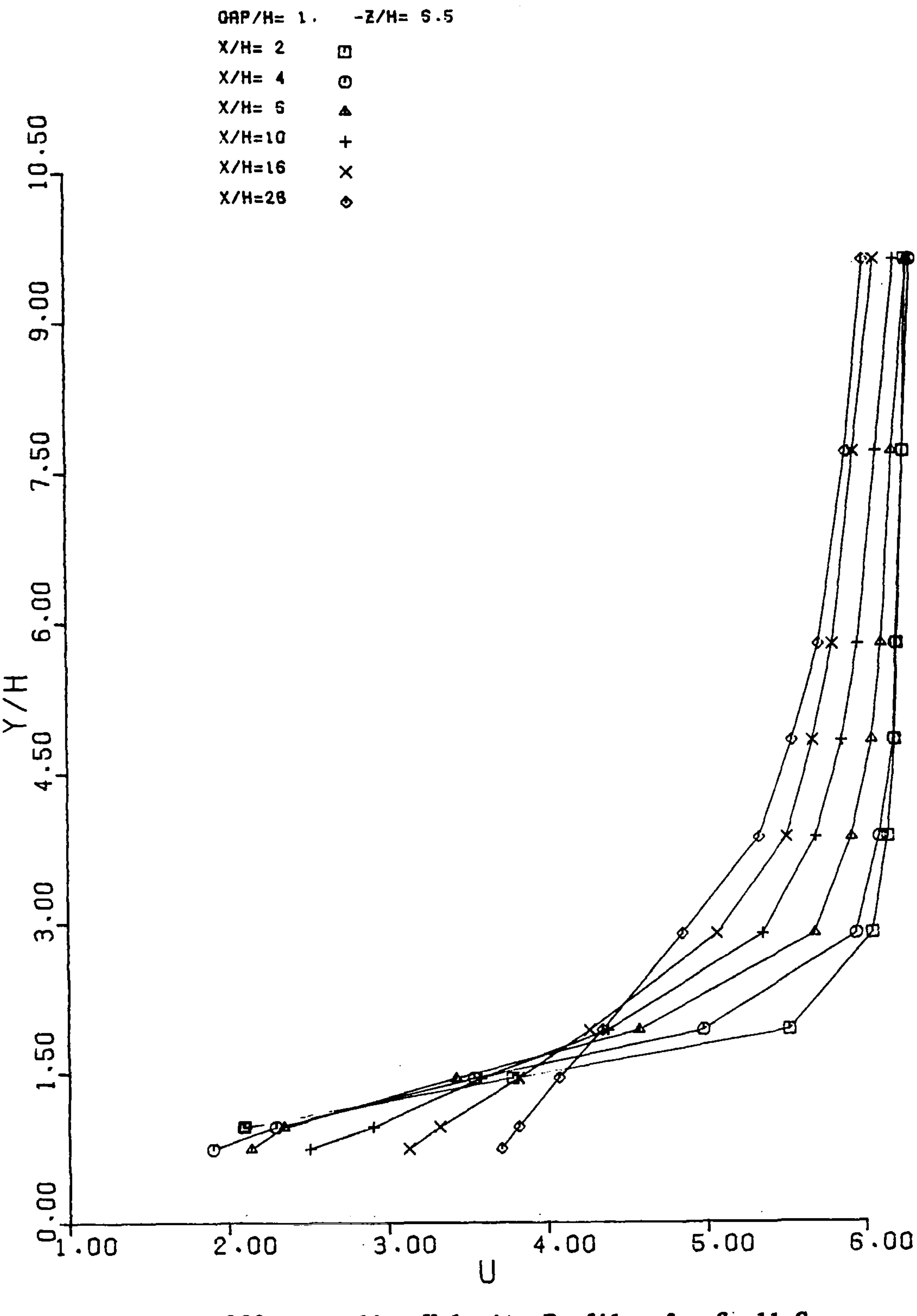


Fig. 18 Off-centerline Velocity Profiles for Small Gap
Z = - 6.5H

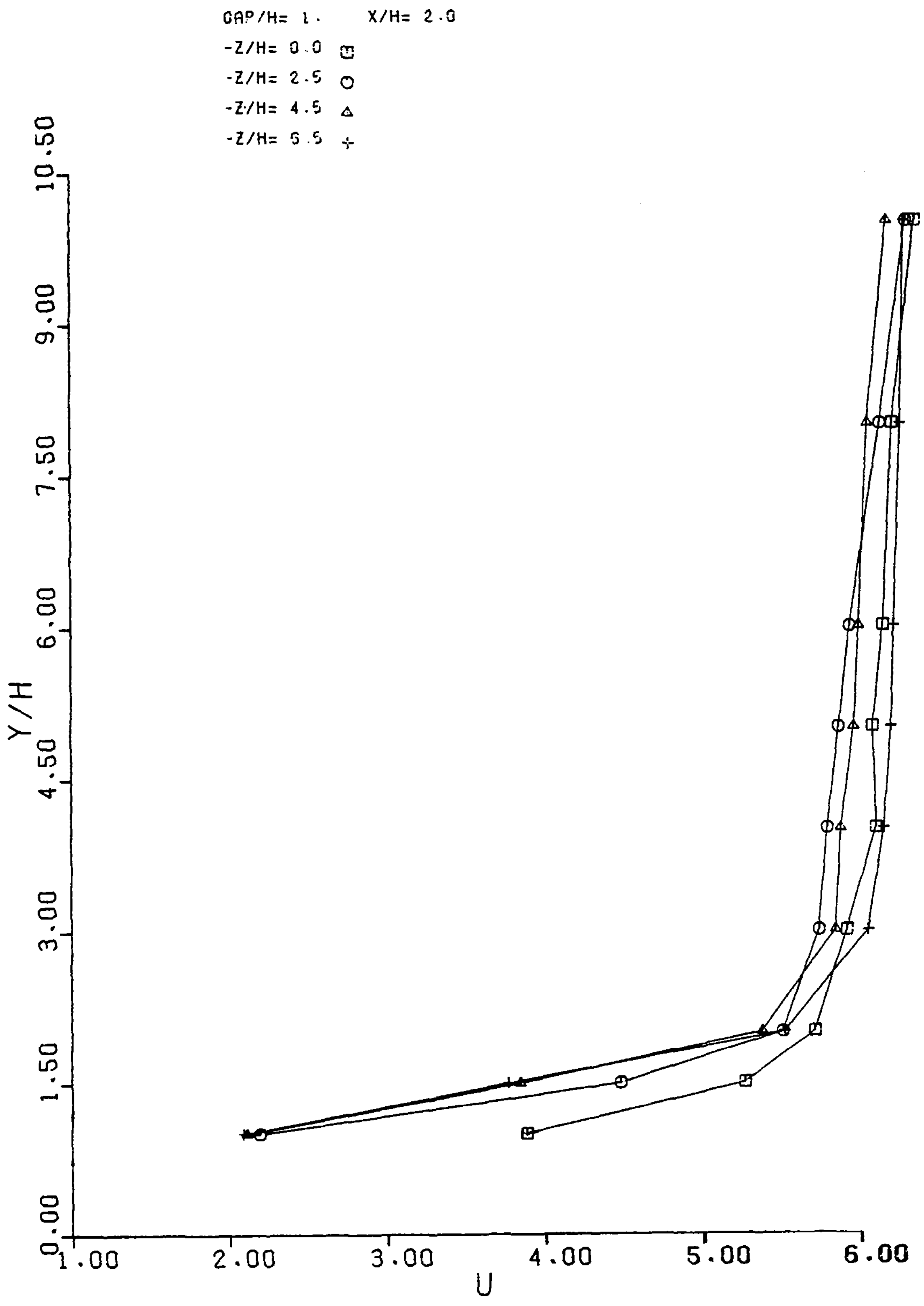


Fig. 19 Comparison of Profiles at X/H = 2 for Small Gap

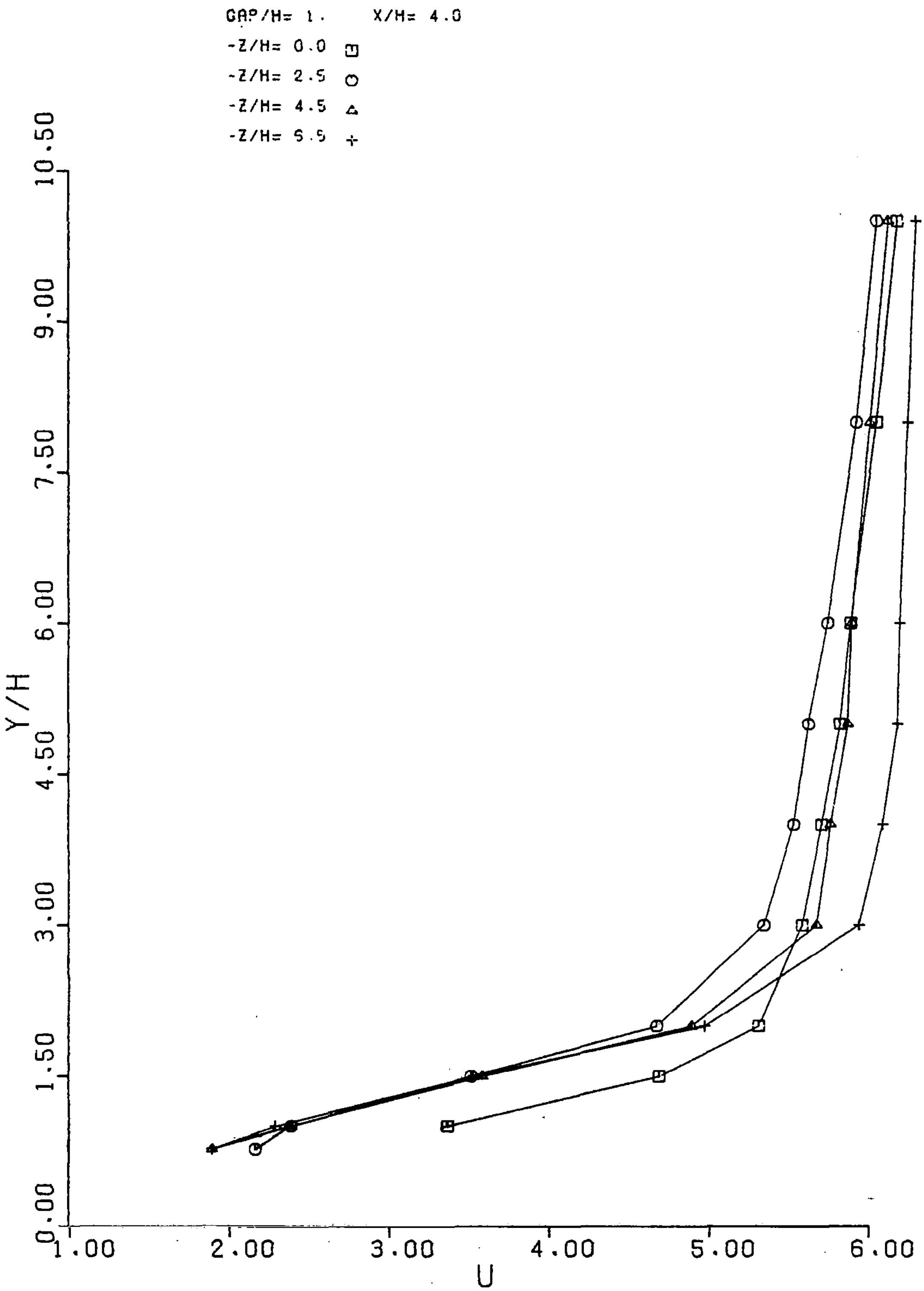


Fig. 20 Comparison of Profiles at X/H = 4 for Small Gap

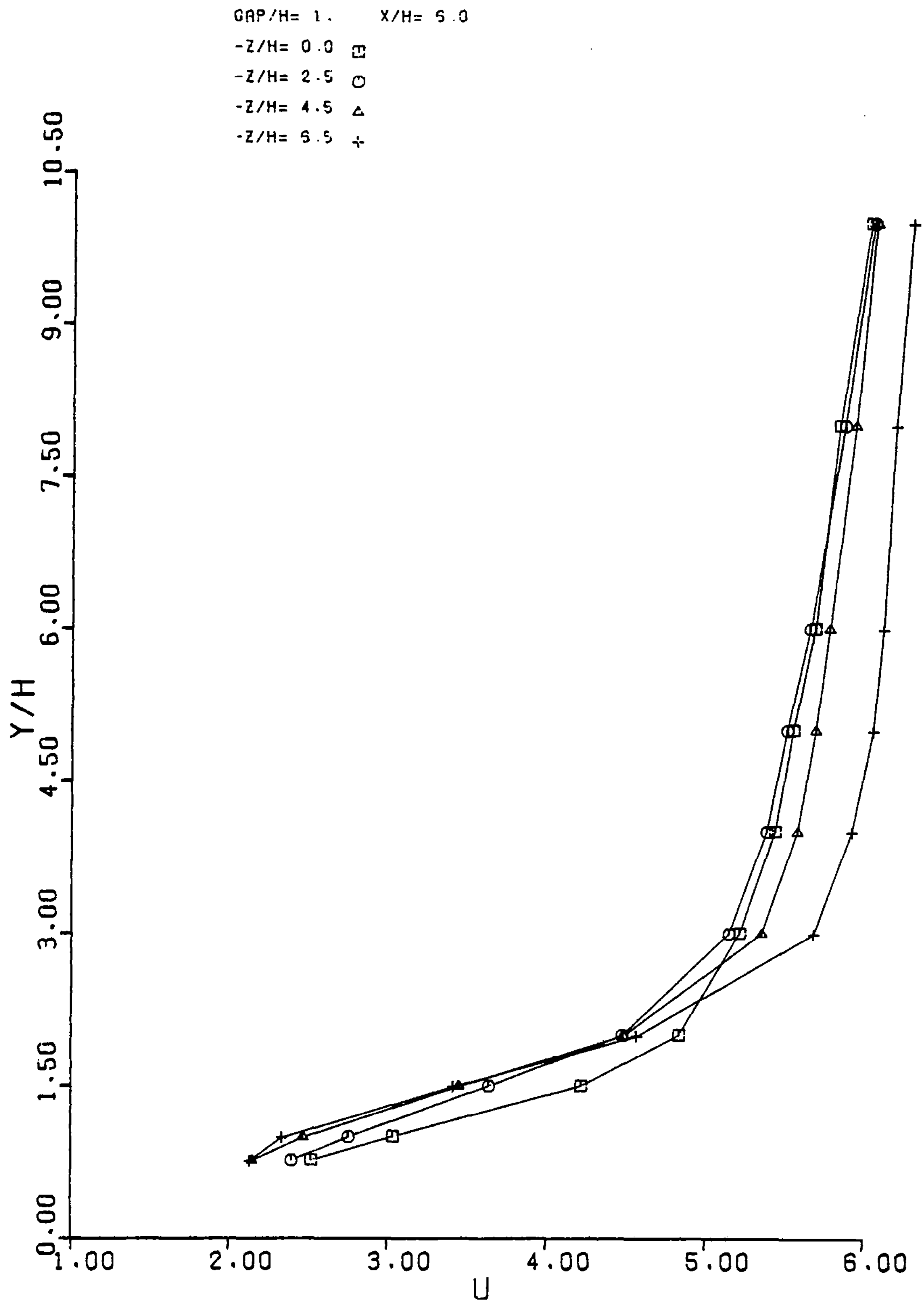
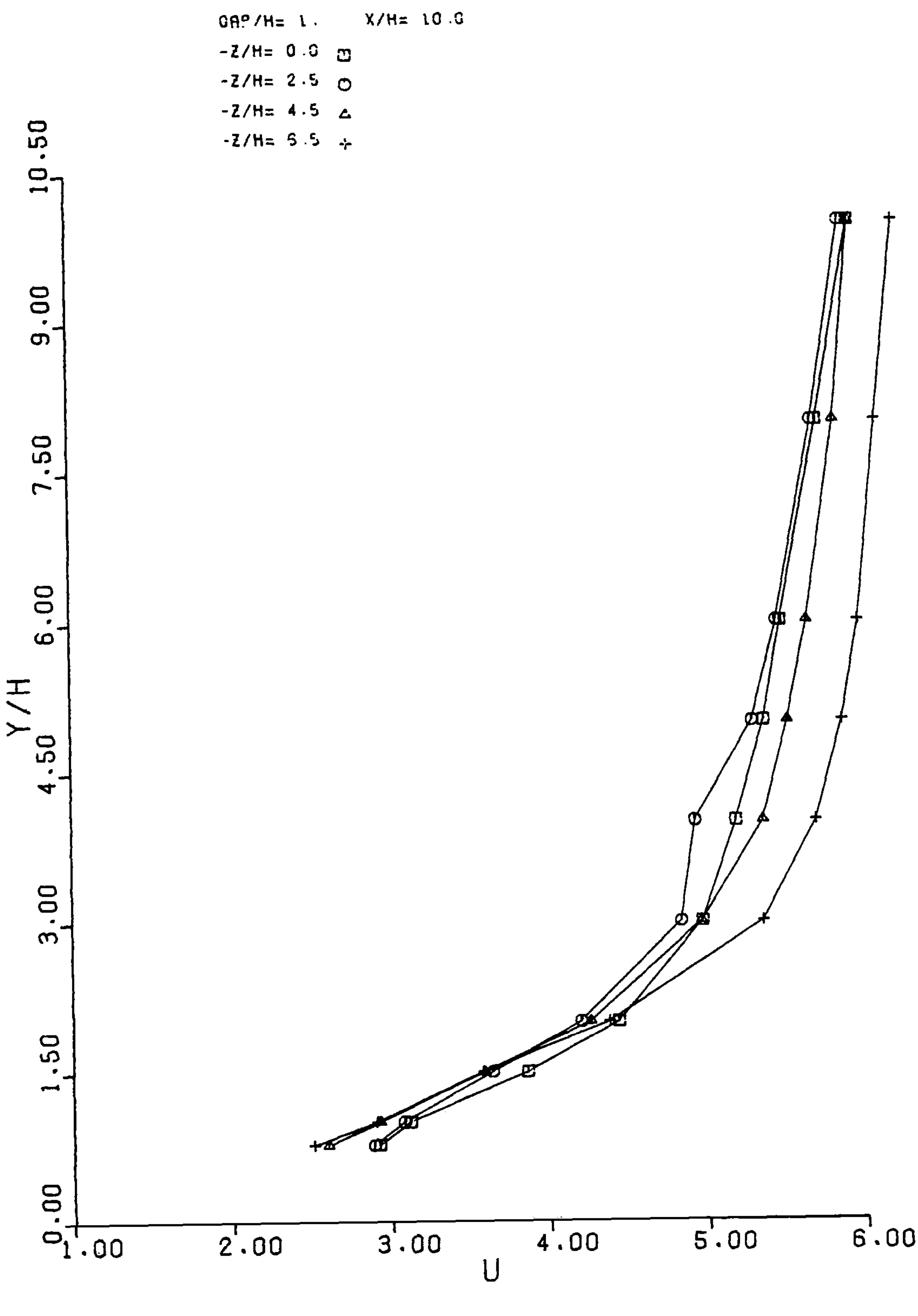


Fig. 21 Comparison of Profiles at X/H = 6 for Small Gap



g. 22 Comparison of Profiles at X/H = 10 for Small Gap

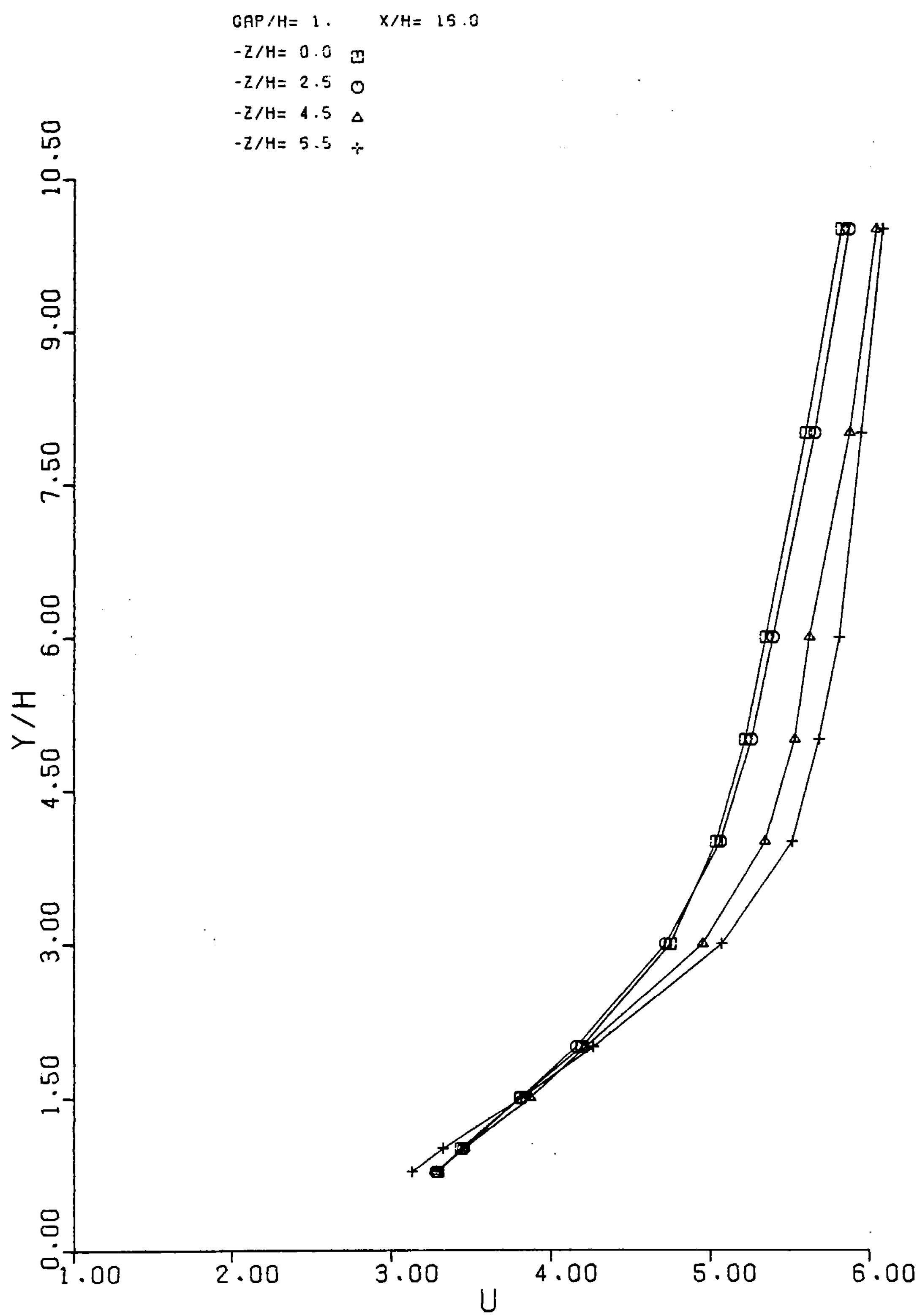


Fig. 23 Comparison of Profiles at X/H = 16 for Small Gap

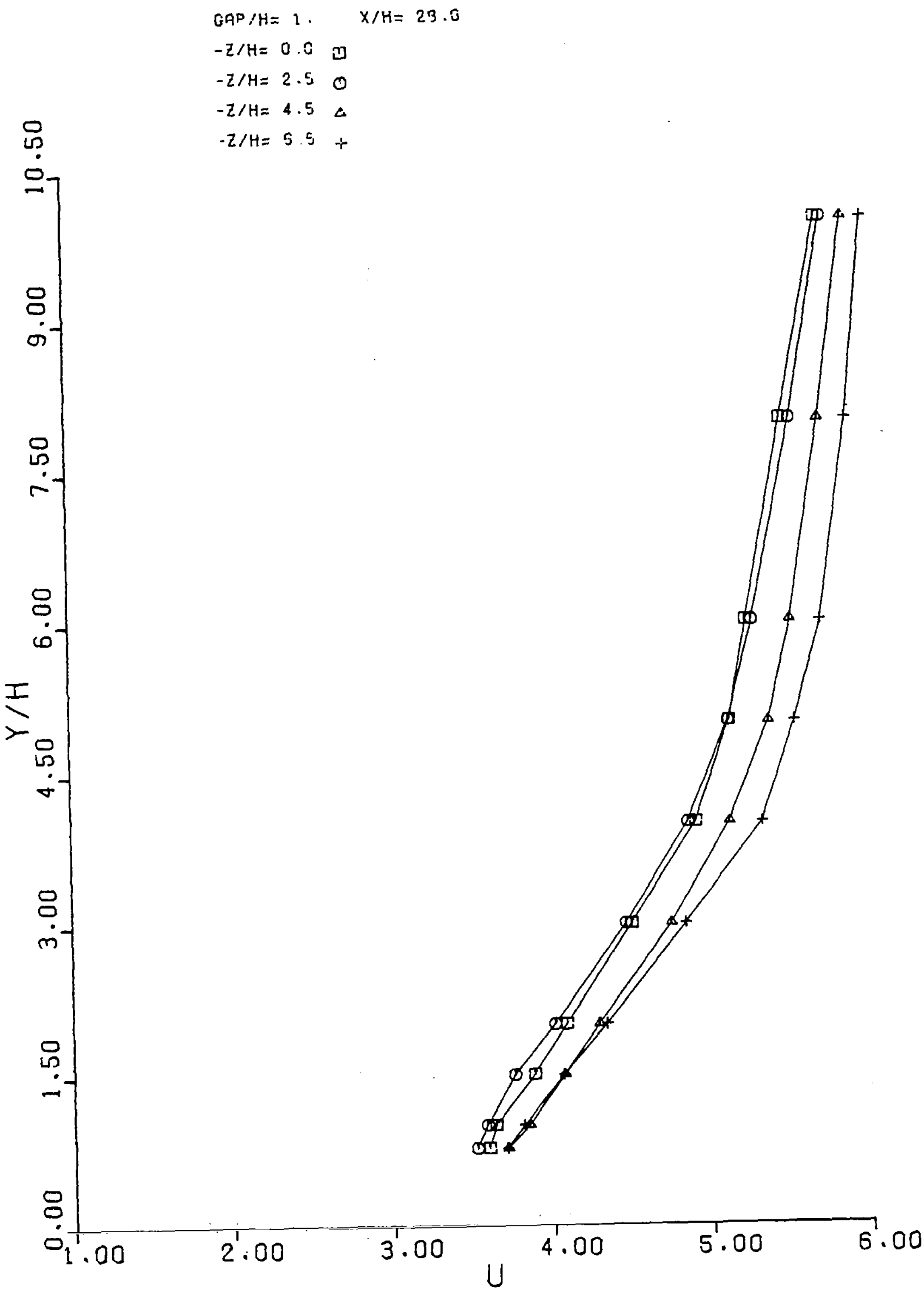


Fig. 24 Comparison of Profiles at X/H = 28 for Small Gap

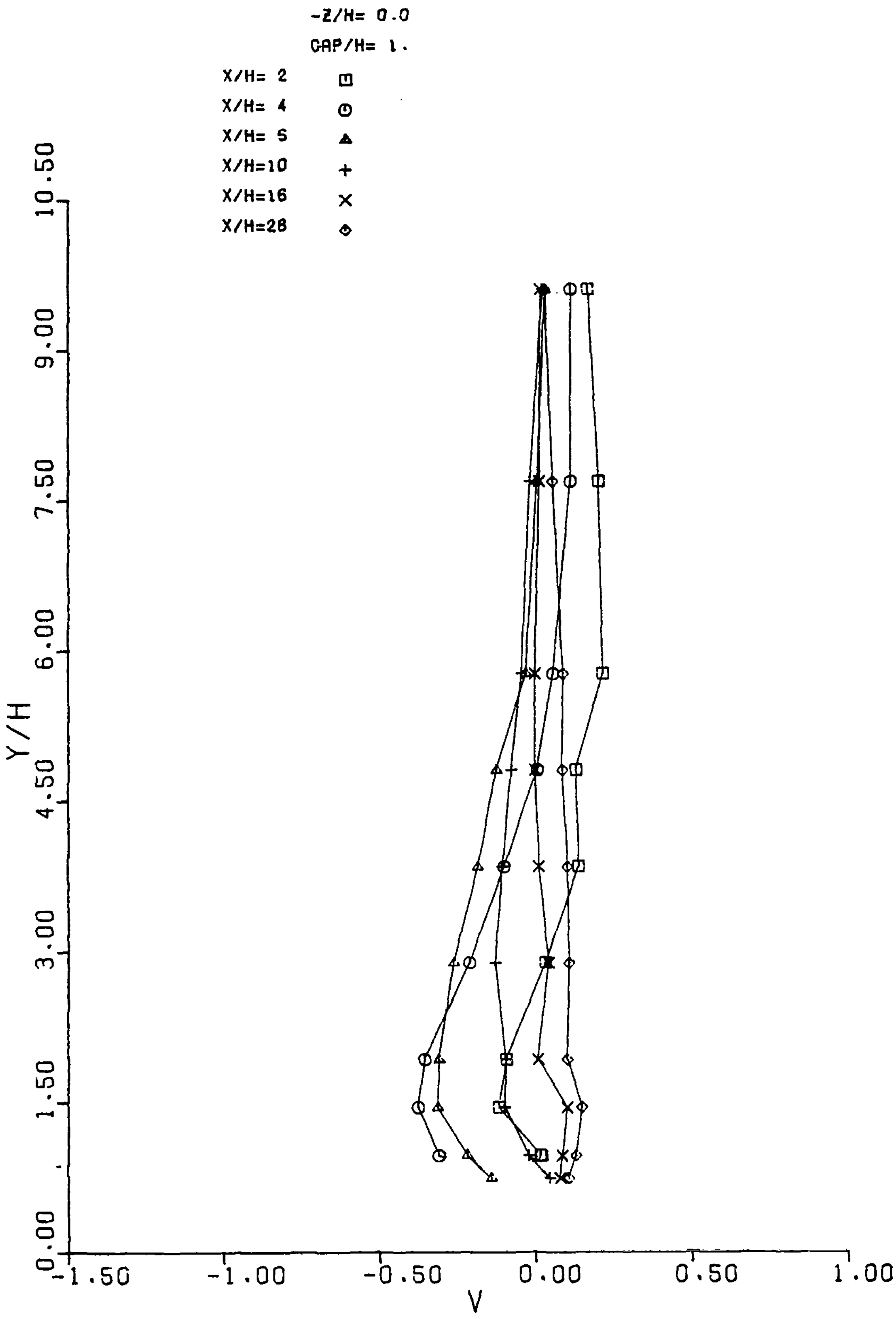


Fig. 25 Vertical Components for Small Gap at Centerline

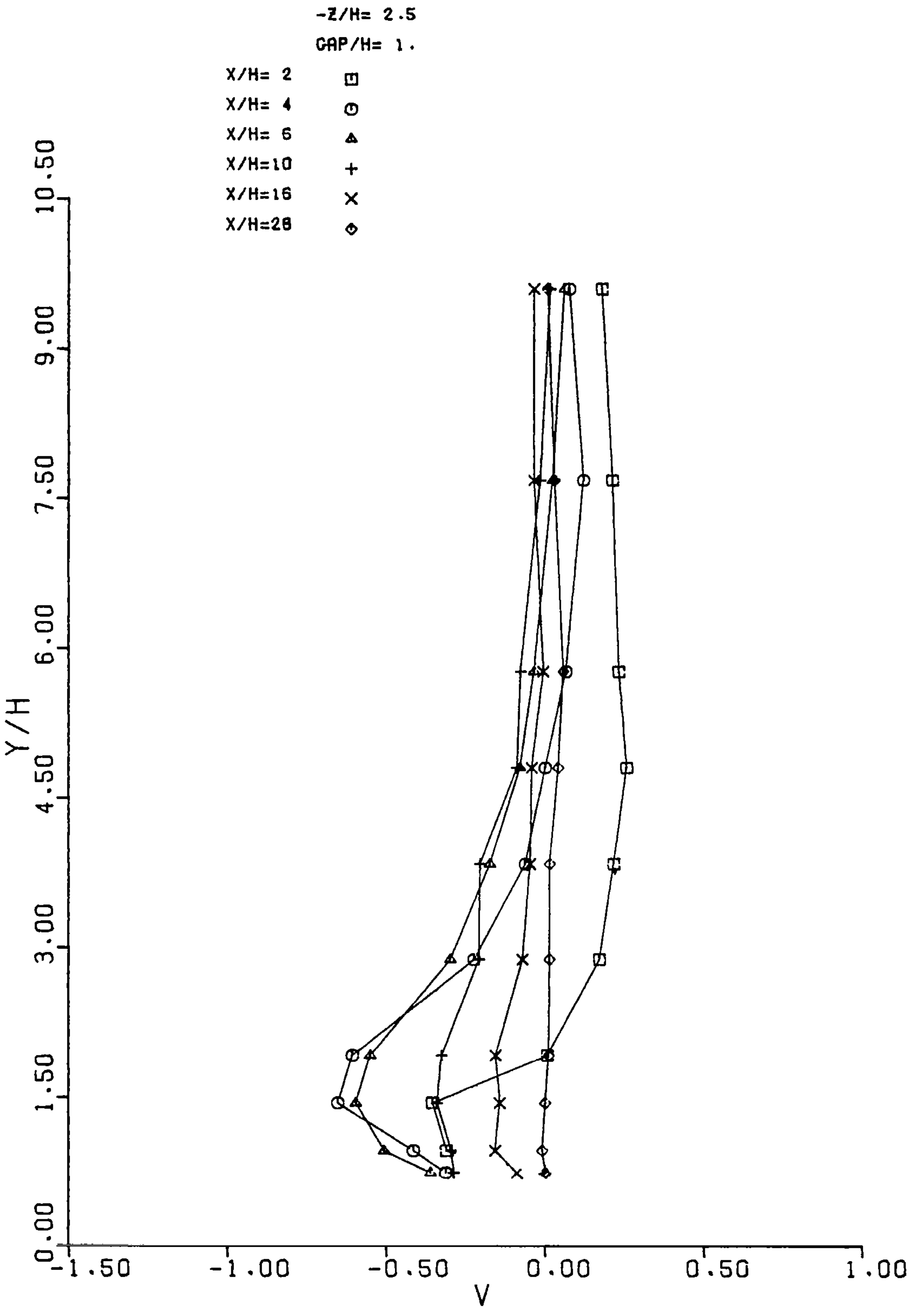


Fig. 26 Vertical Components for Small Gap at Z = - 2.5H

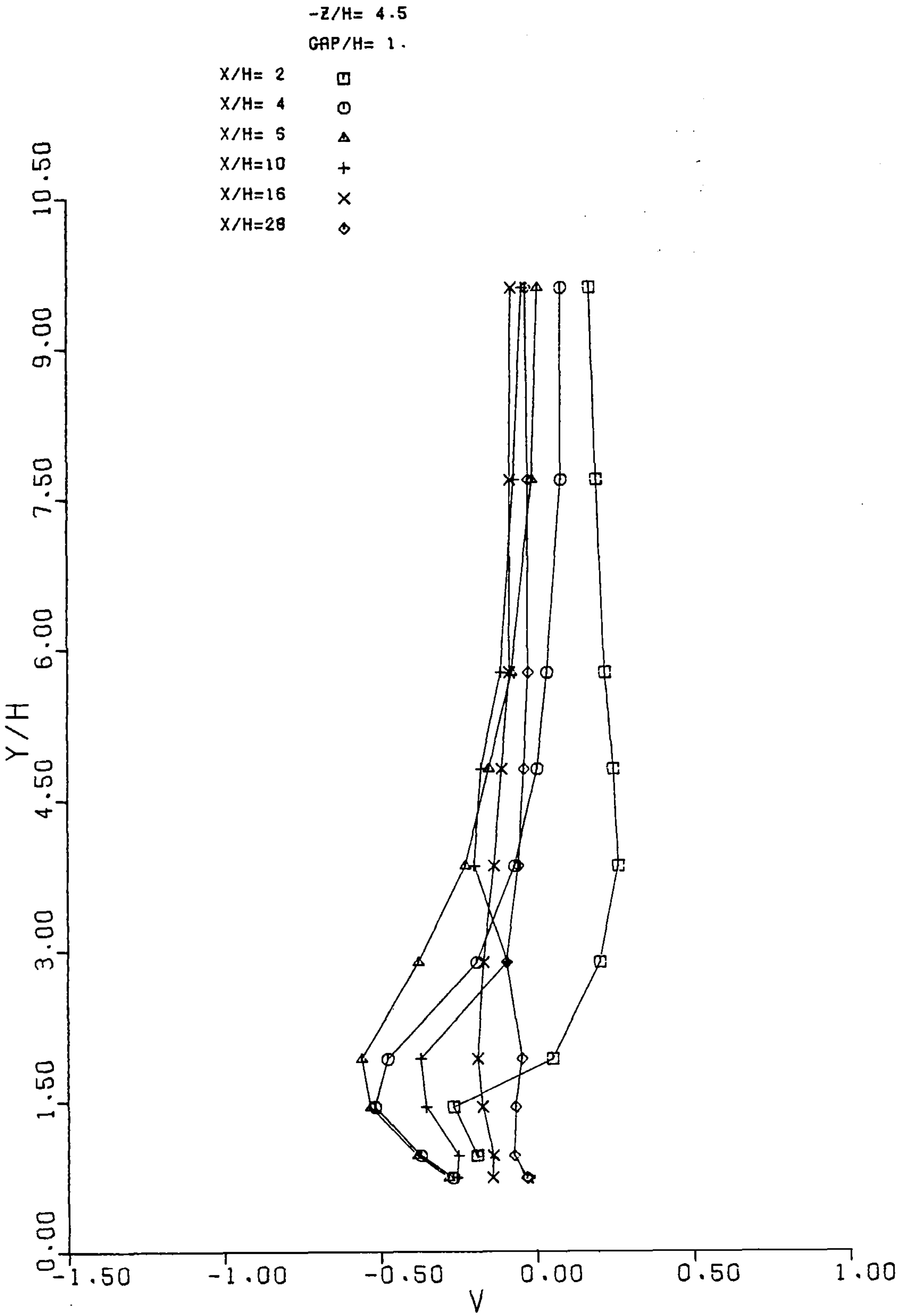


Fig. 27 Vertical Components for Small Gap at Z = - 4.5H

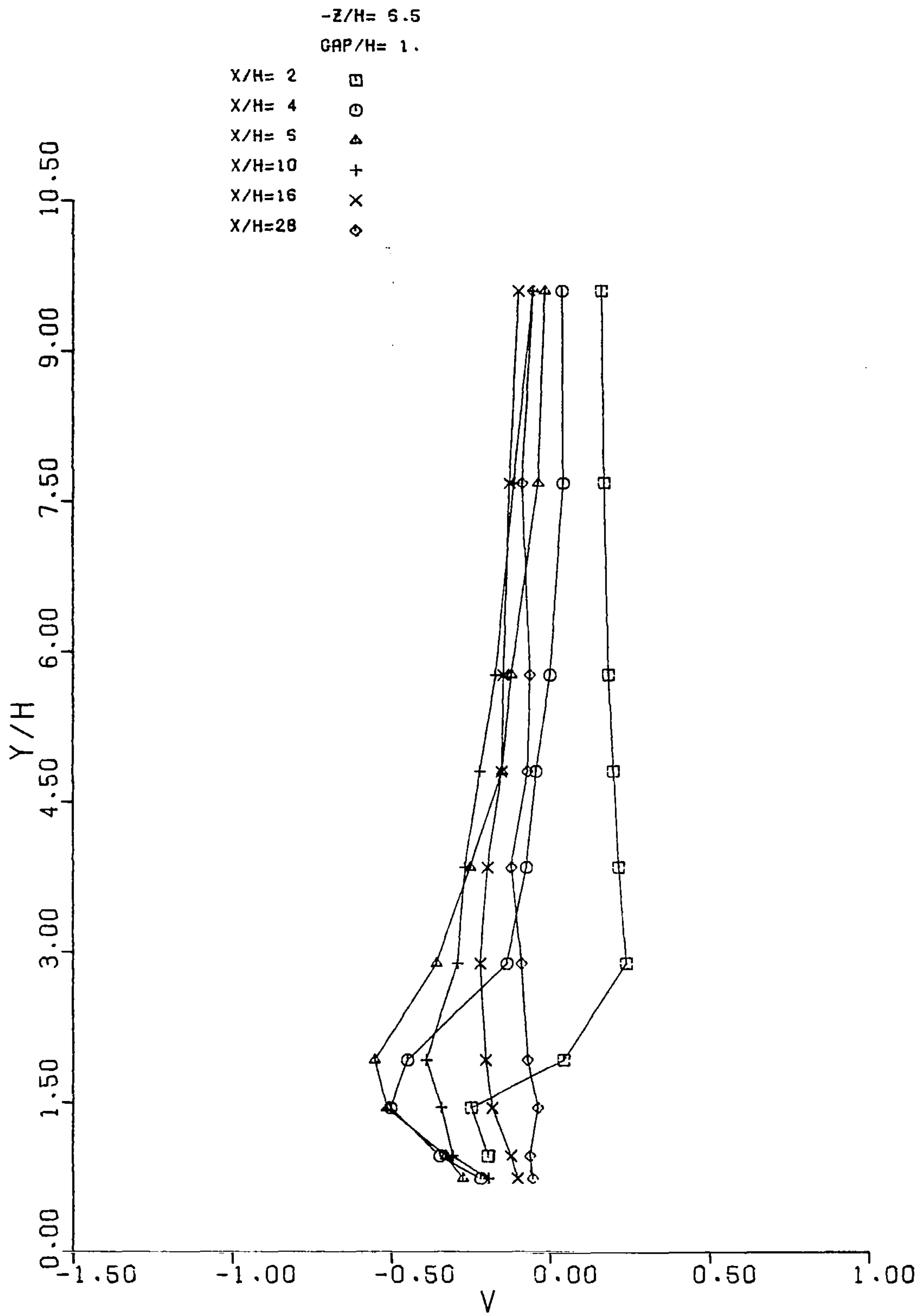


Fig. 28 Vertical Components for Small Gap at Z = − 6.5H

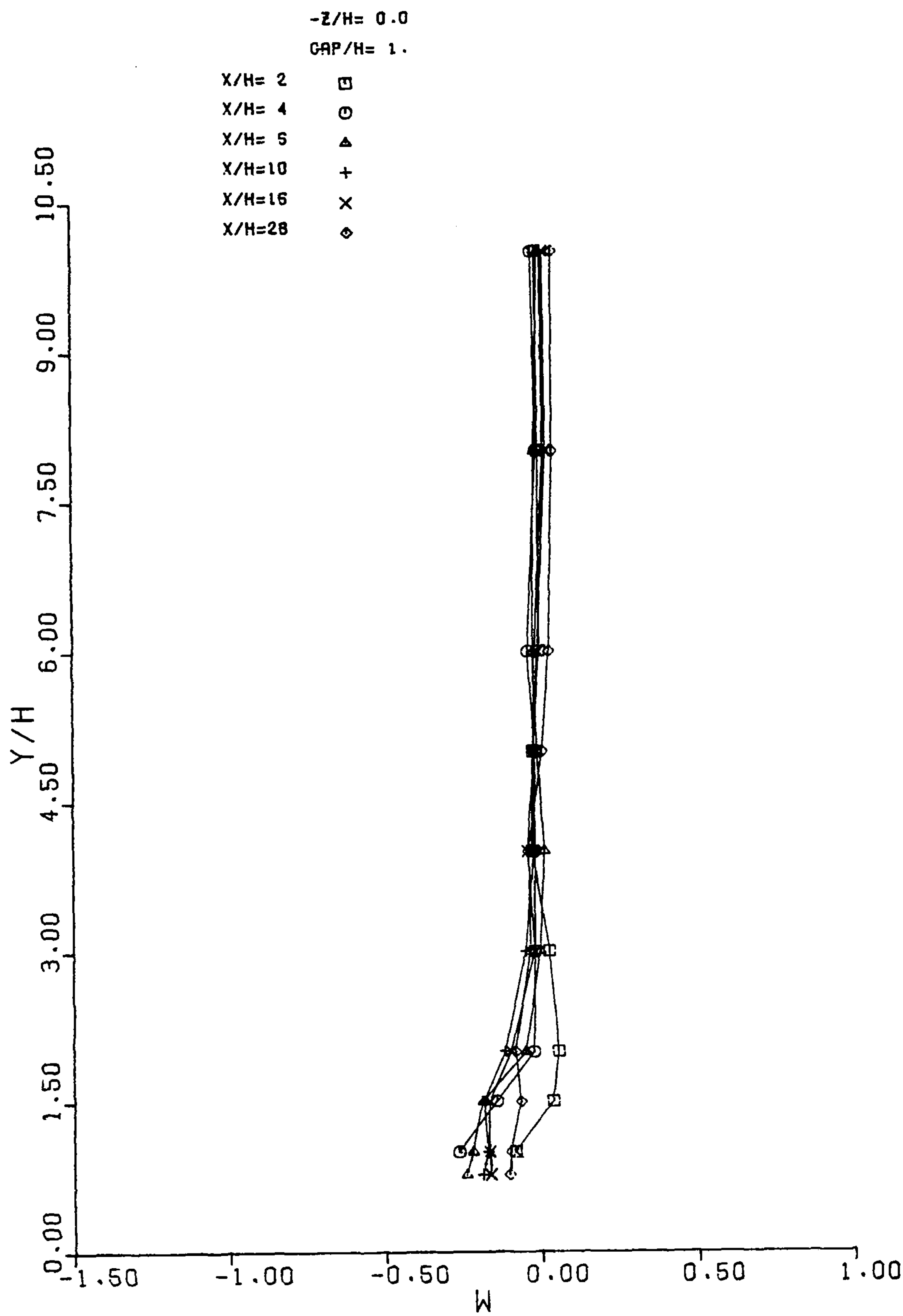


Fig. 29 Lateral Components for Small Gap at Centerline

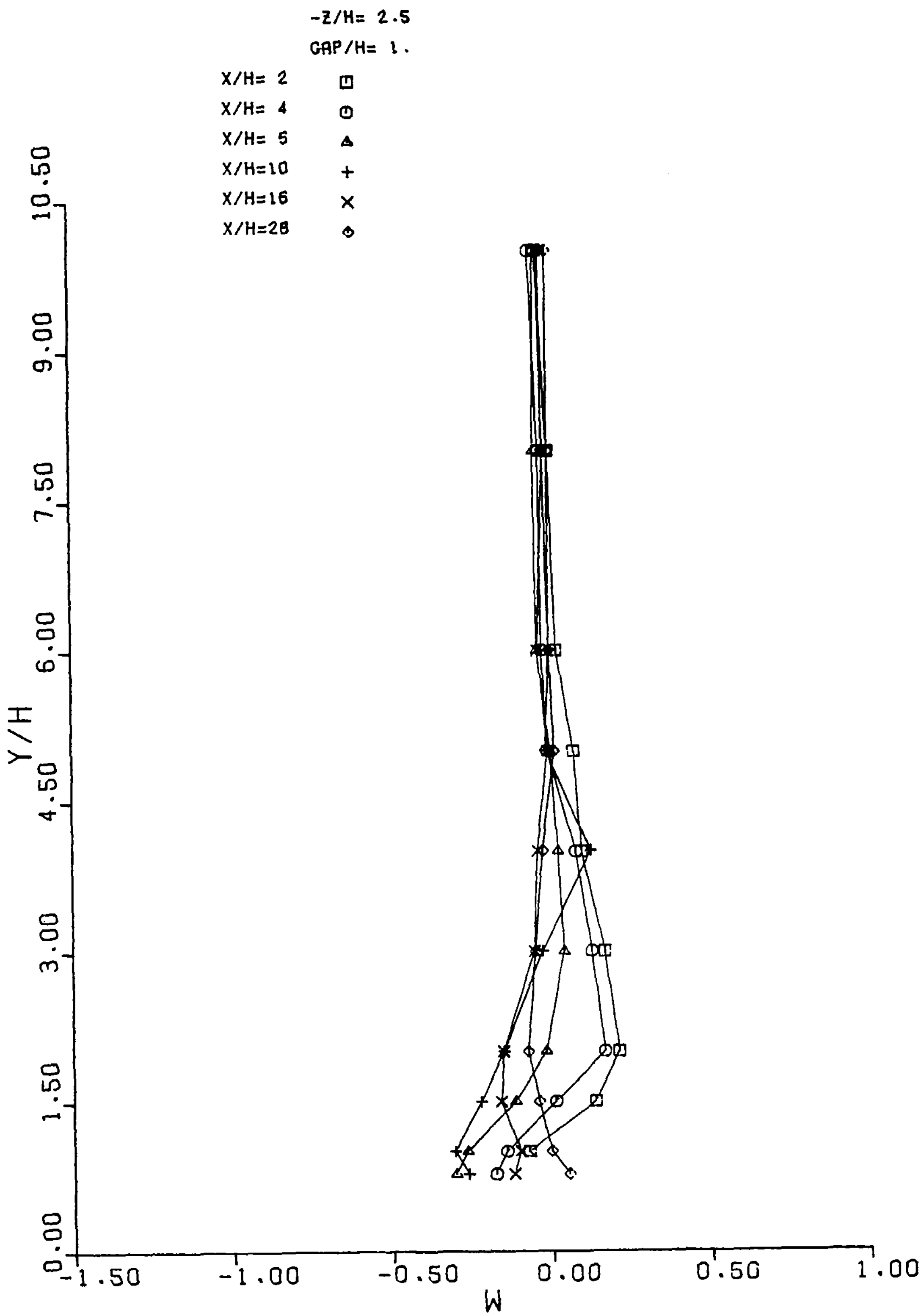


Fig. 30 Lateral Components for Small Gap at Z = - 2.5H

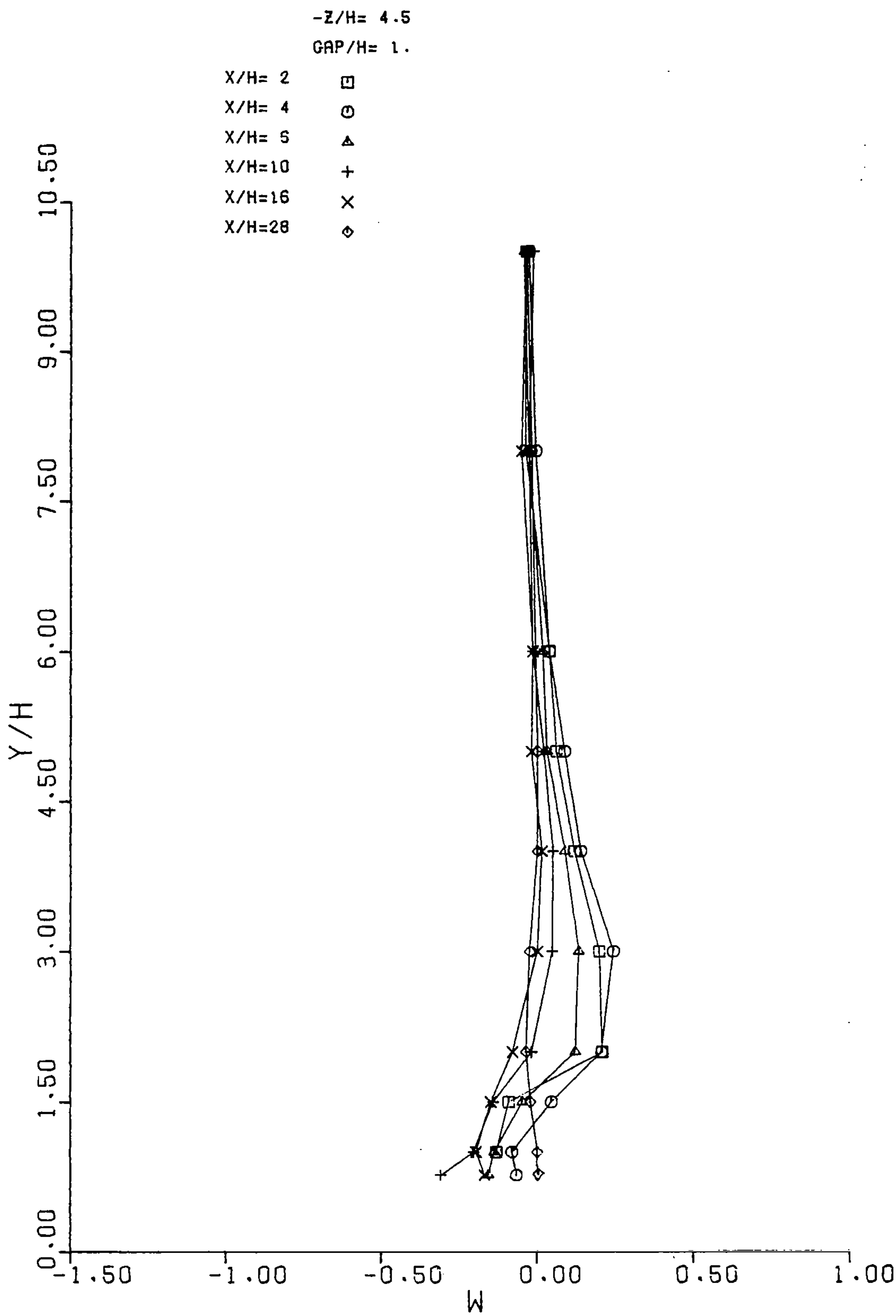


Fig. 31 Lateral Components for Small Gap at Z = - 4.5H

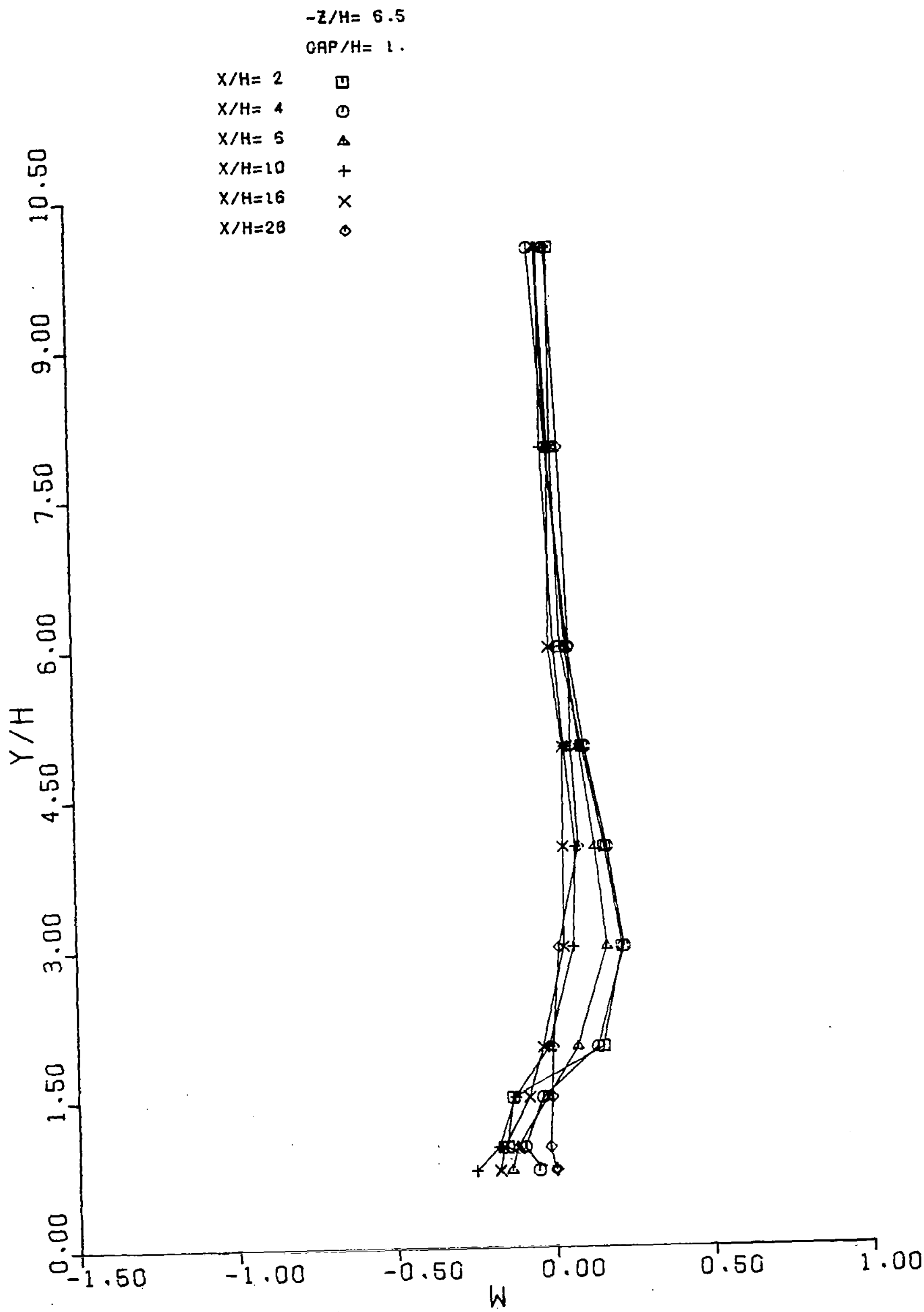


Fig. 32 Lateral Components for Small Gap at Z = - 6.5H

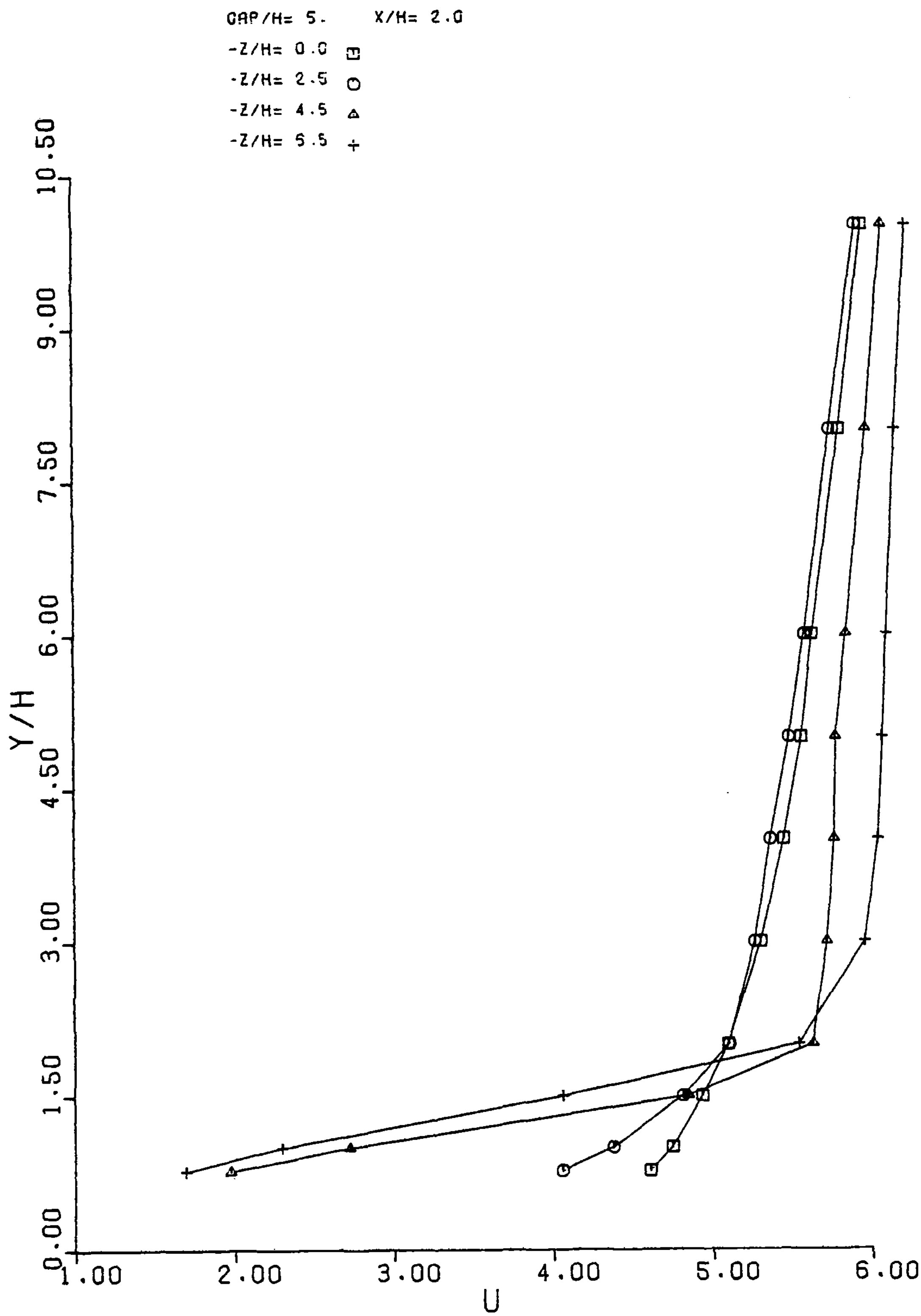


Fig. 33 Comparison of Profiles at X/H = 2 for Large Gap

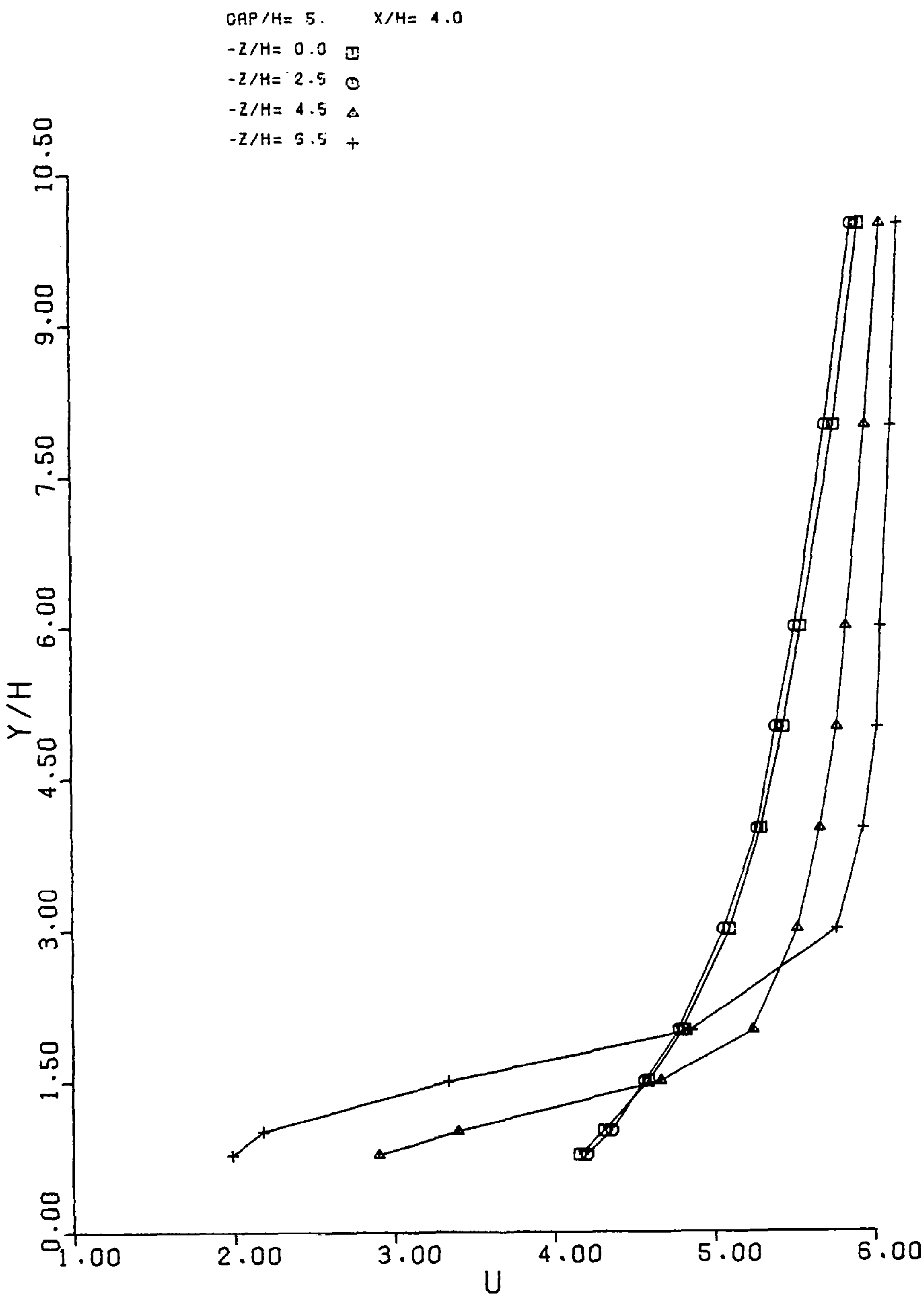


Fig. 34 Comparison of Profiles at X/H = 4 for Large Gap

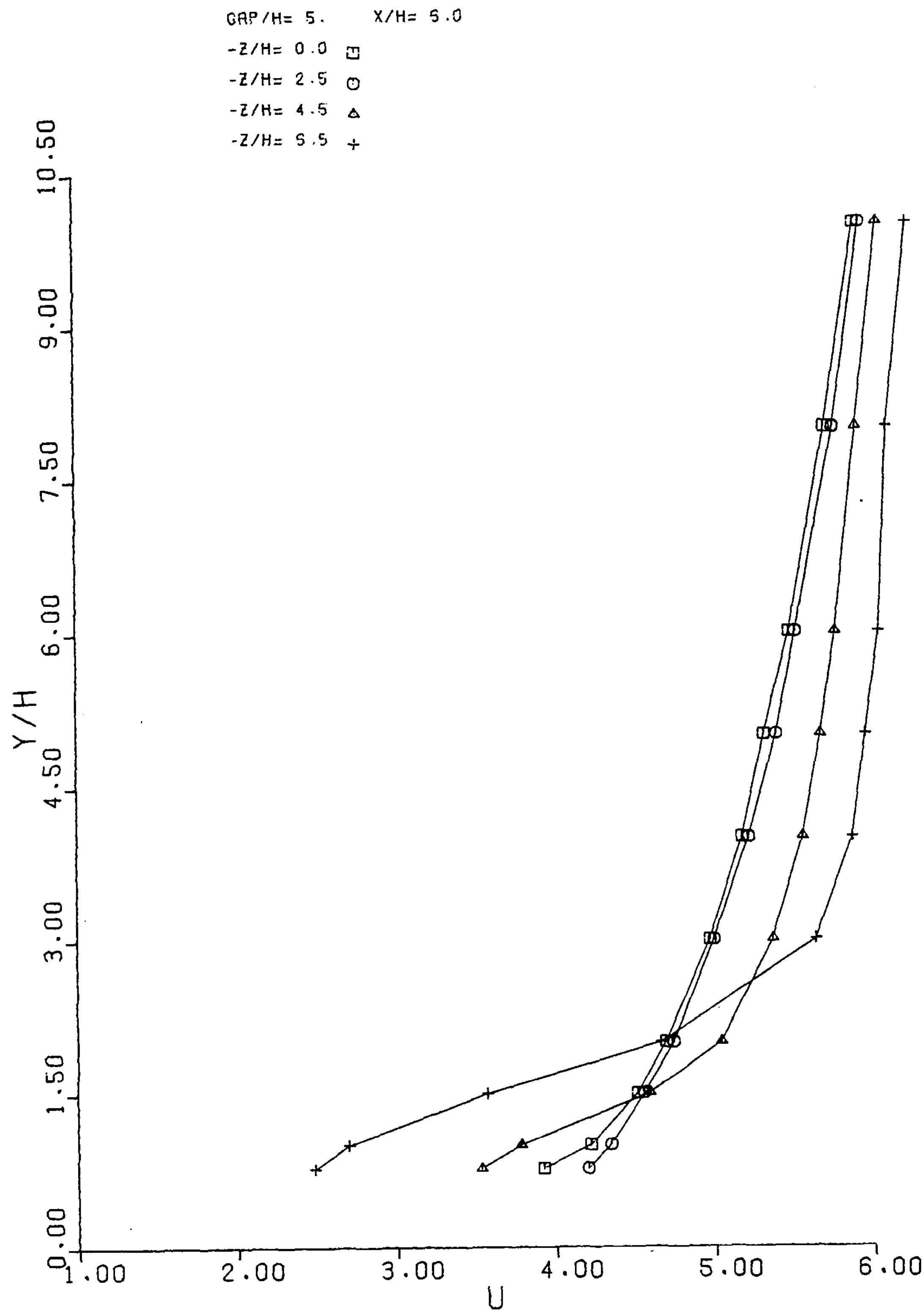


Fig. 35 Comparison of Profiles at X/H = 6 for Large Gap

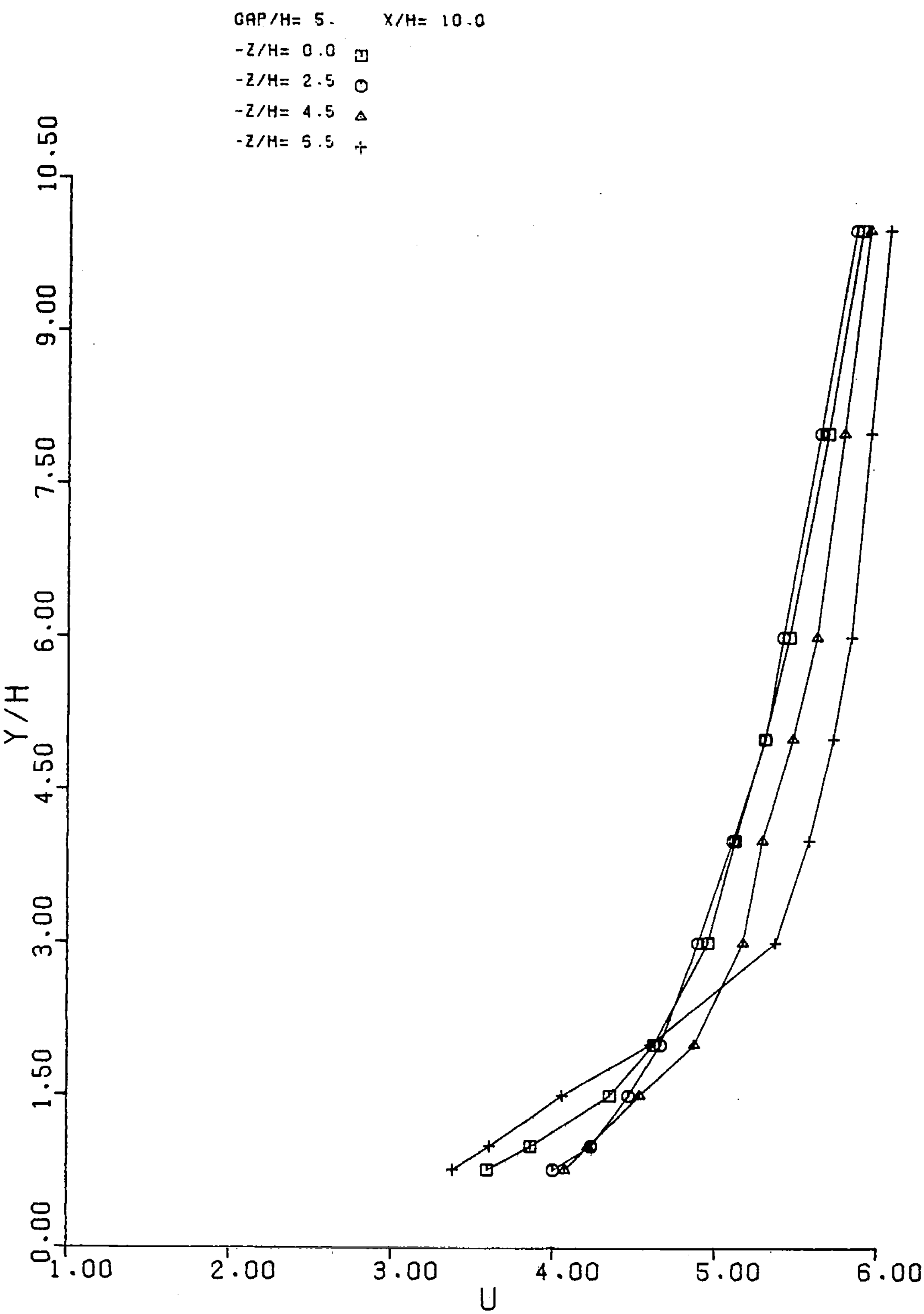


Fig. 36 Comparison of Profiles at X/H = 10 for Large Gap

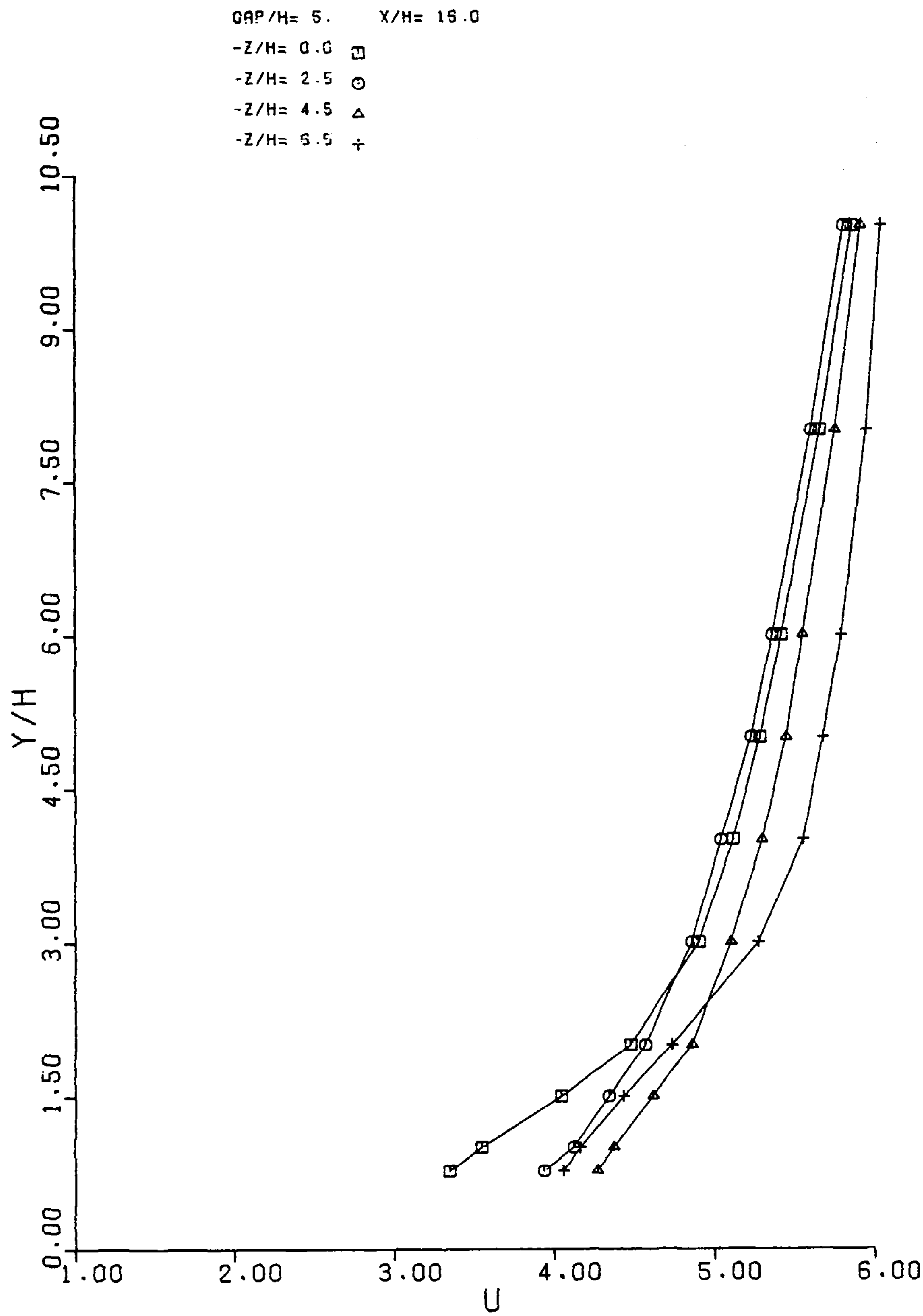


Fig. 37 Comparison of Profiles at X/H = 16 for Large Gap

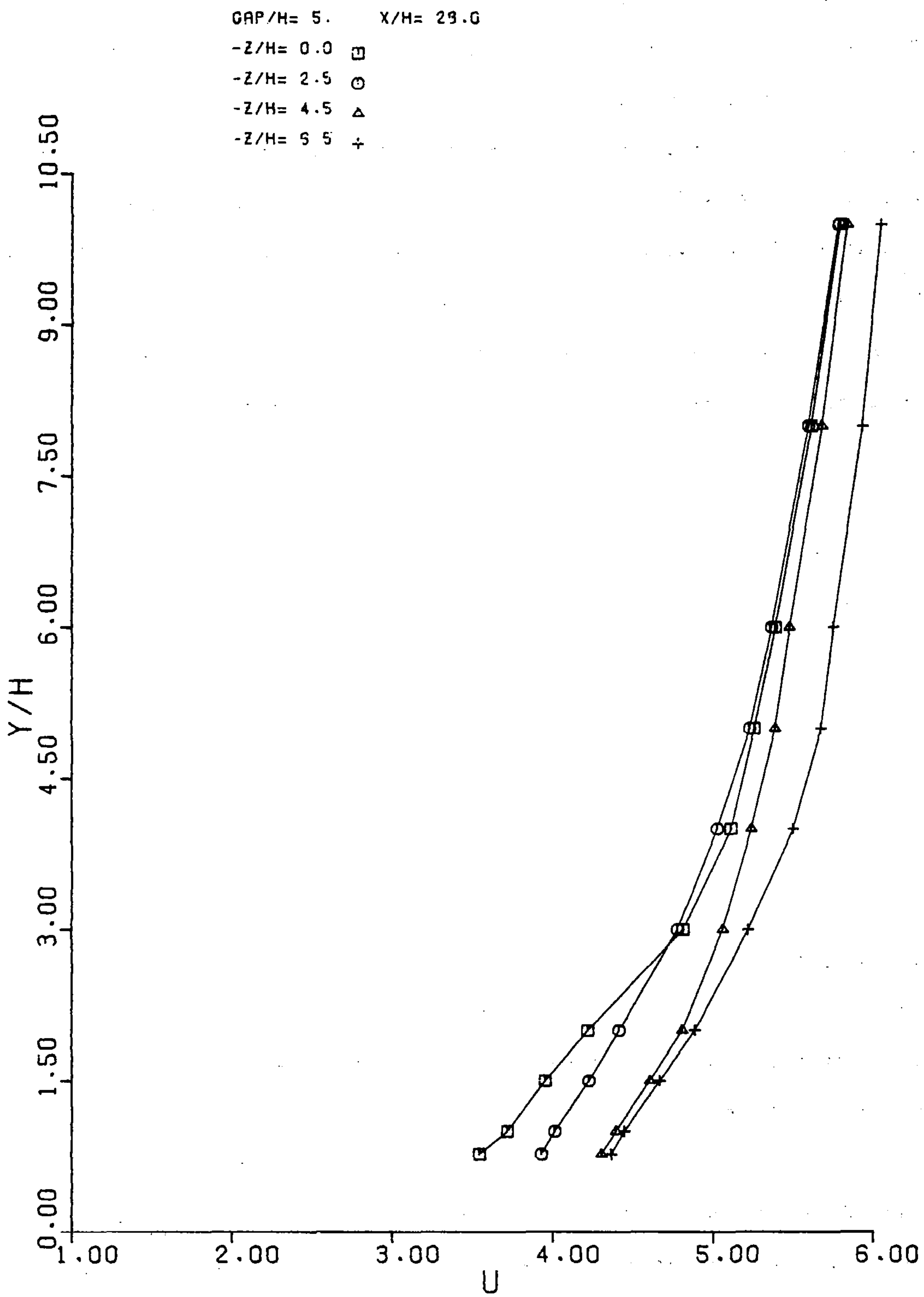


Fig. 38 Comparison of Profiles at X/H = 28 for Large Gap

percent). Changes in spanwise wing loading accompanying flight through such regions could be considerable.

Updrafts, depicted in Figs. 39-42, are less significant than in the small-gap case in the immediate vicinity of the large gap, but this fact implies that the lateral (z-direction) updraft variation will be enhanced by the large gap. Also enhanced are the downdrafts near the obstacle. Figures 40 and 41 show maximum downward vertical components of 18 percent of U close to the obstacle.

Figures 43-46 depict the crossflow component W. Vortical motion is evidenced by the change from negative to positive values of W at the same station. Flow is away from the centerline at lower elevations and towards the centerline at higher levels. This agrees generally with surface patterns, such as that shown in Fig. 8. Figure 45 shows a lateral component W with a magnitude of 0.1U at a height of 2H. Such a magnitude of crosswind velocity could affect the trajectory of low-flying vehicles.

4. Flow Model

A flow model is currently being developed based on the data presented in the Appendix for small and large-gap wakes and for the two-dimensional wake. At present, it is clear that the effect of the gap is to provide a variable wall resistance in the lateral direction. Higher longitudinal velocity components appear in the wake of the gap at low elevations than directly behind the obstacle. The lateral distribution of the U component leads to crosswise velocity gradients and corresponding shear stresses, non-existent in two-dimensional flows.

Secondary flows are known to arise in association with lateral variation of longitudinal velocity or of turbulence energy. Closer to the wall the central region downstream of the gap contains fluid of higher longitudinal velocity. The side regions lie behind the obstacles and contain retarded fluid

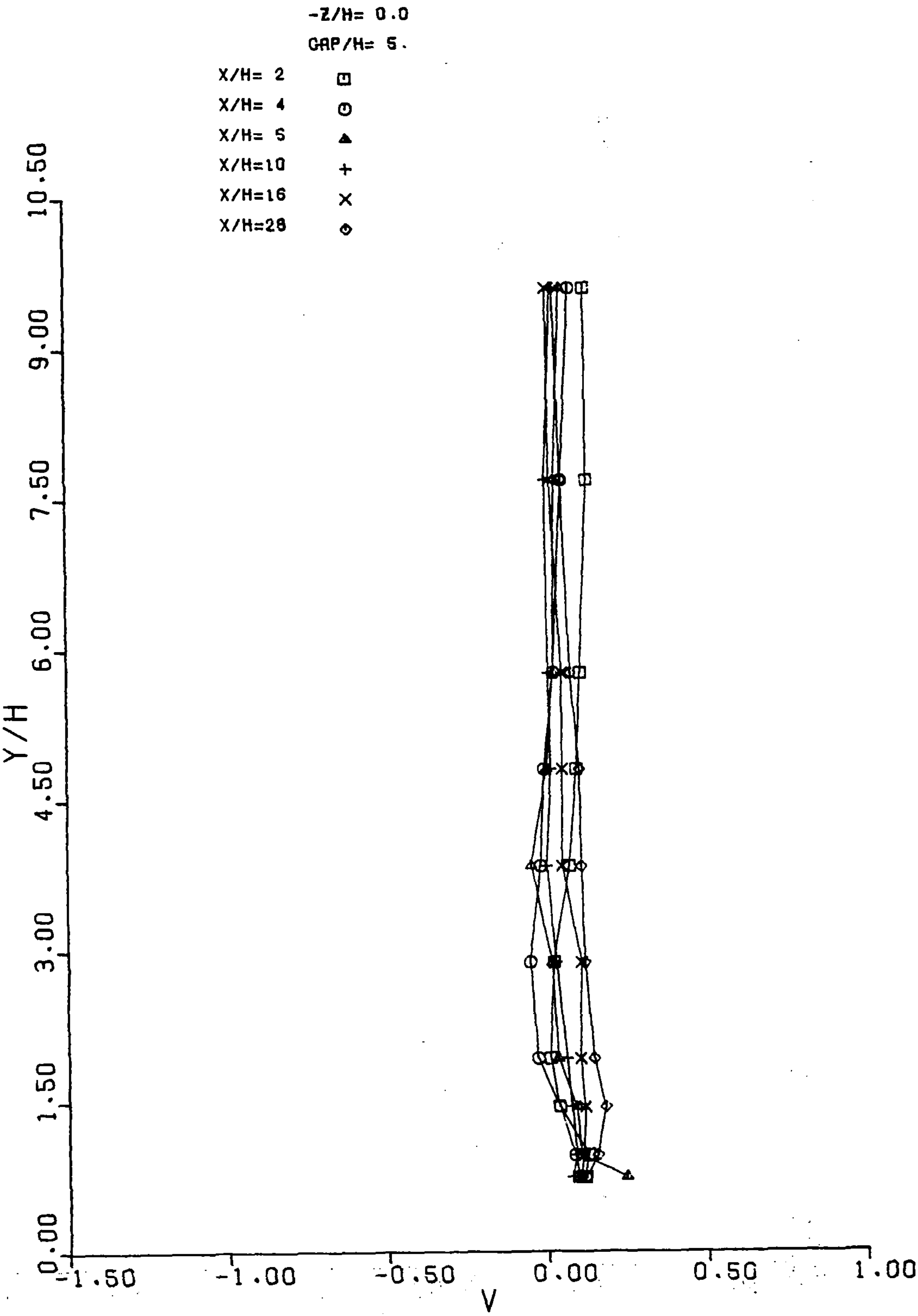


Fig. 39 Vertical Components for Large Gap at Centerline

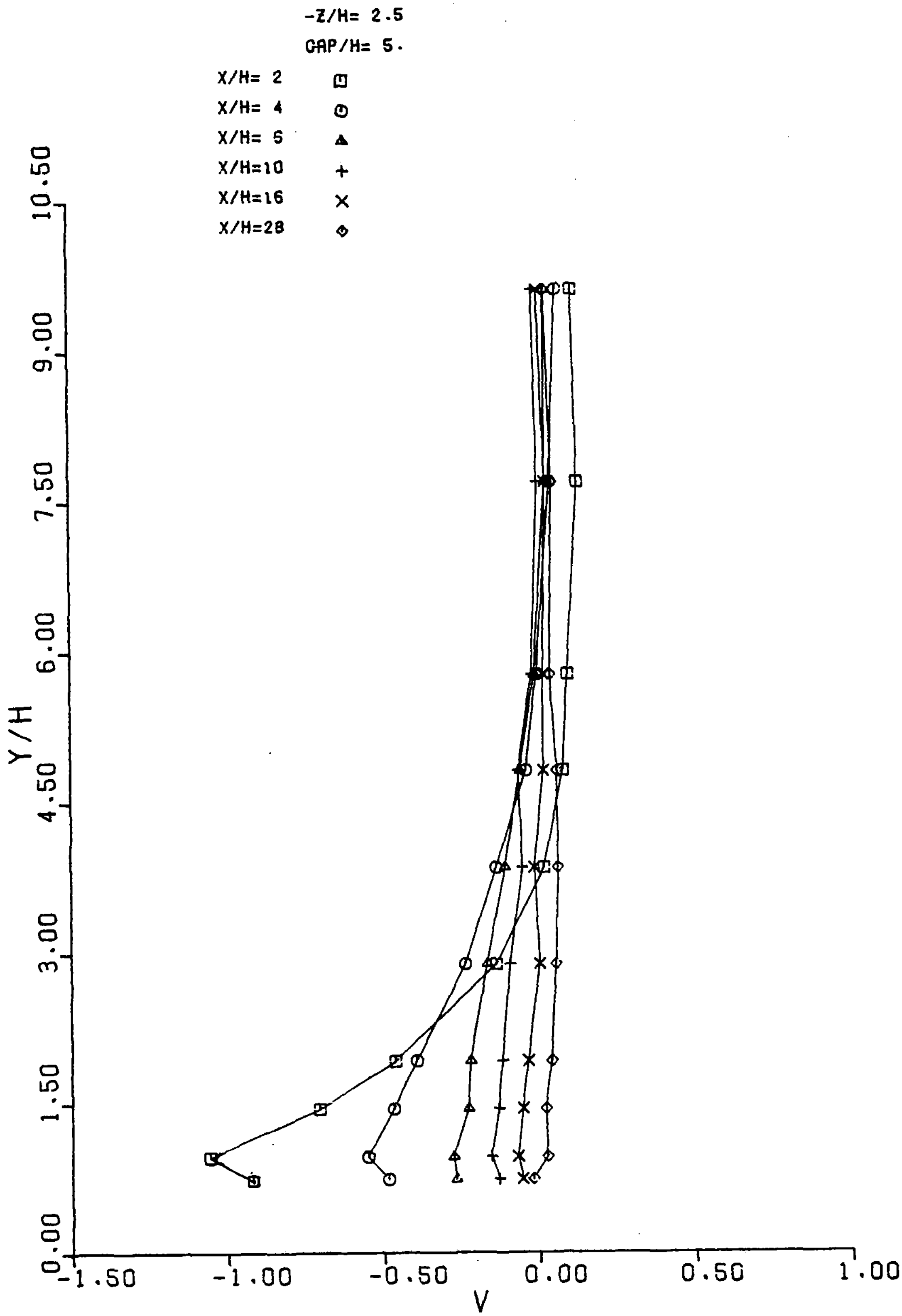


Fig. 40 Vertical Components for Large Gap at Z = - 2.5H

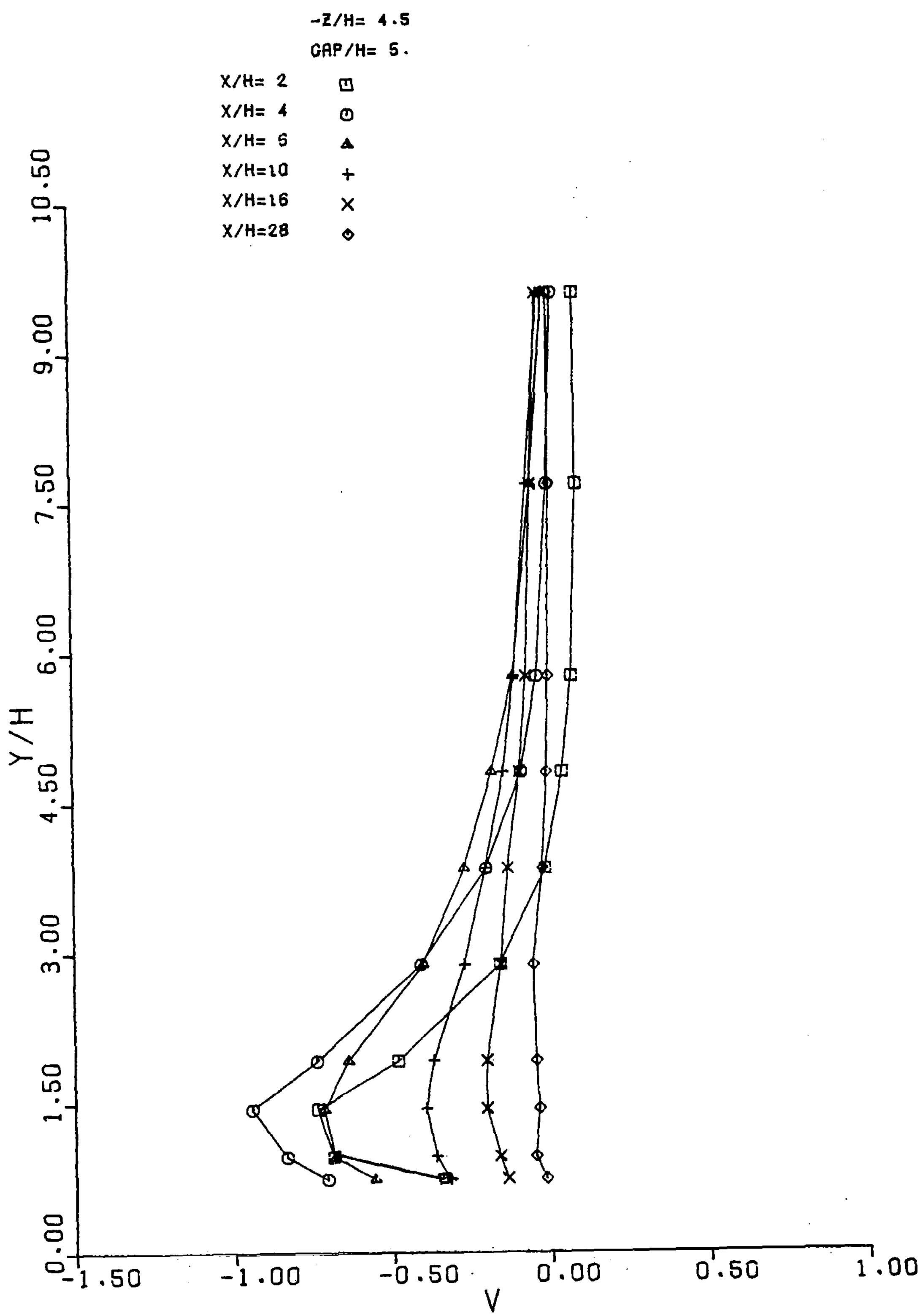


Fig. 41 Vertical Components for Large Gap at Z = - 4.5H

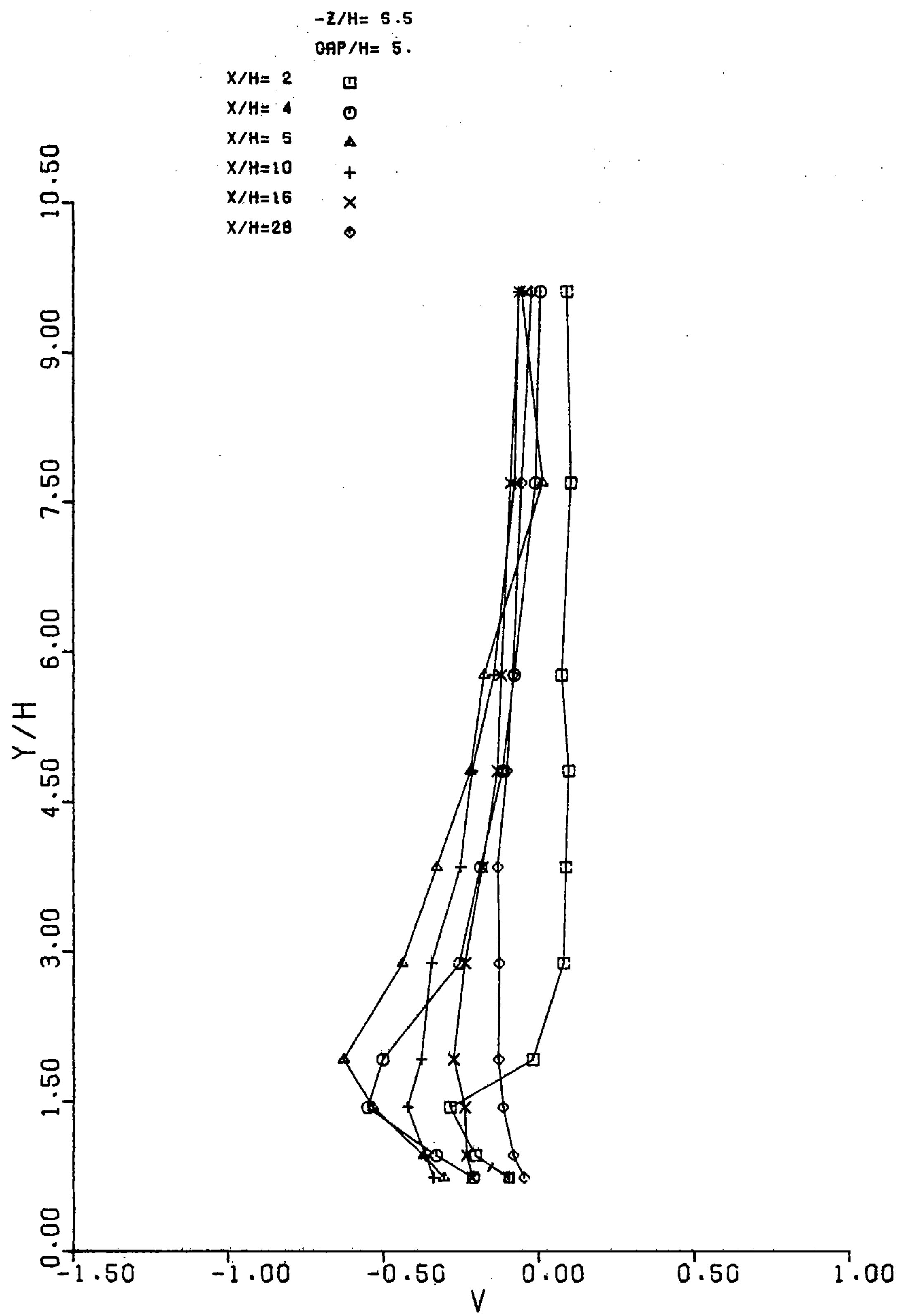


Fig. 42 Vertical Components for Large Gap at Z = - 6.5H

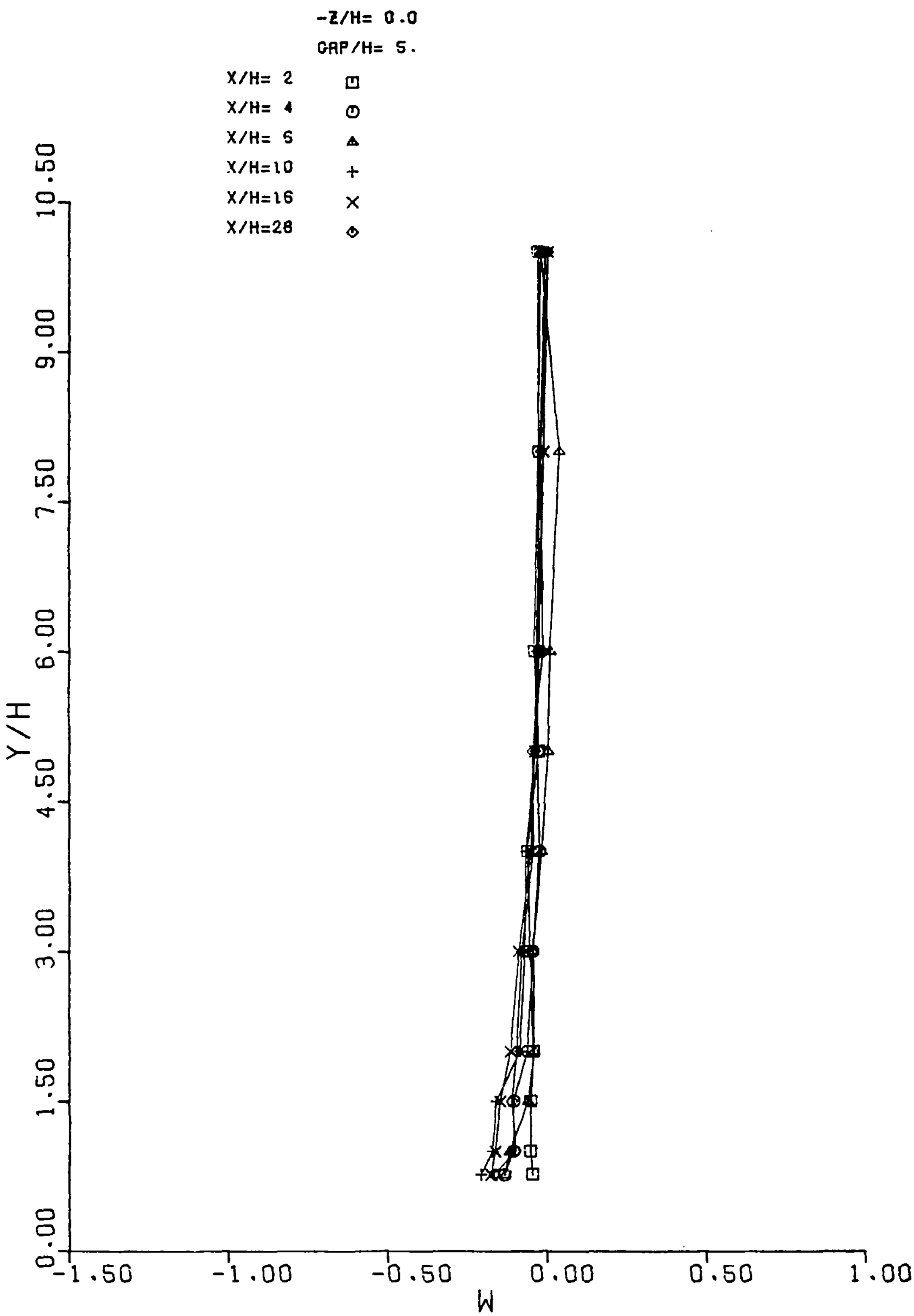


Fig. 43 Lateral Components for Large Gap at Centerline

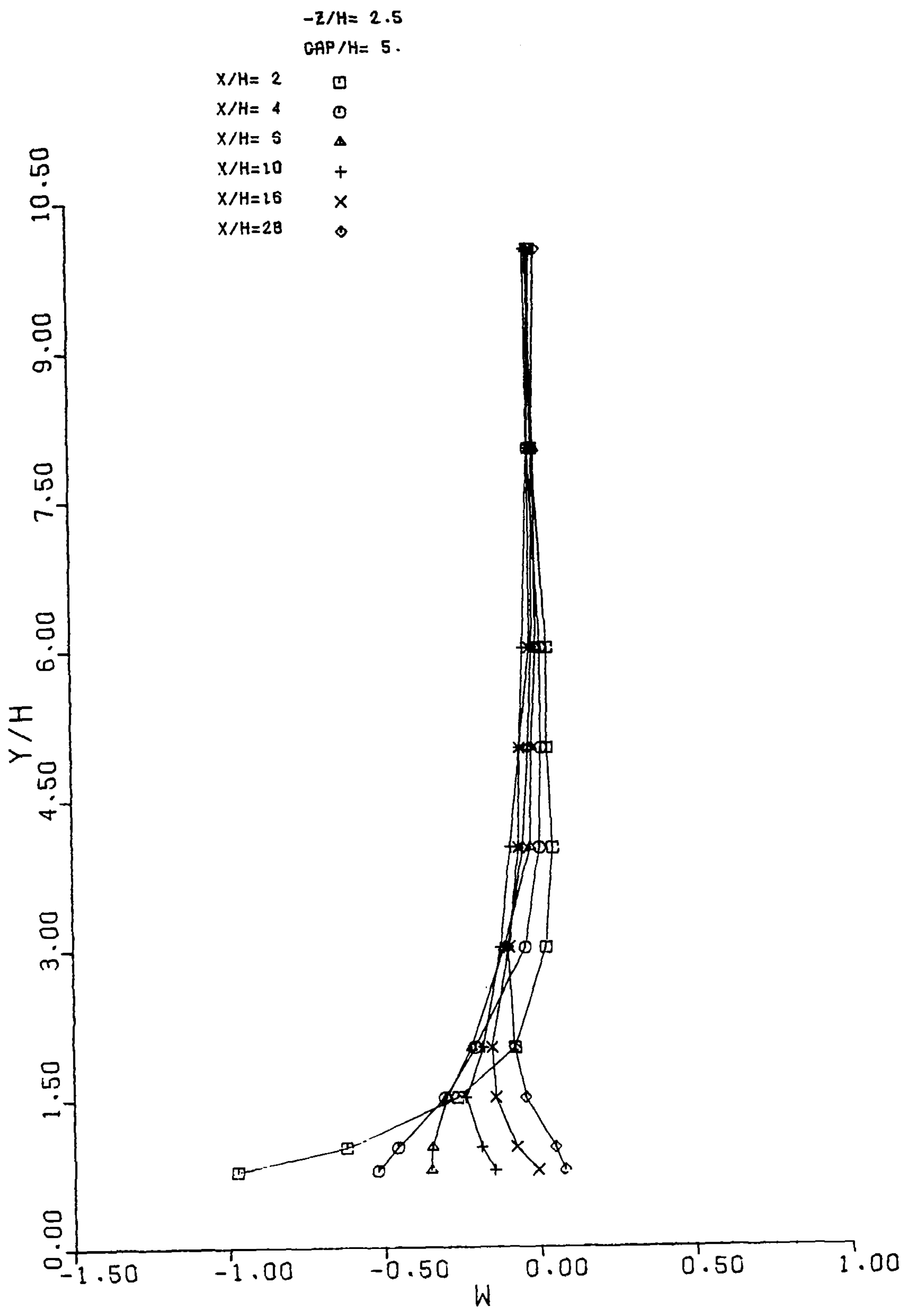


Fig. 44 Lateral Components for Large Gap at Z = - 2.5H

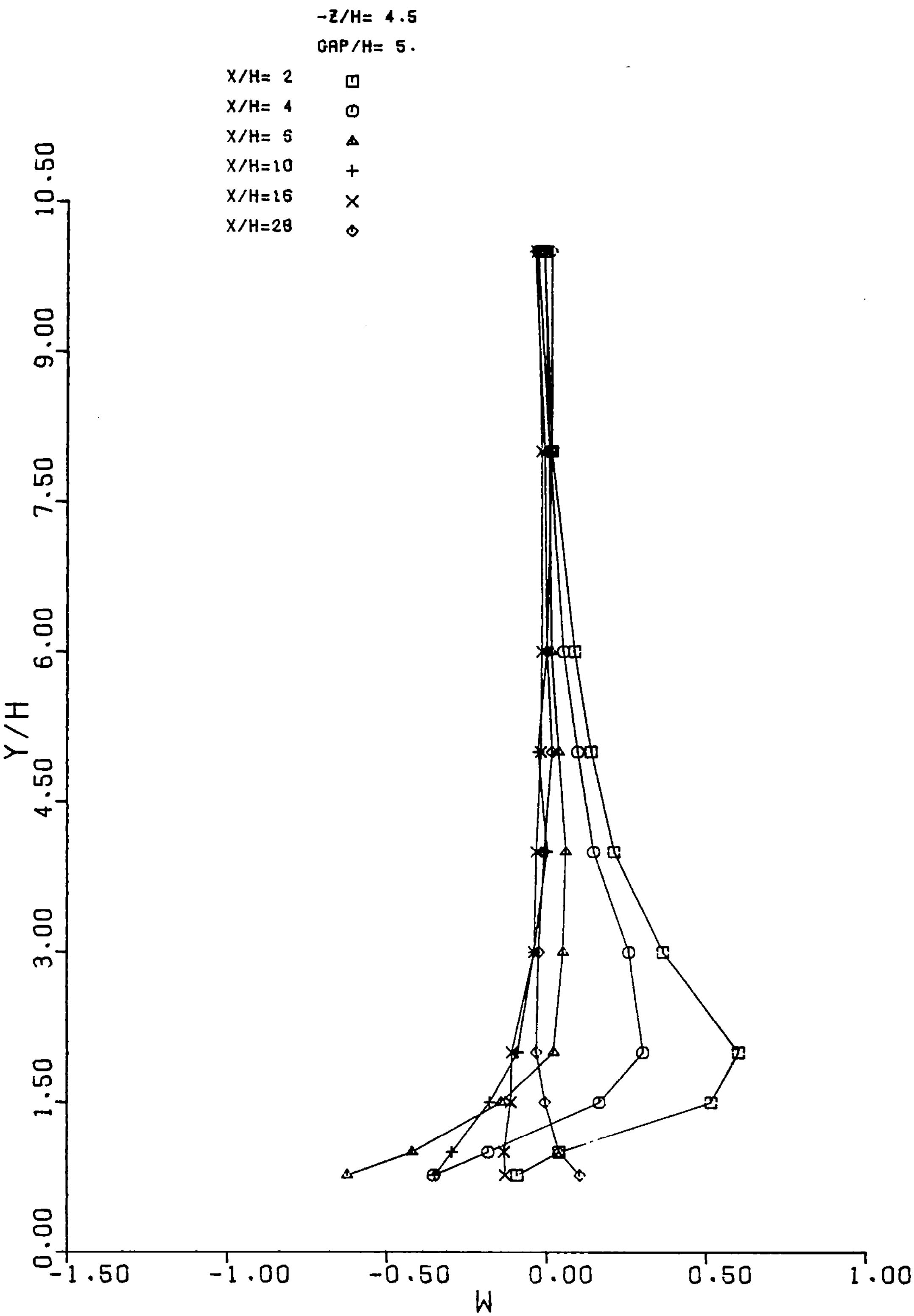


Fig. 45 Lateral Components for Large Gap at Z = - 4.5H

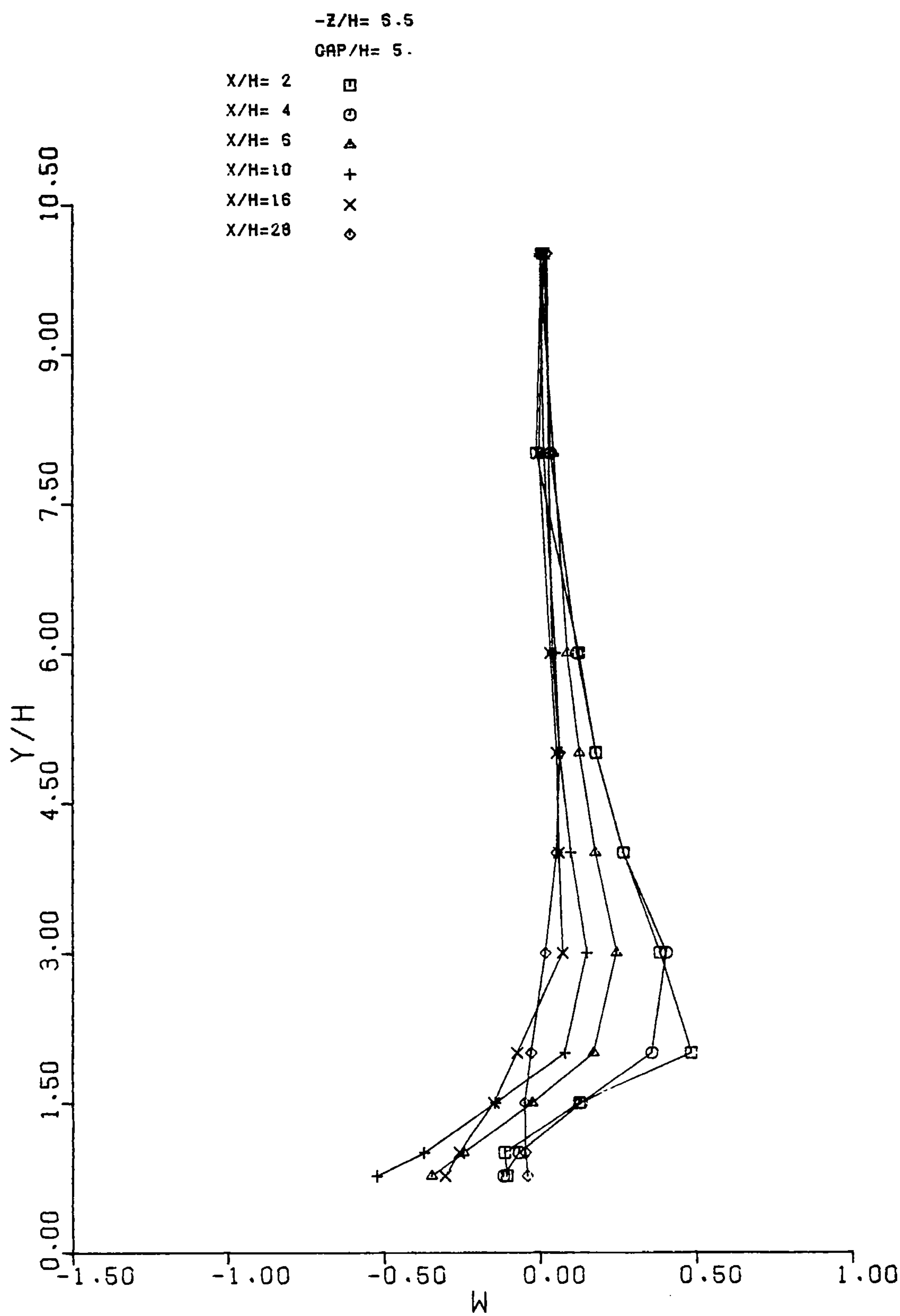


Fig. 46 Lateral Components for Large Gap at Z = - 6.5H

which is being accelerated by faster moving fluid above. Fluid to supply the higher mass flow enters the region of the retarded fluid from the central region via the cross currents, tending to reduce lateral velocity gradients and associated turbulence stresses. Close to the wall the result is the secondary flow directed away from the centerline, as we have observed from flow visualization and from graphs of lateral component W. The graphs also show a secondary motion towards the centerline beginning at elevations in the range $1 < y/H < 2$. Thus counter-rotating secondary cells are observed in the wake on the two sides of the gap.

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APPENDIX

TABLE ARRANGEMENTS

The materials contained in the Appendix are the tabulated data in processed form. The tables are identified by the index K, to which values from 1-55 have been assigned. Vertical distributions of mean-velocity components and Reynolds-stress components taken at a particular station, i.e., at a particular x/H and z/H, and for a particular gap setting are presented in each table. The correspondence between K, x/H, z/H and gap size are indicated above each table. Tables labelled K = 1-24 are for the gap size of 5H, and K = 25-48 reflects measurements for a gap size of 1H. The zero-gap condition is covered by K = 49-54, and the no-obstacle condition by K = 55.

Table A-1

Mean Velocities and Reynolds Stresses

for a Gap of 5H

K= 1 GAP/H= 5.0 X/H= 2.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.612	0.119	-0.051	-0.070	-0.035	0.005
1.00	4.750	0.129	-0.058	-0.068	-0.047	-0.006
1.50	4.937	0.035	-0.056	-0.063	-0.047	0.001
2.00	5.094	0.007	-0.049	-0.063	-0.049	0.004
3.00	5.303	0.021	-0.058	-0.050	-0.046	0.003
4.00	5.446	0.075	-0.068	-0.045	-0.040	-0.006
5.00	5.560	0.098	-0.030	-0.039	-0.030	0.003
6.00	5.626	0.112	-0.044	-0.041	-0.020	0.009
8.00	5.796	0.138	-0.030	-0.033	-0.012	0.008
10.00	5.943	0.133	-0.030	-0.034	-0.005	0.002

K= 2 GAP/H= 5.0 X/H= 2.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.620	-0.867	-0.900	-0.129	0.0	0.233
1.00	4.722	-1.031	-0.609	-0.132	0.053	0.162
1.50	4.895	-0.730	-0.276	-0.087	-0.027	-0.081
2.00	5.124	-0.484	-0.085	-0.063	0.041	0.015
3.00	5.267	-0.146	0.021	-0.056	0.040	0.011
4.00	5.358	0.016	0.044	-0.051	0.028	-0.001
5.00	5.480	0.079	0.028	-0.044	0.023	0.001
6.00	5.574	0.096	0.030	-0.040	0.021	-0.005
8.00	5.736	0.131	-0.016	-0.031	0.011	-0.007
10.00	5.901	0.114	-0.023	-0.023	0.010	-0.009

K= 3 GAP/H= 5.0 X/H= 2.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	1.979	-0.366	-0.099	-0.305	-0.031	-0.315
1.00	2.740	-0.720	0.039	-0.498	0.107	-0.322
1.50	4.895	-0.768	0.535	-0.223	0.151	-0.205
2.00	5.665	-0.504	0.626	-0.043	0.068	-0.093
3.00	5.725	-0.167	0.380	-0.048	0.046	-0.026
4.00	5.766	-0.014	0.219	-0.041	0.048	-0.002
5.00	5.777	0.044	0.145	-0.038	0.045	-0.003
6.00	5.837	0.077	0.091	-0.038	0.042	0.002
8.00	5.964	0.096	0.016	-0.033	0.033	-0.002
10.00	6.062	0.093	-0.007	-0.028	0.020	-0.008

K= 4 GAP/H= 5.0 X/H= 2.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	1.695	-0.106	-0.113	-0.134	-0.025	-0.324
1.00	2.314	-0.215	-0.121	-0.308	-0.036	-0.170
1.50	4.077	-0.301	0.129	-0.338	0.173	-0.089
2.00	5.560	-0.021	0.502	-0.092	0.106	-0.063
3.00	5.972	0.080	0.399	-0.045	0.041	-0.018
4.00	6.047	0.086	0.275	-0.040	0.035	-0.015
5.00	6.069	0.096	0.182	-0.036	0.038	0.000
6.00	6.090	0.072	0.126	-0.029	0.044	-0.007
8.00	6.141	0.103	-0.017	-0.026	0.035	-0.005
10.00	6.213	0.089	0.0	-0.019	0.025	-0.007

K= 5 GAP/H= 5.0 X/H= 4.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.159	0.099	-0.143	-0.071	-0.019	-0.002
1.00	4.310	0.085	-0.115	-0.070	-0.017	-0.002
1.50	4.594	0.035	-0.112	-0.062	-0.025	-0.002
2.00	4.805	-0.033	-0.068	-0.061	-0.035	-0.007
3.00	5.104	-0.056	-0.049	-0.055	-0.029	-0.010
4.00	5.299	-0.021	-0.028	-0.050	-0.033	-0.012
5.00	5.441	-0.007	-0.035	-0.046	-0.028	-0.004
6.00	5.554	0.023	-0.030	-0.040	-0.018	-0.000
8.00	5.763	0.054	-0.030	-0.035	-0.013	-0.002
10.00	5.928	0.084	-0.023	-0.027	-0.007	-0.003

K= 6 GAP/H= 5.0 X/H= 4.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.326	-0.497	-0.537	-0.087	0.006	0.063
1.00	4.473	-0.565	-0.471	-0.086	0.019	0.066
1.50	4.629	-0.486	-0.320	-0.078	0.030	0.025
2.00	4.817	-0.413	-0.218	-0.068	0.036	0.012
3.00	5.074	-0.250	-0.049	-0.051	0.040	-0.005
4.00	5.280	-0.145	0.0	-0.044	0.039	-0.000
5.00	5.392	-0.045	0.007	-0.036	0.029	-0.009
6.00	5.515	-0.007	0.007	-0.037	0.027	-0.002
8.00	5.709	0.040	-0.030	-0.029	0.025	0.008
10.00	5.880	0.063	-0.023	-0.027	0.016	0.000

K= 7 GAP/H= 5.0 X/H= 4.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.097	-0.699	-0.350	-0.412	-0.017	0.114
1.00	3.495	-0.853	-0.188	-0.452	0.058	-0.002
1.50	4.693	-0.987	0.171	-0.207	0.128	-0.107
2.00	5.250	-0.776	0.315	-0.075	0.087	-0.085
3.00	5.534	-0.430	0.268	-0.040	0.057	-0.044
4.00	5.679	-0.210	0.152	-0.037	0.055	-0.012
5.00	5.781	-0.091	0.100	-0.033	0.046	-0.014
6.00	5.840	-0.037	0.054	-0.027	0.049	-0.007
8.00	5.957	0.0	0.009	-0.027	0.034	-0.010
10.00	6.057	0.021	-0.030	-0.020	0.023	-0.006

K= 8 GAP/H= 5.0 X/H= 4.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	1.990	-0.223	-0.126	-0.143	-0.006	-0.195
1.00	2.184	-0.348	-0.073	-0.308	0.031	-0.136
1.50	3.364	-0.577	0.135	-0.436	0.196	-0.084
2.00	4.884	-0.526	0.370	-0.186	0.166	-0.113
3.00	5.796	-0.270	0.419	-0.036	0.044	-0.044
4.00	5.954	-0.200	0.274	-0.033	0.045	-0.019
5.00	6.036	-0.126	0.182	-0.021	0.044	-0.023
6.00	6.054	-0.086	0.119	-0.021	0.046	-0.015
8.00	6.122	-0.016	0.030	-0.016	0.038	-0.011
10.00	6.170	0.0	0.009	-0.013	0.034	-0.010

K= 9 GAP/H= 5.0 X/H= 6.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.928	0.255	-0.140	-0.072	-0.009	0.003
1.00	4.220	0.105	-0.126	-0.076	-0.023	-0.003
1.50	4.516	0.091	-0.065	-0.062	-0.027	0.011
2.00	4.690	0.033	-0.047	-0.056	-0.033	0.001
3.00	4.968	0.014	-0.049	-0.052	-0.033	-0.005
4.00	5.169	-0.052	-0.021	-0.048	-0.025	0.015
5.00	5.306	0.0	0.0	-0.038	-0.025	-0.005
6.00	5.469	0.023	0.007	-0.034	-0.017	0.002
8.00	5.694	0.030	0.037	-0.031	-0.012	-0.006
10.00	5.889	0.054	-0.023	-0.029	-0.005	0.006

K=10 GAP/H= 5.0 X/H= 6.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.249	-0.280	-0.368	-0.084	0.008	0.033
1.00	4.390	-0.290	-0.364	-0.076	0.017	0.049
1.50	4.589	-0.240	-0.315	-0.070	0.027	0.037
2.00	4.764	-0.233	-0.233	-0.064	0.029	0.028
3.00	5.004	-0.177	-0.120	-0.050	0.036	0.013
4.00	5.216	-0.115	-0.031	-0.048	0.026	-0.008
5.00	5.389	-0.065	-0.023	-0.041	0.028	-0.003
6.00	5.509	-0.014	-0.007	-0.038	0.020	0.002
8.00	5.749	0.023	-0.009	-0.035	0.017	-0.002
10.00	5.923	0.023	-0.030	-0.023	0.013	-0.000

K=11 GAP/H= 5.0 X/H= 6.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.748	-0.554	-0.618	-0.278	-0.020	0.242
1.00	3.940	-0.691	-0.425	-0.289	-0.028	0.053
1.50	4.643	-0.746	-0.149	-0.187	0.044	0.009
2.00	5.070	-0.668	0.021	-0.096	0.050	-0.038
3.00	5.379	-0.422	0.052	-0.055	0.052	-0.020
4.00	5.561	-0.282	0.061	-0.045	0.053	-0.001
5.00	5.671	-0.189	0.037	-0.042	0.047	-0.011
6.00	5.763	-0.114	0.014	-0.037	0.046	-0.001
8.00	5.892	-0.054	0.007	-0.026	0.029	-0.003
10.00	6.030	-0.007	-0.007	-0.025	0.020	-0.011

K=12 GAP/H= 5.0 X/H= 6.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.525	-0.318	-0.361	-0.210	-0.047	0.076
1.00	2.736	-0.386	-0.256	-0.355	-0.039	0.030
1.50	3.603	-0.557	-0.028	-0.460	0.058	-0.031
2.00	4.676	-0.659	0.176	-0.239	0.050	-0.126
3.00	5.657	-0.461	0.252	-0.048	0.044	-0.057
4.00	5.879	-0.347	0.180	-0.036	0.042	-0.023
5.00	5.957	-0.234	0.127	-0.029	0.043	-0.005
6.00	6.040	-0.189	0.086	-0.026	0.043	-0.014
8.00	6.084	0.007	0.040	-0.025	0.038	-0.010
10.00	6.219	-0.063	-0.007	-0.017	0.032	-0.002

K=13 GAP/H= 5.0 X/H= 10.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.598	0.077	-0.220	-0.114	-0.013	0.001
1.00	3.862	0.090	-0.182	-0.101	-0.007	0.002
1.50	4.353	0.075	-0.171	-0.071	-0.022	-0.001
2.00	4.622	0.061	-0.093	-0.067	-0.031	-0.002
3.00	4.955	0.028	-0.077	-0.052	-0.040	-0.019
4.00	5.123	0.0	-0.072	-0.047	-0.036	-0.004
5.00	5.305	0.014	-0.042	-0.048	-0.029	0.000
6.00	5.456	0.007	-0.037	-0.042	-0.022	-0.001
8.00	5.695	0.0	-0.023	-0.035	-0.015	0.003
10.00	5.900	0.023	-0.009	-0.028	-0.007	0.004

K=14 GAP/H= 5.0 X/H= 10.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.010	-0.138	-0.156	-0.068	0.026	-0.015
1.00	4.248	-0.163	-0.201	-0.067	0.028	0.012
1.50	4.481	-0.139	-0.251	-0.063	0.029	0.025
2.00	4.673	-0.127	-0.193	-0.060	0.027	0.027
3.00	4.899	-0.099	-0.131	-0.054	0.031	0.012
4.00	5.110	-0.057	-0.098	-0.045	0.025	0.001
5.00	5.311	-0.070	-0.065	-0.041	0.025	0.000
6.00	5.418	-0.023	-0.051	-0.038	0.019	0.002
8.00	5.644	-0.002	-0.031	-0.035	0.012	-0.000
10.00	5.862	-0.016	-0.037	-0.032	0.007	-0.002

K=15 GAP/H= 5.0 X/H= 10.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.125	-0.333	-0.363	-0.164	-0.015	0.085
1.00	4.265	-0.377	-0.308	-0.171	0.015	0.063
1.50	4.568	-0.413	-0.186	-0.140	0.040	0.032
2.00	4.889	-0.387	-0.096	-0.097	0.048	-0.009
3.00	5.184	-0.285	-0.042	-0.061	0.061	-0.001
4.00	5.293	-0.213	0.0	-0.048	0.056	0.001
5.00	5.481	-0.150	-0.030	-0.037	0.051	0.002
6.00	5.627	-0.112	0.0	-0.032	0.038	-0.010
8.00	5.792	-0.068	-0.007	-0.017	0.027	-0.013
10.00	5.948	-0.023	-0.040	-0.021	0.020	-0.008

K=16 GAP/H= 5.0 X/H= 10.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.433	-0.352	-0.543	-0.212	-0.006	0.188
1.00	3.680	-0.377	-0.384	-0.283	0.015	0.170
1.50	4.081	-0.442	-0.152	-0.294	0.060	0.038
2.00	4.610	-0.398	0.081	-0.249	0.058	-0.044
3.00	5.380	-0.364	0.153	-0.064	0.050	-0.056
4.00	5.584	-0.268	0.099	-0.038	0.065	-0.020
5.00	5.732	-0.229	0.061	-0.028	0.055	-0.008
6.00	5.841	-0.154	0.047	-0.018	0.053	-0.008
8.00	5.955	-0.086	0.007	-0.018	0.041	-0.010
10.00	6.071	-0.073	-0.007	-0.017	0.034	-0.007

K=17 GAP/H= 5.0 X/H= 16.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.348	0.103	-0.187	-0.118	-0.034	0.024
1.00	3.552	0.113	-0.173	-0.135	-0.025	0.004
1.50	4.046	0.119	-0.157	-0.112	-0.015	0.027
2.00	4.477	0.106	-0.124	-0.077	-0.023	0.005
3.00	4.899	0.111	-0.096	-0.062	-0.038	-0.007
4.00	5.112	0.049	-0.056	-0.050	-0.032	-0.002
5.00	5.278	0.052	-0.044	-0.041	-0.031	-0.005
6.00	5.414	0.051	-0.030	-0.035	-0.022	-0.001
8.00	5.649	0.014	-0.014	-0.033	-0.016	0.002
10.00	5.850	0.007	0.0	-0.029	-0.010	-0.000

K=18 GAP/H= 5.0 X/H= 16.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.938	-0.061	-0.012	-0.053	0.048	-0.026
1.00	4.126	-0.075	-0.084	-0.065	0.041	-0.004
1.50	4.345	-0.059	-0.152	-0.058	0.038	-0.004
2.00	4.573	-0.040	-0.164	-0.051	0.030	0.003
3.00	4.857	0.0	-0.103	-0.049	0.030	0.016
4.00	5.037	-0.016	-0.070	-0.048	0.017	0.003
5.00	5.221	0.014	-0.065	-0.040	0.019	0.002
6.00	5.356	0.014	-0.028	-0.038	0.022	0.001
8.00	5.594	0.023	-0.028	-0.032	0.013	-0.005
10.00	5.797	0.0	-0.016	-0.028	0.010	-0.003

K=19 GAP/H= 5.0 X/H= 16.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.281	-0.146	-0.137	-0.102	0.0	-0.016
1.00	4.387	-0.170	-0.140	-0.109	0.011	0.025
1.50	4.627	-0.214	-0.119	-0.102	0.028	0.012
2.00	4.869	-0.213	-0.114	-0.094	0.041	0.006
3.00	5.104	-0.164	-0.042	-0.056	0.059	0.004
4.00	5.296	-0.138	-0.035	-0.052	0.049	-0.005
5.00	5.441	-0.096	-0.021	-0.035	0.058	0.008
6.00	5.545	-0.073	-0.016	-0.033	0.043	0.008
8.00	5.747	-0.054	-0.016	-0.027	0.036	0.005
10.00	5.906	-0.030	-0.033	-0.022	0.023	-0.005

K=20 GAP/H= 5.0 X/H= 16.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.090	-0.225	-0.319	-0.148	-0.019	0.077
1.00	4.196	-0.244	-0.272	-0.180	0.012	0.101
1.50	4.453	-0.251	-0.157	-0.212	0.035	0.052
2.00	4.745	-0.289	-0.079	-0.185	0.033	-0.013
3.00	5.277	-0.252	0.072	-0.111	0.047	-0.040
4.00	5.554	-0.194	0.058	-0.042	0.057	-0.030
5.00	5.674	-0.143	0.051	-0.034	0.058	-0.006
6.00	5.790	-0.131	0.030	-0.027	0.053	-0.010
8.00	5.943	-0.100	-0.009	-0.020	0.041	-0.010
10.00	6.031	-0.070	0.007	-0.015	0.032	-0.012

K=21 GAP/H= 5.0 X/H= 28.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.547	0.123	-0.178	-0.070	-0.097	0.002
1.00	3.719	0.159	-0.107	-0.087	-0.073	0.018
1.50	3.955	0.185	-0.118	-0.093	-0.067	-0.014
2.00	4.220	0.150	-0.103	-0.107	-0.055	0.029
3.00	4.814	0.122	-0.087	-0.067	-0.047	0.011
4.00	5.112	0.112	-0.049	-0.053	-0.049	-0.020
5.00	5.258	0.107	-0.052	-0.038	-0.042	0.005
6.00	5.388	0.079	-0.016	-0.031	-0.035	0.007
8.00	5.615	0.051	-0.023	-0.029	-0.027	-0.001
10.00	5.797	0.030	0.0	-0.023	-0.014	0.004

K=22 GAP/H= 5.0 X/H= 28.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.931	-0.024	0.077	-0.057	0.041	-0.042
1.00	4.013	0.024	0.047	-0.056	0.057	-0.005
1.50	4.222	0.019	-0.051	-0.070	0.045	-0.018
2.00	4.414	0.038	-0.089	-0.068	0.043	-0.006
3.00	4.777	0.054	-0.108	-0.050	0.026	0.014
4.00	5.024	0.063	-0.056	-0.046	0.012	0.005
5.00	5.227	0.058	-0.035	-0.038	0.012	0.013
6.00	5.364	0.037	-0.021	-0.036	0.012	0.008
8.00	5.594	0.047	-0.014	-0.030	0.007	-0.000
10.00	5.783	0.023	0.0	-0.029	0.009	0.006

K=23 GAP/H= 5.0 X/H= 28.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.305	-0.019	0.108	-0.061	0.005	-0.026
1.00	4.391	-0.052	0.040	-0.078	0.014	-0.011
1.50	4.599	-0.040	-0.007	-0.082	0.023	-0.014
2.00	4.806	-0.049	-0.035	-0.073	0.037	0.010
3.00	5.055	-0.057	-0.028	-0.067	0.040	0.008
4.00	5.235	-0.023	-0.009	-0.058	0.049	0.016
5.00	5.383	-0.007	0.016	-0.039	0.043	0.007
6.00	5.474	0.0	0.0	-0.034	0.038	0.006
8.00	5.680	0.007	0.016	-0.030	0.029	0.002
10.00	5.839	0.007	0.016	-0.027	0.020	-0.002

K=24 GAP/H= 5.0 X/H= 28.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.362	-0.052	-0.044	-0.088	-0.040	-0.011
1.00	4.446	-0.088	-0.051	-0.095	-0.028	-0.001
1.50	4.668	-0.123	-0.054	-0.109	-0.008	0.019
2.00	4.889	-0.138	-0.033	-0.118	0.0	0.026
3.00	5.219	-0.136	0.014	-0.107	0.032	0.005
4.00	5.502	-0.143	0.051	-0.069	0.039	-0.024
5.00	5.677	-0.112	0.061	-0.042	0.046	-0.011
6.00	5.754	-0.092	0.038	-0.034	0.050	0.002
8.00	5.933	-0.063	0.023	-0.029	0.038	-0.008
10.00	6.051	-0.030	0.016	-0.022	0.031	-0.004

Table A-2

Mean Velocities and Reynolds Stresses

for a Gap of 1H

K=25 GAP/H= 1.0 X/H= 2.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77						
1.00	3.889	0.015	-0.092	-0.123	-0.060	-0.044
1.50	5.263	-0.124	0.035	-0.142	-0.026	-0.028
2.00	5.704	-0.100	0.054	-0.055	-0.023	0.043
3.00	5.900	0.031	0.023	-0.055	-0.064	0.005
4.00	6.089	0.142	-0.033	-0.044	-0.059	-0.002
5.00	6.066	0.131	-0.030	-0.040	-0.052	-0.018
6.00	6.136	0.222	-0.007	-0.043	-0.032	0.009
8.00	6.190	0.208	-0.009	-0.028	-0.028	-0.009
10.00	6.328	0.170	-0.016	-0.020	-0.015	0.006

K=26 GAP/H= 1.0 X/H= 2.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77						
1.00	2.203	-0.327	-0.079	-0.333	0.0	-0.183
1.50	4.498	-0.372	0.141	-0.232	0.097	-0.383
2.00	5.518	0.007	0.222	-0.089	0.041	0.002
3.00	5.745	0.180	0.175	-0.067	0.011	0.016
4.00	5.800	0.226	0.101	-0.060	0.0	0.0
5.00	5.878	0.268	0.077	-0.053	-0.006	-0.009
6.00	5.947	0.243	0.023	-0.051	-0.004	0.001
8.00	6.136	0.222	0.0	-0.032	-0.006	-0.018
10.00	6.301	0.187	-0.033	-0.027	-0.003	0.005

K=27 GAP/H= 1.0 X/H= 2.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77						
1.00	2.140	-0.200	-0.135	-0.290	-0.103	-0.118
1.50	3.864	-0.280	-0.095	-0.422	-0.050	-0.563
2.00	5.385	0.052	0.220	-0.149	0.132	-0.005
3.00	5.855	0.210	0.209	-0.063	0.050	-0.004
4.00	5.891	0.271	0.124	-0.056	0.043	0.006
5.00	5.974	0.254	0.063	-0.058	0.042	0.010
6.00	6.002	0.226	0.040	-0.048	0.037	0.009
8.00	6.056	0.198	-0.040	-0.033	0.022	0.002
10.00	6.177	0.175	-0.040	-0.025	0.010	-0.004

K=28 GAP/H= 1.0 X/H= 2.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77						
1.00	2.123	-0.202	-0.159	-0.272	-0.126	0.028
1.50	3.795	-0.259	-0.139	-0.416	0.0	-0.090
2.00	5.526	0.045	0.163	-0.106	0.135	0.036
3.00	6.062	0.249	0.229	-0.061	0.036	-0.011
4.00	6.159	0.224	0.175	-0.055	0.032	-0.018
5.00	6.205	0.208	0.105	-0.043	0.041	-0.005
6.00	6.221	0.191	0.040	-0.035	0.039	0.007
8.00	6.263	0.177	0.016	-0.033	0.036	0.005
10.00	6.286	0.170	0.016	-0.030	0.028	-0.005

K=29 GAP/H= 1.0 X/H= 4.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77						
1.00	3.423	-0.324	-0.278	-0.217	-0.030	0.067
1.50	4.723	-0.395	-0.154	-0.148	0.0	0.0
2.00	5.334	-0.375	-0.028	-0.072	-0.035	0.004
3.00	5.599	-0.224	-0.023	-0.059	-0.046	0.025
4.00	5.713	-0.108	-0.024	-0.054	-0.055	-0.009
5.00	5.827	0.0	-0.023	-0.043	-0.045	-0.007
6.00	5.895	0.054	-0.047	-0.045	-0.034	0.006
8.00	6.062	0.112	-0.016	-0.027	-0.024	0.000
10.00	6.192	0.112	-0.030	-0.027	-0.011	0.010

K=30 GAP/H= 1.0 X/H= 4.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.220	-0.320	-0.182	-0.264	-0.060	0.023
1.00	2.431	-0.429	-0.149	-0.333	-0.016	0.032
1.50	3.558	-0.679	0.011	-0.375	0.086	-0.080
2.00	4.694	-0.635	0.174	-0.174	0.082	-0.024
3.00	5.359	-0.234	0.132	-0.049	0.030	-0.038
4.00	5.540	-0.065	0.081	-0.046	0.010	-0.035
5.00	5.628	0.0	-0.009	-0.040	0.034	0.012
6.00	5.750	0.068	-0.023	-0.041	0.019	0.005
8.00	5.936	0.126	-0.030	-0.035	0.012	0.002
10.00	6.062	0.079	-0.056	-0.031	0.003	0.008

K=31 GAP/H= 1.0 X/H= 4.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	1.901	-0.282	-0.070	-0.243	0.0	-0.025
1.00	2.414	-0.388	-0.084	-0.321	0.016	-0.032
1.50	3.613	-0.542	0.047	-0.379	0.139	-0.041
2.00	4.919	-0.500	0.216	-0.163	0.107	-0.064
3.00	5.693	-0.202	0.256	-0.042	0.066	-0.046
4.00	5.775	-0.075	0.145	-0.041	0.062	-0.019
5.00	5.880	0.0	0.091	-0.038	0.057	0.011
6.00	5.901	0.033	0.040	-0.037	0.045	-0.006
8.00	6.020	0.079	-0.007	-0.033	0.024	-0.010
10.00	6.133	0.079	-0.030	-0.026	0.018	-0.013

K=32 GAP/H= 1.0 X/H= 4.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	1.901	-0.231	-0.056	-0.160	-0.027	-0.038
1.00	2.327	-0.359	-0.101	-0.308	-0.062	-0.032
1.50	3.564	-0.524	-0.041	-0.404	0.089	-0.027
2.00	4.991	-0.470	0.144	-0.238	0.119	0.010
3.00	5.957	-0.144	0.235	-0.046	-0.027	-0.114
4.00	6.099	-0.080	0.182	-0.040	0.057	0.003
5.00	6.191	-0.047	0.112	-0.033	0.057	0.009
6.00	6.203	0.0	0.063	-0.025	0.055	0.000
8.00	6.255	0.042	0.0	-0.027	0.050	0.002
10.00	6.307	0.040	-0.049	-0.023	0.037	-0.001

K=33 GAP/H= 1.0 X/H= 6.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.556	-0.148	-0.254	-0.260	-0.142	0.064
1.00	3.076	-0.230	-0.233	-0.300	-0.074	0.021
1.50	4.245	-0.330	-0.202	-0.164	-0.012	0.068
2.00	4.852	-0.327	-0.054	-0.068	-0.036	-0.019
3.00	5.227	-0.278	-0.007	-0.063	-0.045	0.040
4.00	5.444	-0.196	0.007	-0.043	-0.050	-0.006
5.00	5.555	-0.136	-0.016	-0.048	-0.048	-0.019
6.00	5.687	-0.037	-0.030	-0.037	-0.035	-0.003
8.00	5.833	0.0	-0.023	-0.038	-0.021	0.006
10.00	6.027	0.026	-0.009	-0.030	-0.018	-0.007

K=34 GAP/H= 1.0 X/H= 6.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.495	-0.364	-0.306	-0.261	-0.107	0.168
1.00	2.863	-0.514	-0.271	-0.271	-0.048	0.120
1.50	3.689	-0.619	-0.120	-0.323	0.016	0.022
2.00	4.510	-0.574	-0.019	-0.148	-0.049	-0.130
3.00	5.160	-0.313	0.042	-0.066	0.032	-0.024
4.00	5.389	-0.182	0.023	-0.050	0.024	-0.003
5.00	5.512	-0.082	0.0	-0.048	0.017	0.006
6.00	5.654	-0.038	-0.040	-0.046	0.017	0.006
8.00	5.866	0.023	-0.047	-0.037	0.006	0.002
10.00	6.047	0.063	-0.040	-0.038	0.009	-0.001

K=35 GAP/H= 1.0 X/H= 6.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.193	-0.292	-0.160	-0.231	-0.088	-0.020
1.00	2.511	-0.398	-0.142	-0.346	0.0	0.053
1.50	3.490	-0.555	-0.049	-0.369	0.050	-0.040
2.00	4.508	-0.588	0.127	-0.237	0.083	-0.050
3.00	5.365	-0.399	0.139	-0.048	0.057	-0.036
4.00	5.584	-0.240	0.092	-0.053	0.055	-0.016
5.00	5.696	-0.161	0.030	-0.047	0.051	-0.012
6.00	5.778	-0.084	0.016	-0.035	0.044	-0.005
8.00	5.935	-0.016	-0.030	-0.037	0.031	-0.008
10.00	6.062	0.002	-0.047	-0.026	0.026	-0.002

K=36 GAP/H= 1.0 X/H= 6.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.173	-0.285	-0.143	-0.255	-0.091	-0.074
1.00	2.380	-0.339	-0.127	-0.344	-0.032	0.067
1.50	3.449	-0.537	-0.025	-0.432	0.025	-0.025
2.00	4.594	-0.577	0.077	-0.288	0.092	-0.002
3.00	5.698	-0.375	0.177	-0.054	0.064	-0.020
4.00	5.925	-0.264	0.141	-0.042	0.058	0.010
5.00	6.056	-0.159	0.096	-0.040	0.052	-0.002
6.00	6.118	-0.128	0.056	-0.032	0.047	0.000
8.00	6.187	-0.040	0.002	-0.035	0.039	-0.007
10.00	6.289	-0.016	-0.023	-0.024	0.035	0.007

K=37 GAP/H= 1.0 X/H= 10.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.922	0.045	-0.201	-0.203	-0.164	0.013
1.00	3.124	-0.026	-0.185	-0.239	-0.102	0.051
1.50	3.872	-0.104	-0.198	-0.201	-0.060	0.018
2.00	4.446	-0.103	-0.124	-0.127	-0.037	0.029
3.00	4.976	-0.138	-0.056	-0.055	-0.053	0.020
4.00	5.190	-0.115	-0.028	-0.044	-0.050	0.010
5.00	5.369	-0.086	-0.030	-0.035	-0.044	-0.009
6.00	5.478	-0.052	-0.023	-0.037	-0.039	-0.003
8.00	5.714	-0.023	0.007	-0.028	-0.023	-0.002
10.00	5.928	0.016	0.0	-0.027	-0.014	0.006

K=38 GAP/H= 1.0 X/H= 10.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.937	-0.297	-0.271	-0.264	-0.055	0.096
1.00	3.132	-0.306	-0.317	-0.271	-0.057	0.088
1.50	3.680	-0.354	-0.231	-0.239	0.0	0.067
2.00	4.219	-0.341	-0.157	-0.154	0.019	0.035
3.00	4.845	-0.217	-0.028	-0.078	0.020	-0.023
4.00	4.931	-0.215	0.131	-0.013	0.048	-0.026
5.00	5.296	-0.093	-0.014	-0.031	0.020	-0.047
6.00	5.453	-0.082	0.0	-0.046	0.017	0.001
8.00	5.682	-0.016	-0.016	-0.040	0.006	-0.002
10.00	5.871	0.016	-0.023	-0.027	0.015	0.000

K=39 GAP/H= 1.0 X/H= 10.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.625	-0.267	-0.320	-0.283	-0.058	0.093
1.00	2.958	-0.262	-0.211	-0.317	-0.015	0.055
1.50	3.609	-0.371	-0.147	-0.334	0.015	0.021
2.00	4.276	-0.391	-0.019	-0.264	0.040	-0.011
3.00	4.970	-0.102	0.051	-0.091	0.057	-0.022
4.00	5.364	-0.210	0.051	-0.049	0.058	-0.003
5.00	5.523	-0.187	0.021	-0.042	0.047	-0.017
6.00	5.648	-0.121	-0.016	-0.041	0.044	-0.001
8.00	5.825	-0.077	-0.030	-0.031	0.033	0.005
10.00	5.930	-0.050	-0.014	-0.032	0.021	-0.004

K=40 GAP/H= 1.0 X/H= 10.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.526	-0.203	-0.260	-0.281	-0.045	0.016
1.00	2.942	-0.319	-0.187	-0.363	0.0	0.133
1.50	3.598	-0.359	-0.133	-0.394	0.0	0.027
2.00	4.396	-0.407	-0.019	-0.328	0.059	0.009
3.00	5.366	-0.306	0.069	-0.088	0.129	0.090
4.00	5.700	-0.280	0.078	-0.051	0.049	-0.026
5.00	5.869	-0.231	0.044	-0.032	0.057	0.003
6.00	5.972	-0.180	0.016	-0.030	0.050	-0.009
8.00	6.089	-0.120	-0.016	-0.020	0.041	-0.005
10.00	6.209	-0.056	-0.016	-0.023	0.036	0.001

K=41 GAP/H= 1.0 X/H= 16.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.292	0.081	-0.175	-0.144	-0.120	0.004
1.00	3.439	0.087	-0.180	-0.159	-0.104	0.038
1.50	3.809	0.104	-0.180	-0.178	-0.076	0.033
2.00	4.195	0.005	-0.105	-0.150	-0.061	0.027
3.00	4.743	0.040	-0.026	-0.074	-0.053	-0.016
4.00	5.031	0.007	-0.049	-0.046	-0.050	-0.015
5.00	5.214	-0.007	-0.028	-0.042	-0.040	-0.001
6.00	5.344	-0.007	-0.014	-0.034	-0.032	0.001
8.00	5.595	0.007	0.014	-0.031	-0.014	0.009
10.00	5.819	0.009	0.007	-0.032	-0.014	0.000

K=42 GAP/H= 1.0 X/H= 16.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.283	-0.092	-0.126	-0.167	-0.012	0.003
1.00	3.459	-0.164	-0.106	-0.196	0.005	0.027
1.50	3.820	-0.149	-0.167	-0.207	0.005	0.048
2.00	4.162	-0.163	-0.159	-0.167	0.016	0.042
3.00	4.717	-0.074	-0.054	-0.089	0.030	0.014
4.00	5.057	-0.049	-0.042	-0.052	0.029	0.016
5.00	5.253	-0.044	-0.007	-0.050	0.023	0.009
6.00	5.389	-0.007	-0.037	-0.042	0.025	0.014
8.00	5.652	-0.037	-0.014	-0.039	0.015	0.017
10.00	5.868	-0.037	-0.030	-0.037	0.005	-0.002

K=43 GAP/H= 1.0 X/H= 16.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S) U	V	W	REYNOLDS STRESS (M/S)*(M/S) SUV	SUW	SVW
0.77	3.288	-0.149	-0.176	-0.193	-0.026	0.008
1.00	3.465	-0.147	-0.204	-0.218	-0.027	0.031
1.50	3.883	-0.182	-0.154	-0.254	0.013	0.028
2.00	4.224	-0.199	-0.083	-0.253	0.039	0.011
3.00	4.952	-0.180	0.0	-0.144	0.045	-0.024
4.00	5.343	-0.145	0.014	-0.060	0.054	-0.006
5.00	5.528	-0.119	-0.021	-0.045	0.051	0.000
6.00	5.620	-0.092	-0.016	-0.046	0.050	0.003
8.00	5.873	-0.091	-0.053	-0.039	0.029	-0.012
10.00	6.041	-0.087	-0.040	-0.028	0.024	-0.004

K=44 GAP/H= 1.0 X/H= 16.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S) U	V	W	REYNOLDS STRESS (M/S)*(M/S) SUV	SUW	SVW
0.77	3.137	-0.109	-0.185	-0.237	0.0	0.048
1.00	3.331	-0.130	-0.171	-0.262	-0.022	0.017
1.50	3.821	-0.192	-0.086	-0.289	0.023	0.032
2.00	4.272	-0.213	-0.037	-0.278	0.005	-0.024
3.00	5.075	-0.231	0.035	-0.156	0.038	-0.001
4.00	5.517	-0.208	0.038	-0.055	0.052	0.002
5.00	5.681	-0.160	0.040	-0.044	0.051	0.001
6.00	5.811	-0.154	0.0	-0.033	0.042	-0.007
8.00	5.944	-0.134	0.007	-0.023	0.042	-0.005
10.00	6.083	-0.103	-0.023	-0.022	0.028	-0.008

K=45 GAP/H= 1.0 X/H= 28.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S) U	V	W	REYNOLDS STRESS (M/S)*(M/S) SUV	SUW	SVW
0.77	3.596	0.109	-0.112	-0.085	-0.107	-0.018
1.00	3.641	0.133	-0.108	-0.094	-0.096	-0.004
1.50	3.887	0.154	-0.074	-0.112	-0.084	-0.006
2.00	4.095	0.103	-0.091	-0.129	-0.075	0.011
3.00	4.512	0.110	-0.039	-0.101	-0.047	-0.001
4.00	4.920	0.103	-0.046	-0.059	-0.039	-0.013
5.00	5.137	0.084	0.0	-0.042	-0.027	0.011
6.00	5.252	0.086	0.023	-0.034	-0.025	0.003
8.00	5.481	0.052	0.038	-0.031	-0.018	0.001
10.00	5.724	0.023	0.037	-0.034	-0.008	0.008

K=46 GAP/H= 1.0 X/H= 28.0 -Z/H= 2.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.518	0.0	0.054	-0.103	0.030	-0.010
1.00	3.583	-0.009	-0.005	-0.110	0.030	-0.010
1.50	3.760	0.0	-0.044	-0.135	0.048	0.039
2.00	4.019	0.012	-0.077	-0.148	0.042	0.005
3.00	4.473	0.014	-0.051	-0.125	0.029	0.008
4.00	4.864	0.014	-0.026	-0.070	0.021	0.001
5.00	5.126	0.042	0.014	-0.057	0.021	0.005
6.00	5.290	0.058	0.0	-0.043	0.022	0.009
8.00	5.542	0.030	0.0	-0.038	0.018	0.011
10.00	5.754	0.007	0.0	-0.028	0.011	0.006

K=47 GAP/H= 1.0 X/H= 28.0 -Z/H= 4.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.710	-0.036	0.0	-0.122	0.011	-0.003
1.00	3.848	-0.078	0.0	-0.122	0.011	-0.014
1.50	4.073	-0.073	-0.023	-0.156	0.011	-0.003
2.00	4.299	-0.052	-0.037	-0.156	0.040	0.008
3.00	4.761	-0.103	-0.026	-0.137	0.047	-0.002
4.00	5.128	-0.063	0.0	-0.089	0.043	-0.014
5.00	5.384	-0.045	0.0	-0.062	0.047	0.000
6.00	5.529	-0.030	-0.007	-0.050	0.047	0.006
8.00	5.723	-0.030	-0.021	-0.034	0.036	0.010
10.00	5.887	-0.037	-0.037	-0.026	0.023	-0.005

K=48 GAP/H= 1.0 X/H= 28.0 -Z/H= 6.5

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.708	-0.060	-0.007	-0.133	0.012	-0.004
1.00	3.816	-0.067	-0.019	-0.145	0.019	-0.005
1.50	4.066	-0.042	-0.012	-0.184	0.024	-0.026
2.00	4.345	-0.075	-0.005	-0.202	0.031	-0.016
3.00	4.850	-0.097	0.019	-0.164	0.064	0.019
4.00	5.339	-0.130	0.088	-0.095	0.049	-0.007
5.00	5.550	-0.075	0.068	-0.059	0.050	-0.009
6.00	5.721	-0.068	0.068	-0.039	0.051	0.010
8.00	5.895	-0.093	0.039	-0.029	0.041	-0.010
10.00	6.012	-0.056	0.007	-0.021	0.027	-0.011

Table A-3

Mean Velocities and Reynolds Stresses

for Zero Gap

K=49 GAP/H= 0.0 X/H= 2.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	1.682	-0.122	-0.026	-0.115	-0.028	-0.063
1.00	2.020	-0.210	-0.059	-0.226	-0.046	-0.101
1.50	3.523	-0.254	-0.035	-0.341	0.073	-0.087
2.00	5.196	0.0	0.117	-0.130	0.112	0.014
3.00	5.706	0.201	0.068	-0.066	0.050	0.019
4.00	5.745	0.264	0.014	-0.055	0.034	0.002
5.00	5.761	0.259	0.0	-0.049	0.036	0.018
6.00	5.799	0.273	-0.014	-0.043	0.028	0.009
8.00	5.892	0.224	-0.035	-0.032	0.016	0.002
10.00	5.985	0.180	-0.044	-0.030	0.014	0.002

K=50 GAP/H= 0.0 X/H= 4.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	1.983	-0.268	-0.061	-0.204	-0.039	-0.054
1.00	2.425	-0.376	-0.051	-0.300	-0.030	-0.027
1.50	3.548	-0.573	-0.025	-0.357	0.077	-0.044
2.00	4.752	-0.511	0.044	-0.172	0.078	-0.051
3.00	5.519	-0.215	0.068	-0.048	0.043	-0.017
4.00	5.656	-0.075	0.042	-0.047	0.046	0.001
5.00	5.758	0.0	0.014	-0.043	0.032	-0.002
6.00	5.799	0.056	-0.021	-0.042	0.037	0.015
8.00	5.913	0.100	-0.028	-0.034	0.023	0.004
10.00	6.039	0.128	-0.028	-0.028	0.017	0.005

K=51 GAP/H= 0.0 X/H= 6.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.178	-0.318	-0.111	-0.242	-0.042	-0.044
1.00	2.580	-0.431	-0.107	-0.316	-0.015	-0.061
1.50	3.556	-0.546	-0.071	-0.322	0.047	0.002
2.00	4.436	-0.540	0.012	-0.195	0.089	0.024
3.00	5.238	-0.359	0.040	-0.057	0.051	-0.010
4.00	5.446	-0.189	0.007	-0.052	0.041	0.001
5.00	5.579	-0.124	-0.014	-0.044	0.040	0.000
6.00	5.699	-0.068	-0.026	-0.037	0.031	-0.001
8.00	5.837	-0.007	-0.042	-0.034	0.017	-0.007
10.00	5.989	0.035	-0.058	-0.028	0.019	0.003

K=52 GAP/H= 0.0 X/H= 10.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	2.729	-0.215	-0.133	-0.244	-0.027	0.009
1.00	2.936	-0.244	-0.117	-0.268	-0.025	0.021
1.50	3.583	-0.308	-0.093	-0.269	0.008	0.035
2.00	4.210	-0.313	-0.051	-0.195	0.037	0.010
3.00	4.888	-0.201	-0.044	-0.074	0.046	0.013
4.00	5.135	-0.165	-0.019	-0.054	0.035	0.003
5.00	5.347	-0.112	-0.054	-0.045	0.030	0.008
6.00	5.501	-0.093	-0.033	-0.042	0.024	-0.000
8.00	5.711	-0.047	-0.047	-0.032	0.018	-0.003
10.00	5.893	-0.021	-0.049	-0.027	0.011	-0.000

K=53 GAP/H= 0.0 X/H= 16.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.156	-0.050	-0.049	-0.182	0.012	-0.024
1.00	3.272	-0.103	-0.087	-0.213	0.025	0.005
1.50	3.660	-0.128	-0.042	-0.242	0.023	0.002
2.00	4.041	-0.089	-0.068	-0.223	0.037	-0.006
3.00	4.734	-0.099	-0.012	-0.113	0.049	0.021
4.00	5.091	-0.065	-0.037	-0.059	0.034	-0.011
5.00	5.264	-0.061	-0.014	-0.050	0.037	0.006
6.00	5.389	-0.047	-0.019	-0.042	0.025	0.004
8.00	5.647	-0.042	-0.049	-0.031	0.018	0.005
10.00	5.822	-0.014	-0.021	-0.031	0.016	0.002

K=54 GAP/H= 0.0 X/H= 28.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	3.534	0.014	0.040	-0.107	0.030	0.007
1.00	3.664	0.0	0.030	-0.118	0.020	-0.010
1.50	3.854	0.028	0.023	-0.143	0.035	0.014
2.00	4.095	0.019	0.007	-0.149	0.034	0.019
3.00	4.526	-0.007	-0.012	-0.132	0.051	0.030
4.00	4.921	0.026	0.0	-0.086	0.030	0.001
5.00	5.161	0.033	0.012	-0.058	0.027	0.013
6.00	5.210	0.048	-0.007	-0.042	0.023	0.000
8.00	5.478	0.014	0.007	-0.036	0.019	0.017
10.00	5.768	0.021	0.007	-0.029	-0.007	-0.022

Table A-4

Mean Velocities and Reynolds Stresses

without Obstacles

K=55 GAP/H= 0.0 X/H= 0.0 -Z/H= 0.0

Y/H	MEAN VELOCITY (M/S)			REYNOLDS STRESS (M/S)*(M/S)		
	U	V	W	SUV	SUW	SVW
0.77	4.053	0.0	-0.030	-0.061	0.019	-0.006
1.00	4.210	-0.012	0.0	-0.065	0.016	-0.005
1.50	4.442	0.026	0.007	-0.064	0.025	0.000
2.00	4.647	0.019	-0.026	-0.060	0.023	-0.002
3.00	4.851	0.040	-0.014	-0.059	0.027	0.006
4.00	5.135	0.086	-0.035	-0.051	0.027	0.007
5.00	5.296	0.079	-0.037	-0.043	0.023	0.012
6.00	5.434	0.075	-0.051	-0.045	0.017	0.007
8.00	5.681	0.070	-0.054	-0.034	0.013	0.007
10.00	5.880	0.063	-0.037	-0.030	0.010	0.004

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16. ABSTRACT

Measurements relevant to the effect of buildings on the low-level atmospheric boundary layer are presented. A wind tunnel experiment was undertaken to determine the nature of the flow downstream from a gap between two transversely aligned, equal-sized models of rectangular cross section. These building models were immersed in an equilibrium turbulent boundary layer which was developed on a smooth floor in a zero longitudinal pressure gradient. Measurements with an inclined (45-degree) hot-wire were made at key positions downstream of models arranged with a large, small, and no gap between them. Hot-wire theory is presented which enables computation of the three mean velocity components, U, V and W, as well as Reynolds stresses. These measurements permit understanding of the character of the wake downstream of laterally spaced buildings. Surface streamline patterns obtained by the oil-film method were used to delineate the separation region to the rear of the buildings for a variety of spacings.

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