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A STUDY OF THE HYDRAULICS OF VERTICAL SLOT FISHWAYS

by

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Abstract

This thesis presents the results of an experimental study on the hydraulics of vertical slot fishways. Seven designs, including some conventional designs, have been tested. A conceptual uniform flow state has been defined for which a linear relation has been found between the dimensionless flow rate and relative depth. Non-uniform flow of both the M1 and M2 types has been analysed using the Bakhmeteff-Chow method. Some observations have also been made on the velocity profiles in the slots and circulation patterns in the pools. Energy dissipation rates and discharge coefficients have been calculated for a variety of flow situations.

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List of Symbols

A = slope of rating curve equation

a = baffle spacing

B = pool width

b_o = slot width

C_d = discharge coefficient

C_f = coefficient of fluid friction

D = y-intercept of rating curve equation

F_o = Froude number

g = acceleration due to gravity

h = height above datum

Δh = head drop across slot

L = length of pool

L_o = depth divided by slope

L_r = ratio of prototype to model lengths

M = hydraulic exponent for critical flow

m = number of fluid shear surfaces on jet

N = hydraulic exponent for uniform flow

p = pressure

Q = discharge

Q_r = ratio of prototype to model discharges

Q_* = dimensionless discharge

R_e = Reynold's number

S_o = slope

u = longitudinal velocity

u_m = maximum velocity

V = average velocity

x = longitudinal distance

$\bar{x}$ = longitudinal distance from start of profile

x' = longitudinal distance from slot in pool

Δx = small longitudinal distance

y = average pool depth

y_c = critical depth through slot

y_d = elevation of downstream pool water surface

y_o = average pool depth for uniform flow

y_u = elevation of upstream pool water surface

$\bar{y}$ = depth just upstream of slot

y' = vertical distance from slot bottom

z' = transverse distance from slot

γ = specific weight of water

η = ratio of actual depth to normal depth (y/y_o)

κ = energy dissipation rate

ν = kinematic viscosity

ρ = mass density of water

$\bar{\tau}_o$ = average boundary shear stress

1. Introduction

1.1 General

Fish protection is a concern for the commercial and sports fishing industries as well as for environmental protection groups. Fish populations may be reduced if barriers, such as dams, block their migration routes, especially for spawning. The law requires that some means be available for fish to bypass these barriers. Fish populations may also be expanded if fish were able to bypass waterfalls and rapids that previously blocked their upstream passage. Fishways are hydraulic structures that provide a means for fish to overcome these obstacles.

Fishways are steep waterways that enable fish to gain elevation rapidly over a short distance without encountering prohibitively high velocities. Because they are physically steep, fishways must dissipate energy efficiently to limit velocities. Many structures have been devised to dissipate this energy but three types are most prevalent: the pool and weir, the Denil, and the vertical slot.

The vertical slot fishway has advantages over other types of fishways. It requires no manual regulation of flow where head and tailwater variations are comparable and maintains a constant flow pattern over a wide range of operating depths (Clay 1961, Bell 1973). Also, fish may swim at any prefered depth and conditions for resting are satisfactory (Clay 1961). One possible disadvantage is that some fish prefer to swim at a constant velocity rather than darting and resting as they would do in the vertical slot fishway.

1.2 Fish Behavior

In the design of fishways, physiological data on the swimming capabilities and behavior of a fish species are used to set the water velocity and dimensions for a fishway. Swimming speed varies with size of fish, water temperature, oxygen level, and many other parameters. The time for which the effort is maintained is also a major factor. Swimming speed is generally divided into three categories: burst, prolonged, and sustained (Blake 1983). The fastest speed a fish can swim is called the burst or darting speed; it can be maintained only for periods less than 15 seconds (Katopodis 1983). The fish is fueled by anaerobic processes and tires quickly. Sustained speed, or cruising speed, is a low level of activity used when schooling or migrating. This activity is fueled aerobically; the fish can maintain it indefinitely. Any intermediate activity, between 15 seconds and 200 minutes in duration, is defined as prolonged speed.

Swimming speeds are of major importance but other behavioral aspects of fish species must also be considered. Fish are able to sense areas of low velocities and therefore may take the easiest path (Bell 1973). This makes knowledge of the velocity field in the pools more important than knowledge of the average velocity in the fishway. Also, when fish swim from a pool or resting area through an area of high velocity into another pool, they should be required to make as little change in direction as possible (Decker 1967). This helps to prevent the fish from hesitating or refusing to enter an area. The fishway design should allow fish to navigate the channel without undue delay or fatigue.

Attracting fish to the fishway is also important. There should be enough flow from the fishway for the fish to distinguish the entrance from the main flow. Fish are attracted to higher velocity flows coming out of the fishway entrance. These velocities should be less than the burst speed of the species but may be greater than the sustained speed (Bell 1973). Considerable care should be taken in placing the fishway entrance where the fish naturally congregate. In many instances, poor placement and design of an entrance limits the effectiveness of a fishway.

Fishways frequently do not perform as expected. An existing design that is considered to successfully pass one species of fish may not be suitable for another species. Vertical slot fishways have been built successfully for Pacific Salmon but now they are being used to pass fresh water fish as well, with varying degrees of success. A more complete understanding of the hydraulics of these fishways is needed, as well as a knowledge of the differences in behavior of different fish species so that they may be designed properly for any conditions.

1.3 History of Vertical Slot Fishways

A fishway resembling a vertical slot fishway was built in Norway by Landmark in the late 1800's (Mcleod and Nemenyi 1940). He improved on the traditional pool fishway by placing angled baffles in the channel with slots along one wall. A jet deflector was put along the wall to direct the jet away from the wall.

The earliest true vertical slot fishway was built at Hell's Gate on the Fraser River in British Columbia in 1946 (C.E.A. 1985). It consisted of a rectangular channel, 6.1 m wide, with vertical baffles dividing the channel into 5.5 m pools (Fig. 1(a)). The slope of this fishway was 0.305 m (1 ft.) vertical in 5.49 m (18 ft.) horizontal (Andrews). In the original design, two slots, 0.737 m wide, extended the full height of the baffles. Water flowed from one pool to the next forming jets as it passed through the slots. The energy in the jets was dissipated as they met in the center of the pool. Extensive testing was done at the University of Washington in Seattle to select the baffle shape and slot size which produced the pool with the least turbulence (Clay 1961). Because of the success of this installation other fishways were designed using the principle of the vertical slot.

The original fishway at Hell's Gate was designed to pass a large number of fish. Smaller, more economical fishways were needed at other sites. The original baffle design was cut in half, leaving only one slot. As well, the slot size was reduced to 0.305 m and the pool length approximately halved (Fig. 1(b)). Clay (1961) states that an 2.44 m (8 ft.) by 3.05 m (10 ft.) pool is the least turbulent and most satisfactory for the 0.305 m slot; while, a pool 1.83 m (6 ft.) by 2.44 m (8 ft.) has proved barely satisfactory. Sills were added to the bottoms of the slots and the slot angles adjusted to force the jet into the resting pool where the jet energy could be dissipated by turbulent mixing before it reached the next slot. The head drop per pool was typically 0.30 m. and the slope was 0.305 m (1 ft.) in 3.05 m (10 ft.).

Vertical slot fishways have been used all over North America, but mostly on the east and west coasts. In Atlantic Canada, there are 40 vertical slot fishways in operation. There are 60 fishways operating in British Columbia at present, 39 are of the vertical slot variety (C.E.A. 1985). This gives some indication of the success these fishways have had in passing Pacific Salmon. In Alberta, a vertical slot fishway at Carsland Dam on the Bow River has been used to pass Rocky Mountain Whitefish successfully. Another vertical slot fishway on the Bow River in Calgary blocked fish passage because of excessive velocity in one slot. This slot had a control gate installed that reduced the slot width. If this modification were removed the fishway would likely pass fish successfully (Katopodis 1985). Temporary fishways have been installed near Lesser Slave Lake and near Lake Athabasca. Studies are in progress to evaluate the performance of these installations.

Most vertical slot fishways have been generally patterned after either the full or one-half width Hell's Gate fishway with its detailed baffle configuration. If the baffle design was different than this, the details were generally finalized based on hydraulic model studies (C.E.A. 1985). The fishway is designed with a certain difference in water level between two adjacent pools. The magnitude of this head drop depends on the species of fish which would ascend the fishway, using its burst speed to get through the slot. The influence of the tailwater level on the variation of head drops through the fishway is not well understood. As well, the present understanding of the behavior of the jet in the pools appears to be incomplete. This investigation was undertaken to gain insight into the hydraulics of the conventional vertical slot fishway and also to develop simpler designs for the baffles in the fishway.

2. Experimental Arrangement

2.1 1:5.33 Scale Model

Designs 1-3 (these designs are described later) were installed in a flume 0.46 m (18 in.) wide, 0.91 m (3 ft.) deep, and 5 m (16 ft.) long. The baffles and floor of the fishway were constructed of wood while the walls were of 12 mm plexiglass. Water was supplied to this horizontal flume from a sump, located at the downstream end of the flume, by means of a pump, located in the pipeline leading from the sump, to the head tank located at the upstream end of the flume. Fig. 2 shows a sectional view of this flume with the Design 1 baffle arrangemnt installed. At the downstream end of this flume, an adjustable tailgate was installed which was used to control the depth of flow in the flume.

2.2 1:8 Scale Model

Designs 3-6 were installed in a flume 0.305 m (12 in.) wide, 0.560 m (22 in.) deep, and 4.88 m (16 ft.) long. This flume had 12 mm plexiglass walls and an aluminum floor. The baffles were set vertical when the bed of the flume was set at a 10% slope. The flume was set on blocks at the desired slope. Water was pumped from a sump to the head tank, which was separated from the fishway with a hogs-hair baffle. An adjustable tailgate, located at a distance of 0.96 m downstream from the last baffle, controlled the tailwater level at the downstream end of the flume.

2.3 1:16 Scale Model

Designs 3 and 7 were installed in a flume 0.152 m (6 in.) wide, 0.545 m (21.5 in.) deep, and 4.88 m (16 ft.) long. This flume had 12 mm plexiglass walls and floor. The water for this flume was supplied by the same system as described for the 12 in. wide flume. The adjustable tailgate was 0.67 m downstream from the last baffle. A 0.038 m (1.5 in.) diameter hole in the bottom of the flume just upstream of the tailgate was fitted with a valve for more accurate control of the tailwater.

2.4 Baffle Geometry

Design 1 was a standard baffle geometry for vertical slot fishways, similar to the baffles used in the Hell's Gate fishways (Fig. 3). In terms of prototype dimensions, the pool size was chosen as 3.05 m (10 ft.) in length and 2.44 m (8 ft.) in width. The width of the slot was taken as 0.305 m (1 ft.). These dimensions were used in all the baffle designs. More details of this design are shown in Fig. 3. The baffles were made of wood except for a thin section extending from one wall to the baffle head near the slot. This thin section was made of aluminum sheeting. All tests on Design 1 were performed in the 1:5.33 model. The model had five sets of baffles making four pools.

Design 2 was a modification of Design 1. The baffles were left the same but a sill of height 0.15 m (6 in.) and width 0.15 m (6 in.) prototype was placed across the bottom of each slot.

The baffles used in Design 3 were simple flat plates extending across the flume, leaving a 0.305 m (1 ft.) slot against the wall. The slots were staggered as can be seen in Fig. 4. The prototype dimensions of the pools were the same as for Design 1. Design 3 was tested in all three scale models. On the 1:5.33 scale model, the baffles were made from 19 mm (3/4 in.) plywood; while in the other two models, 6 mm (1/4 in.) aluminum was used. The 1:5.33 scale model had four pools; the 1:8 had 9 pools; and the 1:16 had both 10 pools and 18 pools.

The baffles used in Design 3 were used in Design 4 as well. The slots in Design 4 were all along the same wall rather than on alternating sides. Design 5 was a modification of Design 4. An auxiliary baffle, projecting 0.305 m (prototype) into the flow, was placed 0.305 m downstream of each slot. Design 6 was identical to Design 5 except for the length of the auxiliary baffle. The auxiliary baffle projected 0.152 m into the flow in this design. This auxiliary baffle was made from 38 mm (1.5 in.) aluminum angle. The slot in Design 7 was along the centerline of the flume rather than along a wall. These designs can be seen in Fig. 4.

2.5 Instrumentation

The depth of flow in the 1:5.33 scale model was measured with a point gauge of least count of 0.3 mm (0.001 ft.). In the other two flumes, a thin metal ruler with a least count of 0.25 mm (0.01 in.) was inserted into the flow. The velocity profiles in the slots were measured with a 2 mm external diameter Prandtl-type pitot-static tube. In regions where the velocity appeared to be three dimensional, a calibrated five-hole probe, of external diameter of 3 mm, was used. In the recirculation areas of the pool, some velocity measurements were made using a mini-current meter with a 10 mm diameter impeller. The circulation patterns in the pools were obtained by using a tuft-probe which was a 3 mm diameter rod with a 30 mm woolen thread tied to its lower end. The flow rate was measured by means of a magnetic flow meter located in the supply line of each of the three models.

3. Experiments and Experimental Results

3.1 Uniform Flow Experiments

Even though fishways are not of uniform cross-section, they do exhibit uniform flow characteristics. Fig. 5 shows the side view of an experiment, for Design 3 in the 1:16 model, done with the tailwater depth set in such a way that all the pools are of equal depth. If the average depth per pool is plotted against horizontal distance, the line passing through the points would be parallel to the bed of the fishway. Such a flow can be refered to as uniform flow in a vertical slot fishway.

Uniform flow experiments were performed on all seven designs for a number of slopes and discharges; the significant details of these experiments are given in Table 1. The average pool depth, for uniform flow conditions, is denoted by y_o. This average pool depth was obtained by measuring the pool depth in the quiescent area behind the main baffle and converting this to center of pool depth. In Table 1, all the quantities have been converted to prototype values using the Froudian similitude criterion:

$$Q_r = (L_r)^{2.5} \tag{1}$$

where Q_r is the ratio of prototype discharge to model discharge and L_r is the ratio of the prototype length to the model length (the scale size). The Reynold's number R_e was checked in the 1:16 scale model to ensure that turbulent flow existed in the model as it would in the prototype. Putting the values of the slot velocity in the model, u_m=0.61 m/s, the slot width, b_o=0.019 m, and the kinematic viscousity of water at 20°C, $\nu=1.006\times10^{-6}m^2/s$ into the Reynold's number formula:

$$R_e = \frac{u_m b_o}{\nu} = \frac{0.61 m/s \cdot 0.019 m}{1.006\times10^{-6} m^2/s} = 11,521 \qquad (2)$$

This value is greater than the $R_e \simeq 5000$ or more needed to produce turbulent flow, therefore turbulent flow would exist in the model.

3.2 Non-uniform Flow Experiments

Fig. 6 shows the side view of a non-uniform flow experiment for Design 3. These non-uniform flow experiments were performed in the 1:16 model on Design 3. Various discharges and tailwater levels were tested for two slopes, 10% and 15.2%, and the results are given in Table 2. Care was taken to insure that uniform flow existed in the upstream end of the fishway so that the full profiles were obtained. Fig. 7 shows the non-uniform flow profiles obtained by plotting average pool depth against horizontal distance. These show typical M1 and M2 type backwater curves (as well as approximate uniform flow profiles). Fig. 8 shows the variation in head drop across the baffles for these same experiments. When the depth increased in the downstream direction, Δh decreased, and when the depth decreased in the downstream direction, Δh increased.

3.3 Submergence Experiments

If the tailwater level is relatively low, the last downstream slot, called the fishway entrance, will act as some form of flow control. In order to find the relationship between the tailwater level, y_d, and the depth in the next upstream pool, y_u, a few experiments were performed with Designs 1 and 3. The results are given in Table 3. In Fig. 9, y_d and y_u are the flow depths in the tailwater region and in the adjacent pool, above a datum passing through the bed in the center of the connecting slot. The figure shows that below a certain value of y_d, y_u was invariant; above this value of y_d, y_u was affected.

3.4 Velocity Profiles in the Slots

Velocity profiles in the centerline of the slots were obtained for various discharges and tailwater levels in Designs 1-3. The profiles can be divided into two zones, as can be seen in Fig. 10, 11, and 12. In the lower zone, the velocity distribution is uniform; in the upper zone, above the lower pool level, the velocity decreases towards the surface. The magnitude of the head drop, Δh, across the baffle compared to the depth in the slot determines the relative size of each zone. In slot 5, the last slot, the lower uniform zone is non-existent when there is very low tailwater. This results in a profile with the maximum velocity near the bottom (Fig 10(r)), like a wall jet.

A few transverse profiles were measured, one for Design 1 and one for Design 3 (Fig. 13). Both profiles show a region of slower velocity near the edge of the main baffle.

3.5 Circulation in Pools

To get some appreciation of the water surface configuration in Design 1, the water surface elevations in the pools were measured for one experiment with a prototype discharge of 1.67 m^3/s and a very low tailwater level. The results are presented in Fig. 14 and 15. Fig. 14 shows the longitudinal water surface profiles in two planes, one passing through the slots and the other further into the pools (away from the slot). Fig. 15(a-d) show the local dips and high points in the pools while Fig. 15(e) shows the deformation of the jet as it falls to the floor of the channel due to the very low tailwater level.

The circulation patterns, obtained from the tuft probe and flow visualization experiments with dye, are shown in Fig. 16 for the same discharge and tailwater level as for the surface contour measurements. The figures show the circulation in three horizontal planes, one near the surface, one near the mid-depth, and one near the bed. The coherent jet, recirculation cells, and regions of upwelling and sinking can be seen clearly. Fig. 17 shows the flow in three vertical planes located at different distances from the side wall. These diagrams emphasize the complicated three dimensional nature of the turbulent flow in the pools.

To obtain some appreciation of the velocity field in the pools, the velocity field in the second pool was mapped, using a five-hole probe, Prandtl probe and mini-current meter, for the same experiment as for the surface profiles and circulation patterns. Fig. 18 shows the coordinate system used, while Figs. 19(a-d) show the velocity contours at four cross-sections located at 0.49 m, 0.76 m, 1.30 m and 1.84 m downstream of the slot. In these four figures, one can see the gradual widening of the jet from the slot. Fig. 20 shows the three velocity components at one location as measured with the five-hole probe. The velocity is primarily in the longitudinal direction. Figure 21 shows the path, in plan view, of the maximum velocity filament of the jet.

The addition of the 0.15 m sills to Design 1 changed the circulation pattern slightly. The jet angle changed; it was directed more to the opposite corner of the pool as shown in Fig. 22. This caused the eddies on either side of the jet to be of more or less equal size.

The baffle geometry of Design 3 caused the jet to stay along the wall (Fig. 22). When the jet hit the next baffle, it was forced to turn and flow across the pool. The direction of the jet changed abruptly again at the next slot. The jet split against the side wall, just upstream of the slot opening, with one part going through the slot and the other recirculating in the pool. This set up an eddy that was centered near the center of the pool.

Since all the slots were against one wall in Design 4, the jet stayed along that wall (Fig. 22). This set up a large eddy in the pool which rotated about the center of the pool. The water surface rose just upstream of each slot as the jet was obstructed by the baffle constriction. The flow appeared more turbulent in this model than in others.

The auxiliary baffle installed in Design 5 caused the jet to be deflected along the back side of the main baffle (Fig. 22). The circulation in this design was similar to that of Design 3 except the jet traveled along three walls instead of two.

In Design 6, a shorter auxiliary baffle was used. This baffle configuration had different flow patterns for different flow rates (Fig. 22). With the low flow rate, the flow pattern was similar to that of Design 1; the jet reattached to the side wall three-quarters of the distance to the next baffle. With higher flow rates, the jet penetrated much deeper into the pool before being deflected back to the next slot opening. At a flow rate of 0.90 m^3/s and a 5.7% slope, the flow was observed to change from the lower flow rate pattern to the higher flow rate pattern. This was accompanied by an increase in uniform flow depth.

The jet did not stay along the center line of the flume in Design 7. On the surface, the jet appeared to swing over to one side wall before going through the next slot. It would then go to the opposite wall in the next pool. An eddy formed in the opposite side of the pool from the jet. Near the bottom, the jet behavior was completely opposite. If the jet swung to one side on the surface, it would swing to the opposite wall near the bottom (Fig. 22). This change took place near the midpoint in depth.

4. Analysis

4.1 Uniform Flow

Uniform flow in the vertical slot was previously defined as the condition when all or most of the pools were of the same depth. For such an idealized uniform flow, a simple approximate analysis can be developed, mainly to find a functional form involving the flow rate Q, with the hope of developing a rating curve for the vertical slot fishway. With this in mind, an approximate force balance can be written:

$$b_o y_o \Delta x \gamma S_o = \bar{\tau}_o m y_o \Delta x \tag{3}$$

where b_o is taken approximately as the width of the stream in the pool, y_o is the depth in the pool, γ is the unit weight of water, Δx is the length of the element, $\bar{\tau}_o$ is the shear stress between the stream and the recirculating water mass; the bed shear stress on the stream is neglected in comparison with $\bar{\tau}_o$; m = 1 when the stream is bounded on one side by a solid wall and m = 2 when surrounded by fluid on both sides. Obviously, the slope S_o will have to be adjusted for each design because the stream path will be different.

The shear stress $\bar{\tau}_o$ can be written as:

$$\bar{\tau}_o = C_f \frac{\rho V^2}{2} \tag{4}$$

where C_f is a fluid friction coefficient, V is a characteristic velocity, and ρ is the density of water. Combining Eq. 1 and 2:

$$V^2 = \frac{2}{m} \frac{gS_o b_o}{C_f} \tag{5}$$

This can be reduced further using:

$$Q = V y_o b_o \tag{6}$$

where the Q is the discharge, to obtain:

$$Q_* = \frac{Q}{\sqrt{gS_o b_o^5}} = \frac{y_o}{b_o} \frac{\sqrt{2}}{\sqrt{mC_f}} \tag{7}$$

where Q_* is a dimensionless discharge parameter. If C_f is a constant, then Q_* will be a linear function of y_o/b_o.

Experimental results on Design 3 are shown plotted with Q_* against y_o/b_o for a number of scales and slopes in Fig. 23(a). Tangent slopes, rather than sine slopes, were used for convenience in these calculations. All the experimental results were correlated by this simple analysis; a linear relation appears to exist between Q_* and y_o/b_o indicating that C_f is approximately constant. This can be seen in Fig. 24, where values of C_f are plotted against y_o/b_o, especially for y_o/b_o greater than about 5.

The equation:

$$Q_* = A(\frac{y_o}{b_o}) + D \tag{8}$$

was fitted to the data using linear regression to find the slope of the line, A, and the intercept, D. Table 3 lists these values, as well as the correlation coefficients, for the various designs. As can be seen in Fig. 23(b), the slopes of the lines describing Designs 1 and 2 are greater than that for Design 3. This means that these designs require more discharge to obtain a given depth of flow. The line describing Design 4 has a much greater slope than any of the others. The slope of the lines for Designs 5 and 7 are similar to that of Design 3. For Design 6, for smaller values of y_o/b_o, the experimental results fall on the line describing Design 1, whereas for y_o/b_o greater than about 10, they are close to the line for Design 3, indicating a shift in the path of the jet in the pool.

The rating curves must obviously pass through the origin because there can be no depth of flow without discharge. These best fit curves do not pass through the origin but have negative y-intercepts except for Design 4, assuming that the curves are linear throughout. For y_o/b_o < 2, the linear relationship breaks down because bed friction, which was neglected in the derivation, becomes more significant as the depth to width ratio decreases. This is of no consequence; the fishway will not function properly at these depths. The minimum functional depth in a fishway, according to Decker (1967) and Clay (1961) is 0.6 m, which makes $y_o/b_o \simeq 2$.

The baffle configuration of Design 7 was similar to that of the standard Denil type fishway studied by Katopodis and Rajaratnam (1983) in that it had a centerline slot. The Denil fishway had a pool width to slot width ratio, B/b_o = 1.58 while Design 7 had a B/b_o = 8.0. As well, the Denil had a baffle spacing to slot width ratio of a/b_o = 0.72 while Design 7 had a/b_o = 10. These differences in geometry make the rating curves drastically different (Fig. 23(b)). The Denil rating curve is exponential (Katopodis) while Design 7 has a linear rating curve. A linear rating curve has the advantage that large depths can be used without using extremely large discharges and slot velocities.

This simple analysis has helped in developing a dimensionless calibration or rating curve for predicting the discharge characteristics of the vertical slot fishway. Of the seven designs tested, Design 4 gave the the highest flow rate for a given value of y_o/b_o with the same bed slope while Design 3 gave the lowest. All the designs had linear rating curves for uniform flow conditions.

4.2 Non-uniform Flow

Often, the depth of flow through the fishway is not uniform; it varies gradually. These gradually varied flow profiles can be analysed using the Bakhmeteff-Chow gradually varied flow theory (Chow 1959). According to this theory, the function:

$$x = \frac{y_o}{S_o} G \left[\eta, N, M, \frac{y_c}{y_o}\right] \tag{9}$$

can be written, where x is the longitudinal distance along the bed (from some origin), y_o is the normal (or uniform) flow depth, S_o is the bed slope, G is the Bakhmeteff-Chow varied flow function, $\eta = y/y_o$ with y being the depth at any x, N and M are respectively the hydraulic exponents for uniform and critical flow, and y_c is the critical depth.

The hydraulic exponent for uniform flow, N, can be defined as:

$$\frac{Q^2}{S_o} = C y_o^N \tag{10}$$

The hydraulic exponent for critical flow, M, may be defined as:

$$\frac{Q^2}{g} = Cy_c^M \tag{11}$$

For a rectangular channel, such as a slot, Chow (1959) states that M = 3 for all depths of flow, therefore it can be eliminated as a variable from the function in equation 9. As well, because M = 3, y_c/y_o may be replaced by the Froude number F_o:

$$F_o^2 = (\frac{y_c}{y_o})^3 \tag{12}$$

Also, the term y_o/S_o can be expressed as L_o. This reduces the function to:

$$\frac{\bar{x}}{L_o} = G\ [\eta,\ N,\ F_o] \tag{13}$$

The experimental results were plotted with y/y_o versus $\bar{x}/L_o$ where $\bar{x}$ is the horizontal distance measured downstream from the section where the (vertical) depth y is equal to 1.05 y_o for M1 curves and 0.95 y_o for M2 curves, and L_o is y_o/S_o. Even for the largest slope of 15%, the difference between longitudinal and horizontal distances was less than 2%; horizontal distances were used for convenience. From

Fig. 25 it can be seen that the results are well described by two curves, one for M1 profiles and one for M2 profiles. This shows that the relative distance $\bar{x}/L_o$ is a strong function of the relative depth y/y_o, at least for this specific geometry. The variation of $\bar{x}/L_o$ with N and F_o is lost in the scatter of the experimental results, therefore they are assumed to much less important than y/y_o in determining the shape of the profile, at least for the range of N and F_o studied. The values of N and F_o did not vary greatly for these experiments. Table 2 shows that N ranged from 2.035 to 2.176 and F_o ranged from 0.198 to 0.518.

4.3 Submergence of Fishway Entrance

Even though fish may pass through the fishway during uniform flow conditions, they may be blocked from entering the fishway if an M2 profile occurs in the fishway. To show what occurs in this situation, values of y_u/y_c were plotted against y_d/y_c in Fig. 26(a), where the critical depth in the slot, y_c, is defined by:

$$y_c^3 = \frac{Q^2}{gb_o^2} \tag{14}$$

This collapses the data from various discharges onto the same curve. Fig. 26(b) shows all the results from the experiments done on Designs 1 and 3. Each design appears to have a separate curve, with each curve varying slightly with slope. For values of y_d/y_c less than about 0.5, y_u/y_c is independant of y_d/y_c in both designs. As the tailwater level rises above this point, the pool depth increases and the head drop across the slot decreases.

4.4 Velocity Profiles in the Slots

The maximum velocity in each slot, u_m, was equal to the velocity of the lower uniform zone of that slot (Fig. 10). Bernoulli's equation:

$$\frac{p_1}{\gamma} + h_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + h_2 + \frac{V_2^2}{2g} + \text{losses} \qquad (15)$$

is used to approximate the slot velocity, V_2, where p is the pressure and h is the height above a datum. On the water surface, the pressures, p_1 and p_2 upstream and downstream of the slot, are zero and the losses are assumed to be negligible. Making h_1-h_2 equal to Δh, equation 15 reduces to:

$$V_2 = \sqrt{2g\Delta h + V_1^2} \qquad (16)$$

If the upstream velocity is small and V_2 is taken as u_m then equation 16 can be approximated as:

$$u_m = \sqrt{2g\Delta h} \tag{17}$$

Fig. 27 shows u_m plotted against Δh. The values for u_m fall slightly below the curve described by the equation 17, probably because the incoming velocity, V_1, is not negligible. Equation 17 gives a good upper bound for u_m and may be used to approximate slot velocities from Δh's.

4.5 Circulation in Pools

The flow in the fishway can be described as a confined three-dimensional turbulent jet. When the water flows through the slot, the surface dips as the jet plunges into the pool (Fig. 15). It is underneath this dip that the maximum velocities in the pool occur (Fig. 21). After this point, the maximum velocity of the jet decreases as it flows through the pool and the jet spreads (Fig. 28). The jet seems to spread more on the surface than on the bottom, at least for the more detailed measurements in Design 1 (Fig. 19). The water in the pool is entrained by the jet as it enters the pool, but because the same discharge leaves the pool as enters it (steady flow), the excess discharge entrained by the jet is turned back into the pool as the jet enters the downstream slot. This sets up one or two eddies in the pool depending on whether the jet flows along a wall or through the middle of the pool (Fig. 22). Figure 16 shows this circulation in detail for Design 1. This backflow is much slower than the flow in the main jet (Fig. 19). Energy is dissipated due to the turbulent mixing between the jet and these eddies. This is only a qualitative analysis, more detailed velocity measurements must be made to perform a quantitative analysis of this complex three-dimensional flow.

4.6 Energy Dissipation

To get a measure of the rate of energy dissipation, κ, in each pool, the equation:

$$\kappa = \frac{Q\gamma\Delta h}{BLy_o} \tag{18}$$

was used, where Q is the discharge, Δh is the head drop into the pool under consideration, y_o is the average pool depth and B and L are the pool width and length respectively. In this equation, it is assumed that the energy is completely dissipated in the pool and there is no carry-over into the next pool. For uniform flow conditions, the energy dissipation rate per unit volume, κ should be relatively constant for similar slopes. Table 1 shows that this is the case. The value of κ gives some indication of how turbulent the flow is in a pool. A high value for κ would suggest that the flow is very turbulent. No quantitative turbulence measurements have been made yet, so a definite relationship has not been established. Bell (1973) suggests that the maximum allowable energy dissipation rate be 0.191 kW/m^3 (4 $ftlb/s\text{-}ft^3$). For uniform flow, Designs 1, 2, and 4 exceeded this rate at a 10% slope. Design 4 had rates lower than this allowable rate at a slope of 5.6% while Design 3 exceeded it at a slope of 15.2% (Table 1). The energy dissipation rates for some non-uniform cases are given in Table 4. They range from 0.007 kW/m^3 for small drops in head to 1.32 kW/m^3 for large drops in head. Equation 18 may be used to find a minimum pool volume for a certain head drop, so as not to exceed a maximum level of turbulence.

4.7 Discharge Coefficient

Andrew and Clay (1961) have defined a discharge coefficient, C_d, for the slot with the equation:

$$Q = C_d(b_o\bar{y})\sqrt{2g\Delta h} \qquad (19)$$

where $\bar{y}$ is the depth of flow on the upstream side of the slot (Fig. 29). Discharge coefficients were calculated for various discharges and tailwater levels for Designs 1, 2, and 3. Tables 5, 6, and 7 list the data used to calculate these discharge coefficients. The average values of C_d for Designs 1, 2, and 3 were 0.71, 0.64, and 0.57 respectively. The values of C_d tended to be lower for situations with high Δh and low depth.

Discharge coefficients were calculated for the uniform flow data as well (Table 1). Figure 30 shows C_d plotted against y_o/b_o. All the different designs showed an increase in C_d with an increase in y_o/b_o. The two designs tested at high values of y_o/b_o, Designs 3 and 7, showed a trend toward a constant C_d of about 0.60 as y_o/b_o increased. Designs 1 and 2 have C_d ranging from 0.6 to 0.8, Designs 3, 5, and 7 from 0.3 to 0.6, Design 4 from 1.05 to 1.35, and Design 6 from 0.55 to 0.7. For the Hell's Gate Design, Andrew obtained an average value of 0.76 for C_d. Equation 19 describes the flow through the slots rather than the flow through the pools. It is more general in that it will handle both uniform and non-uniform flow conditions but has the limitation that C_d varies with the depth and head drop. As well, it does not relate the depths and Δh's of the various pools to each other but only defines the flow though an individual slot.

5. Conclusions and Recommendations

5.1 Conclusions

It was felt that the present day knowledge of the hydraulics of vertical slot fishways was incomplete. This experimental study was undertaken to gain insight into the hydraulics of the conventional type vertical slot fishway and also to develop simpler designs for the baffles. Seven slot designs were tested, including more detailed studies of the Hell's Gate slot configuration. Depths, head drops, velocities, and flow patterns were recorded and analysed.

Based on these results, a conceptual idea of uniform and non-uniform flow states has been developed. For this idealized uniform flow state, using a simple analysis and the experimental results, a calibration or rating curve has been developed for each design in terms of the dimensionless flow rate, Q_*, and the relative depth of flow, y_o/b_o. It was found that each of these designs had a linear rating curve. For non-uniform flow, general M1 and M2 surface profiles have been developed using the Bakhmeteff-Chow method as a guide. As well, the submergence of the fishway entrance by the tailwater has been studied. It was found that when the tailwater was below half of the critical depth in the slot, the pool depths were not affected by a change in the tailwater level.

The jets formed in the slots were also studied. The maximum velocity in a slot was found to vary directly with the square root of the head difference across that slot. This velocity was independant of depth and was essentially constant for all depths below the lower pool surface. The flow patterns in the pools consisted of a coherent jet issuing from the slot with lower velocity eddies taking up the remainder of the volume. Energy dissipation rates and discharge coefficients were calculated for various experiments. The energy dissipation rates per unit volume were higher for pools with high head drops and low tailwater levels. The energy dissipation rate per unit volume is an indication of the level of turbulence in a pool. Discharge coefficients varied considerably from pool to pool depending on the depths and head differences.

5.2 Recommendations

A number of recommendations for further research on vertical slot fishways can be made. First of all, more detailed measurement of the flow structure for various baffle designs may be helpful in identifying the flow types which are more attractive to fish. As well, numerical analysis could be applied to the flow in the fishway to predict the best slot arrangement both in terms of energy dissipation and attractiveness to fish. Variations in length and width of the pool in terms of the slot width should also be studied. These studies are best done in a hydraulics laboratory.

Field studies are also necessary in evaluating the performance of fishways in passing various fish species. Biological studies as well as hydraulic studies should be carried out in the field. When biological studies are done, slot velocities and flow depths should be recorded as well. In this way the various biological and hydraulic data can be pieced together to give a more complete picture of vertical slot fishways.

Table 1. Uniform Flow Data - Vertical Slot Fishways

Expt.	Scale	Slope (tangent)	No. of Pools	Q (m^3/s)	y_0 (m)	Q_*	y_0/b_0	m	C_f	C_d	κ (kW/m^3)	F_0
105B0.33u	1:5.33	0.100	4	0.328	0.58	6.48	1.90	2	0.136	0.602	0.227	0.777
105B0.66u	1:5.33	0.100	4	0.656	1.21	12.97	3.97	2	0.118	0.646	0.218	0.516
105B1.20u	1:5.33	0.100	4	1.20	1.95	23.58	6.39	2	0.085	0.766	0.247	0.461
105B1.67u	1:5.33	0.100	4	1.67	2.75	32.82	9.02	2	0.084	0.772	0.244	0.383
205B0.33u	1:5.33	0.100	4	0.328	0.75	6.45	2.56	2	0.145	0.586	0.176	0.529
205B0.66u	1:5.33	0.100	4	0.656	1.40	12.89	4.59	2	0.127	0.628	0.188	0.415
205B1.20u	1:5.33	0.100	4	1.20	2.25	23.58	7.38	2	0.098	0.715	0.214	0.372
205B1.67u	1:5.33	0.100	4	1.67	2.9	32.82	9.51	2	0.084	0.772	0.232	0.354
305B0.33u	1:5.33	0.100	4	0.328	0.75	6.48	2.46	1	0.414	0.488	0.176	0.529
305B0.66u	1:5.33	0.100	4	0.656	1.49	12.97	4.48	1	0.344	0.536	0.177	0.378
305B1.20u	1:5.33	0.100	4	1.20	2.51	23.58	8.23	1	0.274	0.605	0.192	0.316
305B1.41u	1:5.33	0.100	4	1.41	2.84	27.71	9.31	1	0.250	0.632	0.200	0.308
308A0.27u	1:8	0.056	9	0.27	0.803	7.12	2.63	1	0.273	0.507	0.076	0.393
308A0.54u	1:8	0.056	9	0.54	1.63	14.23	5.33	1	0.281	0.543	0.075	0.272
308A0.82u	1:8	0.056	9	0.82	2.39	21.34	7.83	1	0.269	0.578	0.077	0.232
308A1.09u	1:8	0.056	9	1.09	3.16	28.46	10.37	1	0.266	0.590	0.078	0.203
308A1.36u	1:8	0.056	9	1.36	3.84	35.58	12.60	1	0.251	0.610	0.080	0.189
308B0.33u	1.00	0.100	9	0.33	0.71	6.40	2.33	1	0.265	0.514	0.187	0.577
308B0.65u	1.00	0.100	9	0.65	1.44	12.81	4.73	1	0.273	0.548	0.182	0.394
308B0.89u	1.00	0.100	9	0.89	1.93	17.43	6.33	1	0.264	0.573	0.185	0.347
308B1.20u	1.00	0.100	9	1.20	2.58	23.48	8.47	1	0.260	0.584	0.187	0.303
308B1.41u	1.00	0.100	9	1.41	3.02	27.75	9.90	1	0.255	0.596	0.188	0.281
308B1.67u	1.00	0.100	9	1.67	3.49	32.73	11.43	1	0.244	0.615	0.192	0.268

Expt.	Scale	Slope (tangent)	No. of Pools	Q (m^3/s)	y_0 (m)	Q_*	y_0/b_0	m	C_f	C_d	κ (kW/m^3)	F_0
316A0.20u	1:16	0.051	18	0.20	0.925	5.62	3.03	1	0.581	0.349	0.044	0.235
316A0.51u	1:16	0.051	18	0.51	1.90	14.06	6.23	1	0.393	0.467	0.055	0.204
316A1.02u	1:16	0.051	18	1.02	3.51	28.12	11.50	1	0.334	0.523	0.060	0.162
316A1.54u	1:16	0.051	18	1.54	4.99	42.19	16.37	1	0.301	0.562	0.063	0.134
316A2.05u	1:16	0.051	18	2.05	6.35	56.25	20.83	1	0.274	0.592	0.066	0.134
316A2.56u	1:16	0.051	18	2.56	7.68	70.31	25.17	1	0.256	0.600	0.068	0.126
315C0.20u	1:16	0.069	18	0.20	0.78	4.85	2.57	1	0.562	0.347	0.071	0.304
316C0.51u	1:16	0.069	18	0.51	1.66	12.12	5.43	1	0.401	0.455	0.085	0.250
316C1.02u	1:16	0.069	18	1.02	3.05	24.24	10.00	1	0.340	0.514	0.093	0.200
315C1.54u	1:16	0.069	18	1.54	4.32	36.37	14.17	1	0.304	0.556	0.099	0.180
316C2.04u	1:16	0.069	18	2.04	5.48	48.25	17.97	1	0.277	0.586	0.103	0.166
316C2.54u	1:16	0.069	18	2.54	6.74	60.12	22.10	1	0.270	0.595	0.104	0.152
316C3.07u	1:16	0.069	18	3.07	7.86	72.68	25.77	1	0.251	0.618	0.108	0.146
316B0.33u	1:16	0.100	10	0.33	0.84	6.48	2.75	1	0.360	0.447	0.156	0.449
*316B0.51u	1:16	0.100	10	0.51	1.27	10.02	4.16	1	0.345	0.481	0.162	0.373
316B0.66u	1:16	0.100	10	0.66	1.58	12.97	5.17	1	0.318	0.511	0.168	0.348
316B1.20u	1:16	0.100	10	1.20	2.75	23.58	9.01	1	0.292	0.555	0.175	0.275
316B1.41u	1:16	0.100	10	1.41	3.15	27.71	10.32	1	0.277	0.573	0.180	0.264
*316B1.54u	1:16	0.100	10	1.54	3.49	30.26	11.43	1	0.285	0.567	0.177	0.247
*316B2.56u	1:16	0.100	10	2.56	5.55	50.31	18.19	1	0.261	0.602	0.185	0.205
316B3.58u	1:16	0.100	10	3.58	7.45	70.36	24.42	1	0.241	0.631	0.193	0.184
316B0.20u	1:16	0.100	18	0.20	0.70	4.025	2.30	1	0.653	0.315	0.115	0.357
*316B0.51u	1:16	0.100	18	0.51	1.29	10.02	4.23	1	0.356	0.475	0.159	0.364
316B1.02u	1:16	0.100	18	1.02	2.43	20.04	7.97	1	0.316	0.530	0.169	0.282
*316B1.54u	1:16	0.100	18	1.54	3.51	30.26	11.51	1	0.289	0.564	0.176	0.245
316B2.05u	1:16	0.100	18	2.05	4.52	40.25	14.83	1	0.272	0.588	0.182	0.223
*316B2.56u	1:16	0.100	18	2.56	5.67	50.31	18.59	1	0.273	0.590	0.182	0.198
316B3.07u	1:16	0.100	18	3.07	6.52	60.37	21.37	1	0.251	0.617	0.189	0.193
316B3.48u	1:16	0.100	18	3.48	7.37	68.42	24.16	1	0.249	0.620	0.190	0.182

Expt.	Scale	Slope (tangent)	No. of Pools	Q (m^3/s)	y_0 (m)	Q_*	y_0/b_0	m	C_f	C_d	κ (kW/m^3)	F_0
316D0.51u	1:16	0.152	18	0.51	1.02	8.18	3.35	1	0.335	0.474	0.306	0.518
316D1.02u	1:16	0.152	18	1.02	1.98	16.37	6.48	1	0.313	0.521	0.315	0.383
316D1.54u	1:16	0.152	18	1.54	2.95	24.71	9.68	1	0.307	0.540	0.319	0.318
316D2.56u	1:16	0.152	18	2.56	4.74	41.08	15.55	1	0.287	0.569	0.330	0.260
316D3.58u	1:16	0.152	18	3.58	6.45	57.44	21.15	1	0.271	0.590	0.339	0.229
408A.054u	1:8	0.056	9	0.54	0.68	14.23	2.23	1	0.049	1.165	0.179	1.008
408A0.82u	1:8	0.056	9	0.82	1.03	21.34	3.37	1	0.050	1.245	0.179	0.821
408A1.09u	1:8	0.056	9	1.09	1.38	28.46	4.53	1	0.051	1.276	0.178	0.704
408A1.36u	1:8	0.056	9	1.36	1.73	35.58	5.67	1	0.051	1.296	0.177	0.626
408A1.81u	1:8	0.056	9	1.81	2.28	47.43	7.47	1	0.050	1.334	0.179	0.550
408A2.39u	1:8	0.056	9	2.39	3.29	62.61	10.80	1	0.060	1.244	0.164	0.419
408B0.54u	1:8	0.100	9	0.54	0.54	10.67	1.77	1	0.055	1.049	0.402	1.425
408B0.82u	1:8	0.100	9	0.82	0.84	16.01	2.77	1	0.060	1.110	0.392	1.115
408B1.09u	1:8	0.100	9	1.09	1.16	21.34	3.80	1	0.063	1.115	0.378	0.913
408B1.36u	1:8	0.100	9	1.36	1.44	26.68	4.73	1	0.063	1.146	0.380	0.824
408B1.81u	1:8	0.100	9	1.81	1.89	35.58	6.20	1	0.061	1.189	0.385	0.729
408B2.35u	1:8	0.100	9	2.35	2.41	46.25	7.90	1	0.058	1.230	0.392	0.658
508A0.27u	1:8	0.057	9	0.27	0.85	7.07	2.80	1	0.314	0.483	0.073	0.363
508A0.54u	1:8	0.057	9	0.54	1.67	14.14	5.47	1	0.299	0.527	0.074	0.262
508A0.90u	1:8	0.057	9	0.90	2.67	23.56	8.77	1	0.277	0.567	0.077	0.216
508A1.36u	1:8	0.057	9	1.36	4.05	35.34	13.27	1	0.282	0.575	0.077	0.175
508Bo.27u	1:8	0.100	9	0.27	0.66	5.34	2.17	1	0.330	0.293	0.164	0.527
508B0.54u	1:8	0.100	9	0.54	1.31	10.67	4.30	1	0.325	0.496	0.166	0.377
508B0.82u	1:8	0.100	9	0.82	1.88	16.01	6.17	1	0.297	0.541	0.175	0.333
508B1.09u	1:8	0.100	9	1.09	2.51	21.34	8.23	1	0.297	0.549	0.175	0.287
508B1.36u	1:8	0.100	9	1.36	3.17	26.68	10.40	1	0.304	0.549	0.172	0.252
508B1.63u	1:8	0.100	9	1.63	3.74	32.02	12.27	1	0.294	0.562	0.175	0.236

Expt.	Scale	Slope (tangent)	No. of Pools	Q (m^3/s)	y_0 (m)	Q_*	y_0/b_0	m	C_f	C_d	κ (kW/m^3)	F_0
608A0.27u	1:8	0.057	9	0.27	0.661	7.07	2.17	2	0.094	0.591	0.094	0.526
608A0.54u	1:8	0.057	9	0.54	1.34	14.14	4.40	2	0.097	0.643	0.092	0.364
608A0.82u	1:8	0.057	9	0.82	1.96	21.20	6.43	2	0.092	0.690	0.096	0.313
608A0.90u	1:8	0.057	9	0.90	2.30	23.56	7.53	2	0.102	0.652	0.090	0.270
608A0.90u	1:8	0.057	9	0.90	2.76	23.56	9.03	2	0.147	0.599	0.075	0.205
608A1.00u	1:8	0.057	9	1.00	3.04	25.92	9.97	2	0.148	0.557	0.075	0.197
608A1.09u	1:8	0.057	9	1.09	3.31	28.27	10.87	2	0.148	0.559	0.076	0.189
608A1.36u	1:8	0.057	9	1.36	4.13	35.34	13.53	2	0.147	0.564	0.076	0.170
608B0.54u	1:8	0.100	9	0.54	1.08	10.67	3.53	2	0.109	0.588	0.201	0.504
608B0.81u	1:8	0.100	9	0.81	1.50	16.01	4.93	2	0.095	0.658	0.217	0.462
608B1.09u	1:8	0.100	9	1.09	2.54	21.34	8.33	2	0.152	0.543	0.172	0.282
608B1.36u	1:8	0.100	9	1.36	3.19	26.68	10.47	2	0.154	0.546	0.171	0.250
608B1.63u	1:8	0.100	9	1.63	3.76	32.02	12.33	2	0.148	0.559	0.174	0.234
716A0.51u	1.16	0.054	10	0.51	1.87	13.69	6.13	2	0.200	0.460	0.059	0.209
716A1.02u	1.16	0.054	10	1.02	3.17	27.38	10.40	2	0.144	0.560	0.070	0.189
716A1.54u	1.16	0.054	10	1.54	4.43	41.08	14.53	2	0.125	0.613	0.076	0.173
716A2.05u	1.16	0.054	10	2.05	6.14	54.77	20.13	2	0.135	0.599	0.072	0.141
716A2.56u	1.16	0.054	10	2.56	7.40	68.46	24.27	2	0.126	0.618	0.075	0.133
716B0.51u	1.16	0.100	10	0.51	1.38	10.06	4.53	2	0.203	0.447	0.149	0.329
716B1.02u	1.16	0.100	10	1.02	2.60	20.12	8.53	2	0.180	0.478	0.158	0.255
715B2.05u	1.16	0.100	10	2.05	4.33	40.29	14.20	2	0.124	0.613	0.190	0.238
716B3.07u*	1.16	0.100	10	3.07	6.91	60.33	22.67	2	0.141	0.583	0.179	0.177

Note: Uniform flow could not be clearly established with only four pools in Expt.'s 105, 205 and 305. Values for y_0 are estimates.

* Redundant Code - only difference is in number of pools.

TABLE 2: EXPERIMENTAL RESULTS FOR NON-UNIFORM FLOW - 10 pools

EXP.: 316B1.41NO.33 Q=1.41 cu.m/s Yo=3.30 m Yt/Yo=0.33 So=0.10 Fo=0.246 N=2.059

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.35	0.35	0.39	0.37	0.39	0.43	0.49	0.53	0.67
y (m)	3.12	3.12	3.08	3.04	2.96	2.90	2.82	2.69	2.51	2.29	1.92
y/yo	0.99	0.99	0.98	0.97	0.94	0.92	0.89	0.86	0.80	0.73	0.61
x̄/Lo	-0.33	-0.24	-0.15	-0.06	0.04	0.13	0.22	0.31	0.41	0.50	0.59

EXP.: 316B1.41NO.53 Q=1.41 cu.m/s Yo=3.30 m Yt/Yo= 0.53 So=0.10 Fo=0.246 N=2.059

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.33	0.35	0.37	0.37	0.39	0.39	0.45	0.45	0.57
y (m)	3.12	3.12	3.10	3.06	3.00	2.94	2.86	2.78	2.63	2.49	2.23
y/yo	0.99	0.99	0.99	0.97	0.95	0.93	0.91	0.88	0.84	0.79	0.71
x̄/Lo	-0.38	-0.29	-0.20	-0.11	-0.01	0.08	0.17	0.26	0.36	0.45	0.54

EXP.: 316B1.41NO.82 Q=1.41 cu.m/s Yo=3.30 m Yt/Yo= 0.82 So=0.10 Fo=0.246 N=2.059

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.31	0.35	0.35	0.33	0.33	0.35	0.35	0.39	0.35
y (m)	3.18	3.18	3.18	3.14	3.10	3.08	3.06	3.02	2.98	2.90	2.86
y/yo	1.01	1.01	1.01	1.00	0.99	0.98	0.97	0.96	0.95	0.92	0.91
x̄/Lo	-0.71	-0.62	-0.53	-0.44	-0.34	-0.25	-0.16	-0.07	0.03	0.12	0.21

EXP.: 316B1.20NO.34 Q=1.20 cu.m/s Yo=2.90 m Yt/Yo= 0.34 So=0.10 Fo=0.254 N=2.067

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.37	0.31	0.47	0.26	0.39	0.41	0.43	0.51	0.63
y (m)	2.71	2.71	2.65	2.65	2.49	2.53	2.45	2.35	2.23	2.02	1.70
y/yo	0.99	0.99	0.97	0.97	0.91	0.92	0.89	0.85	0.81	0.74	0.62
x̄/Lo	-0.34	-0.24	-0.13	-0.03	0.08	0.18	0.29	0.39	0.50	0.60	0.71

EXP.: 316B1.20NO.56 Q=1.20 cu.m/s Yo=2.90 m Yt/Yo= 0.56 So=0.10 Fo=0.254 N=2.067

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.35	0.31	0.39	0.33	0.39	0.39	0.39	0.47	0.51
y (m)	2.71	2.71	2.67	2.67	2.59	2.57	2.49	2.41	2.33	2.17	1.96
y/yo	0.99	0.99	0.97	0.97	0.94	0.94	0.91	0.88	0.85	0.79	0.71
x̄/Lo	-0.40	-0.29	-0.19	-0.08	0.02	0.13	0.23	0.34	0.44	0.55	0.65

EXP.: 316B1.20NO.84 Q=1.20 cu.m/s Yo=2.90 m Yt/Yo= 0.84 So=0.10 Fo=0.254 N=2.067

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.28	0.33	0.31	0.35	0.31	0.35	0.31	0.35	0.33	0.35
y (m)	2.76	2.78	2.76	2.76	2.71	2.71	2.67	2.67	2.63	2.61	2.57
y/yo	1.00	1.01	1.00	1.00	0.99	0.99	0.97	0.97	0.96	0.95	0.94
x̄/Lo	-0.95	-0.85	-0.74	-0.64	-0.53	-0.43	-0.32	-0.22	-0.11	-0.01	0.10

TABLE 2: EXPERIMENTAL RESULTS FOR NON-UNIFORM FLOW - 10 pools

EXP.: 316B1.20N0.93 Q=1.20 cu.m/s Yo=2.90 m Yt/Yo= 0.93 So=0.10 Fo=0.254 N=2.067

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.26	0.33	0.31	0.35	0.28	0.31	0.31	0.31	0.31	0.28
y (m)	2.76	2.80	2.78	2.78	2.73	2.76	2.76	2.76	2.76	2.76	2.78
y/yo	1.00	1.02	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.01
x̄/Lo	-1.06	-0.95	-0.85	-0.74	-0.64	-0.53	-0.43	-0.32	-0.22	-0.11	-0.01

EXP.: 316B0.66N0.31 Q=0.66 cu.m/s Yo=1.73 m Yt/Yo= 0.31 So=0.10 Fo=0.304 N=2.108

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.31	0.33	0.33	0.33	0.35	0.35	0.37	[illegible]	0.45
y (m)	1.58	1.58	1.58	1.56	1.54	1.51	1.47	1.43	1.37	[illegible]	1.07
y/yo	1.00	1.00	1.00	0.99	0.97	0.96	0.93	0.91	0.87	0.77	0.68
x̄/Lo	-0.95	-0.78	-0.60	-0.42	-0.25	-0.07	0.11	0.28	0.46	0.63	0.81

EXP.: 316B0.66N0.88 Q=0.66 cu.m/s Yo=1.73 m Yt/Yo= 0.88 So=0.10 Fo=0.304 N=2.108

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.28	0.31	0.31	0.33	0.28	0.31	0.31	0.31	0.31	0.26
y (m)	1.56	1.58	1.58	1.58	1.56	1.58	1.58	1.58	1.58	1.58	1.62
y/yo	0.99	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.02
x̄/Lo	-1.76	-1.58	-1.41	-1.23	-1.05	-0.88	-0.70	-0.52	-0.35	-0.17	0.00

EXP.: 316B0.66N1.69 Q=0.66 cu.m/s Yo=1.73 m Yt/Yo= 1.69 So=0.10 Fo=0.304 N=2.108

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.24	0.28	0.22	0.24	0.18	0.18	0.16	0.12	0.12	0.08
y (m)	1.66	1.72	1.74	1.82	1.88	2.00	2.12	2.27	2.45	2.63	2.86
y/yo	1.05	1.09	1.10	1.15	1.19	1.27	1.35	1.44	1.55	1.67	1.81
x̄/Lo	0.00	0.18	0.35	0.53	0.71	0.88	1.06	1.24	1.41	1.59	1.77

EXP.: 316B0.33N1.17 Q=0.33 cu.m/s Yo=1.00 m Yt/Yo= 1.17 So=0.10 Fo=0.345 N=2.176

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.33	0.28	0.31	0.31	0.28	0.28	0.24	0.22	0.16
y (m)	0.84	0.84	0.82	0.84	0.84	0.84	0.86	0.88	0.95	1.03	1.17
y/yo	1.00	1.00	0.97	1.00	1.00	1.00	1.02	1.04	1.12	1.21	1.38
x̄/Lo	-2.16	-1.86	-1.55	-1.25	-0.94	-0.64	-0.33	-0.03	0.28	0.58	0.89

EXP.: 316B0.33N2.03 Q=0.33 cu.m/s Yo=1.00 m Yt/Yo= 2.03 So=0.10 Fo=0.345 N=2.176

Pool:	0	1	2	3	4	5	6	7	8	9	10
Δh (m)		0.31	0.28	0.26	0.26	0.20	0.22	0.14	0.12	0.08	0.06
y (m)	0.84	0.84	0.86	0.90	0.95	1.05	1.13	1.29	1.47	1.70	1.94
y/yo	1.00	1.00	1.02	1.07	1.12	1.24	1.33	1.52	1.74	2.00	2.29
x̄/Lo	-0.80	-0.50	-0.19	0.11	0.42	0.72	1.03	1.33	1.64	1.94	2.25

TABLE 2: EXPERIMENTAL RESULTS FOR NON-UNIFORM FLOW - 18 pools

EXP.: 316B2.56N1.04 Q=2.56 cu.m/s Yo=5.68 m : Yt/Yo= 1.04 So=0.10 Fo=0.198 N=2.035

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.24	0.31	0.33	0.28	0.31	0.31	0.28	0.31	0.26	0.31	0.28	0.28	0.28	0.28	0.28	0.26	0.28	0.26
y (m)	5.62	5.68	5.68	5.66	5.68	5.68	5.68	5.70	5.70	5.74	5.74	5.76	5.78	5.81	5.83	5.85	5.89	5.91	5.95
y/yo	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.04	1.05
x̄/Lo	-0.99	-0.94	-0.89	-0.83	-0.78	-0.72	-0.67	-0.62	-0.56	-0.51	-0.46	-0.38	-0.32	-0.27	-0.21	-0.16	-0.11	-0.05	0.00

EXP.: 316B1.54N1.16 Q=1.54 cu.m/s Yo=3.51 m Yt/Yo= 1.16 So=0.10 Fo=0.245 N=2.056

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.28	0.28	0.33	0.31	0.28	0.31	0.26	0.28	0.26	0.28	0.26	0.31	0.24	0.24	0.26	0.24	0.22	0.18
y (m)	3.49	3.51	3.53	3.51	3.51	3.53	3.53	3.57	3.59	3.63	3.65	3.69	3.69	3.75	3.81	3.85	3.91	4.00	4.12
y/yo	0.99	1.00	1.01	1.00	1.00	1.01	1.01	1.02	1.02	1.03	1.04	1.05	1.05	1.07	1.09	1.10	1.12	1.14	1.17
x̄/Lo	-0.94	-0.85	-0.77	-0.68	-0.59	-0.51	-0.42	-0.33	-0.24	-0.16	-0.07	0.06	0.15	0.23	0.32	0.41	0.49	0.58	0.67

EXP.: 316B1.02N1.17 Q=1.02 cu.m/s Yo=2.43 m Yt/Yo= 1.17 So=0.10 Fo=0.282 N=2.079

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.26	0.31	0.31	0.31	0.31	0.33	0.28	0.28	0.26	0.28	0.28	0.31	0.26	0.28	0.24	0.26	0.22	0.22
y (m)	2.39	2.43	2.43	2.43	2.43	2.43	2.41	2.43	2.45	2.49	2.51	2.53	2.53	2.57	2.59	2.65	2.69	2.78	2.86
y/yo	0.98	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.01	1.03	1.03	1.04	1.04	1.06	1.07	1.09	1.11	1.14	1.18
x̄/Lo	-1.63	-1.50	-1.38	-1.25	-1.13	-1.00	-0.88	-0.75	-0.63	-0.50	-0.37	-0.19	-0.06	0.06	0.19	0.32	0.44	0.57	0.69

EXP.: 316B0.51N1.50 Q=0.51 cu.m/s Yo=1.29 m Yt/Yo= 1.50 So=0.10 Fo=0.364 N=2.141

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.26	0.31	0.31	0.31	0.31	0.33	0.28	0.31	0.28	0.28	0.31	0.31	0.24	0.26	0.22	0.20	0.18	0.14
y (m)	1.25	1.29	1.29	1.29	1.29	1.29	1.27	1.29	1.29	1.31	1.33	1.33	1.33	1.39	1.43	1.51	1.62	1.74	1.90
y/yo	0.97	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.02	1.03	1.03	1.03	1.08	1.11	1.17	1.25	1.35	1.47
x̄/Lo	-3.05	-2.81	-2.57	-2.34	-2.10	-1.86	-1.63	-1.39	-1.16	-0.92	-0.68	-0.33	-0.09	0.14	0.38	0.62	0.85	1.09	1.32

EXP.: 316B0.51N2.05 Q=0.51 cu.m/s Yo=1.29 m Yt/Yo= 2.05 So=0.10 Fo=0.364 N=2.141

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.26	0.31	0.31	0.31	0.28	0.33	0.28	0.26	0.28	0.24	0.24	0.26	0.18	0.18	0.14	0.12	0.10	0.06
y (m)	1.25	1.29	1.29	1.29	1.29	1.31	1.29	1.31	1.35	1.37	1.43	1.49	1.54	1.66	1.78	1.94	2.12	2.33	2.57
y/yo	0.97	1.00	1.00	1.00	1.00	1.02	1.00	1.02	1.05	1.06	1.11	1.16	1.19	1.28	1.38	1.50	1.65	1.80	1.99
x̄/Lo	-1.93	-1.69	-1.46	-1.22	-0.99	-0.75	-0.51	-0.28	-0.04	0.19	0.43	0.79	1.02	1.26	1.49	1.73	1.97	2.20	2.44

EXP.: 316D2.56N0.0 Q=2.56 cu.m/s Yo=4.74 m Yt/Yo= 0.0 So=0.15 Fo=0.260 N=2.042

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.33	0.42	0.50	0.46	0.50	0.50	0.46	0.56	0.44	0.50	0.52	0.56	0.56	0.62	0.64	0.74	0.82	1.07
y (m)	4.57	4.70	4.74	4.70	4.70	4.66	4.62	4.62	4.52	4.54	4.50	4.44	4.34	4.23	4.07	3.89	3.60	3.24	2.63
y/yo	0.96	0.99	1.00	0.99	0.99	0.98	0.97	0.97	0.95	0.96	0.95	0.94	0.91	0.89	0.86	0.82	0.76	0.68	0.55
x̄/Lo	-0.95	-0.85	-0.76	-0.66	-0.56	-0.47	-0.37	-0.27	-0.18	-0.08	0.02	0.16	0.26	0.35	0.45	0.55	0.64	0.74	0.84

TABLE 2: EXPERIMENTAL RESULTS FOR NON-UNIFORM FLOW - 18 pools

EXP.: 316D1.54N0.0 Q=1.54 cu.m/s Yo=2.95 m Yt/Yo= 0.0 So=0.15 Fo=0.318 N=2.066

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.35	0.38	0.50	0.46	0.52	0.44	0.46	0.50	0.42	0.48	0.48	0.50	0.52	0.52	0.56	0.62	0.68	0.88
y (m)	2.80	2.91	2.99	2.95	2.95	2.89	2.91	2.91	2.87	2.91	2.89	2.87	2.83	2.77	2.71	2.61	2.45	2.22	1.79
y/yo	0.95	0.99	1.01	1.00	1.00	0.98	0.99	0.99	0.97	0.99	0.98	0.97	0.96	0.94	0.92	0.88	0.83	0.75	0.61
x̄/Lo	-2.00	-1.85	-1.69	-1.54	-1.38	-1.23	-1.07	-0.92	-0.76	-0.61	-0.45	-0.22	-0.07	0.09	0.24	0.40	0.55	0.71	0.86

EXP.: 316D1.02N0.0 Q=1.02 cu.m/s Yo=1.98 m Yt/Yo= 0.0 So=0.15 Fo=0.383 N=2.095

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.37	0.40	0.48	0.50	0.46	0.48	0.44	0.48	0.44	0.44	0.48	0.50	0.48	0.48	0.50	0.56	0.60	0.72
y (m)	1.89	1.98	2.04	2.02	1.98	1.98	1.96	1.98	1.96	1.98	2.00	1.98	1.94	1.92	1.90	1.86	1.75	1.61	1.35
y/yo	0.95	1.00	1.03	1.02	1.00	1.00	0.99	1.00	0.99	1.00	1.01	1.00	0.98	0.97	0.96	0.94	0.89	0.81	0.68
x̄/Lo	-3.45	-3.22	-2.99	-2.76	-2.53	-2.30	-2.07	-1.83	-1.60	-1.37	-1.14	-0.79	-0.56	-0.33	-0.10	0.13	0.36	0.59	0.83

EXP.: 316D0.51N0.0 Q=0.51 cu.m/s Yo=1.02 m Yt/Yo= 0.0 So=0.15 Fo=0.518 N=2.173

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.43	0.40	0.46	0.48	0.48	0.46	0.44	0.48	0.44	0.46	0.46	0.48	0.48	0.44	0.48	0.48	0.50	0.58
y (m)	0.95	0.98	1.04	1.04	1.02	1.00	1.00	1.02	1.00	1.02	1.02	1.02	1.00	0.98	1.00	0.98	0.96	0.92	0.80
y/yo	0.93	0.96	1.02	1.02	1.00	0.98	0.98	1.00	0.98	1.00	1.00	1.00	0.98	0.96	0.98	0.96	0.94	0.90	0.78
x̄/Lo	-7.17	-6.72	-6.27	-5.83	-5.38	-4.93	-4.48	-4.04	-3.59	-3.14	-2.69	-2.02	-1.57	-1.12	-0.68	-0.23	0.22	0.67	1.11

EXP.: 316D2.56N1.02 Q=2.56 cu.m/s Yo=4.74 m Yt/Yo= 1.02 So=0.15 Fo=0.260 N=2.042

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.28	0.38	0.50	0.46	0.46	0.48	0.42	0.50	0.42	0.46	0.46	0.46	0.44	0.46	0.44	0.44	0.44	0.44
y (m)	4.53	4.70	4.78	4.74	4.74	4.74	4.72	4.76	4.72	4.76	4.76	4.76	4.76	4.78	4.78	4.80	4.82	4.84	4.86
y/yo	0.95	0.99	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.02	1.02	1.03
x̄/Lo	-1.78	-1.69	-1.59	-1.49	-1.40	-1.30	-1.20	-1.11	-1.01	-0.91	-0.82	-0.67	-0.58	-0.48	-0.38	-0.29	-0.19	-0.09	0.00

EXP.: 316D2.56N1.10 Q=2.56 cu.m/s Yo=4.74 m Yt/Yo= 1.10 So=0.15 Fo=0.260 N=2.042

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.26	0.40	0.48	0.46	0.46	0.46	0.44	0.46	0.44	0.42	0.44	0.44	0.42	0.44	0.38	0.42	0.38	0.36
y (m)	4.53	4.72	4.78	4.76	4.76	4.76	4.76	4.78	4.78	4.80	4.84	4.86	4.89	4.93	4.95	5.03	5.07	5.15	5.25
y/yo	0.95	1.00	1.01	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.02	1.03	1.03	1.04	1.04	1.06	1.07	1.09	1.11
x̄/Lo	-1.44	-1.34	-1.25	-1.15	-1.05	-0.96	-0.86	-0.76	-0.67	-0.57	-0.47	-0.33	-0.23	-0.14	-0.04	0.06	0.15	0.25	0.35

EXP.: 316D1.54N1.25 Q=1.54 cu.m/s Yo=2.95 m Yt/Yo= 1.25 So=0.15 Fo=0.318 N=2.066

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.35	0.40	0.50	0.44	0.50	0.42	0.46	0.46	0.46	0.38	0.42	0.44	0.46	0.38	0.40	0.34	0.34	0.27
y (m)	2.80	2.91	2.97	2.93	2.95	2.91	2.95	2.95	2.95	2.95	3.03	3.08	3.10	3.10	3.18	3.24	3.36	3.48	3.67
y/yo	0.95	0.99	1.01	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.03	1.04	1.05	1.05	1.08	1.10	1.14	1.18	1.24
x̄/Lo	-2.10	-1.95	-1.79	-1.64	-1.48	-1.33	-1.17	-1.02	-0.86	-0.71	-0.55	-0.32	-0.17	-0.01	0.14	0.30	0.45	0.61	0.76

TABLE 2: EXPERIMENTAL RESULTS FOR NON-UNIFORM FLOW - 18 pools

EXP.: 316D1.54N1.36 Q=1.54 cu.m/s Yo=2.95 m Yt/Yo= 1.36 So=0.15 Fo=0.318 N=2.066

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.35	0.38	0.50	0.44	0.52	0.40	0.46	0.46	0.44	0.38	0.46	0.40	0.42	0.34	0.36	0.29	0.27	0.25
y (m)	2.80	2.91	2.99	2.95	2.97	2.91	2.97	2.97	2.97	2.99	3.08	3.08	3.14	3.18	3.30	3.40	3.56	3.75	3.95
y/yo	0.95	0.99	1.01	1.00	1.01	0.99	1.01	1.01	1.01	1.01	1.04	1.04	1.06	1.08	1.12	1.15	1.21	1.27	1.34
x̄/Lo	-1.85	-1.69	-1.54	-1.38	-1.23	-1.07	-0.92	-0.76	-0.61	-0.45	-0.30	-0.07	0.09	0.24	0.40	0.55	0.71	0.86	1.02

EXP.: 316D1.02N1.10 Q=1.02 cu.m/s Yo=1.98 m Yt/Yo= 1.10 So=0.15 Fo=0.383 N=2.095

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.37	0.40	0.48	0.50	0.46	0.46	0.44	0.50	0.42	0.46	0.44	0.50	0.44	0.46	0.40	0.44	0.40	0.38
y (m)	1.87	1.96	2.02	2.00	1.96	1.96	1.96	1.98	1.94	1.98	1.98	2.00	1.96	1.98	1.98	2.04	2.06	2.12	2.20
y/yo	0.94	0.99	1.02	1.01	0.99	0.99	0.99	1.00	0.98	1.00	1.00	1.01	0.99	1.00	1.00	1.03	1.04	1.07	1.11
x̄/Lo	-3.88	-3.65	-3.42	-3.19	-2.96	-2.73	-2.50	-2.26	-2.03	-1.80	-1.57	-1.22	-0.99	-0.76	-0.53	-0.30	-0.07	0.16	0.40

EXP.: 316D1.02N1.58 Q=1.02 cu.m/s Yo=1.98 m Yt/Yo= 1.58 So=0.15 Fo=0.383 N=2.095

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.37	0.40	0.50	0.46	0.46	0.48	0.44	0.48	0.40	0.44	0.44	0.44	0.36	0.36	0.29	0.29	0.23	0.19
y (m)	1.87	1.96	2.02	1.98	1.98	1.98	1.96	1.98	1.96	2.02	2.04	2.06	2.08	2.18	2.28	2.45	2.61	2.83	3.10
y/yo	0.94	0.99	1.02	1.00	1.00	1.00	0.99	1.00	0.99	1.02	1.03	1.04	1.05	1.10	1.15	1.24	1.32	1.43	1.57
x̄/Lo	-2.86	-2.63	-2.40	-2.17	-1.93	-1.70	-1.47	-1.24	-1.01	-0.78	-0.55	-0.20	0.03	0.26	0.49	0.73	0.96	1.19	1.42

EXP.: 316D0.51N1.50 Q=0.51 cu.m/s Yo=1.04 m Yt/Yo= 1.50 So=0.15 Fo=0.503 N=2.171

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.43	0.40	0.46	0.48	0.46	0.48	0.44	0.48	0.44	0.44	0.46	0.48	0.44	0.46	0.40	0.38	0.34	0.25
y (m)	0.95	0.98	1.04	1.04	1.02	1.02	1.00	1.02	1.00	1.02	1.04	1.04	1.02	1.04	1.04	1.10	1.18	1.31	1.51
y/yo	0.91	0.94	1.00	1.00	0.98	0.98	0.96	0.98	0.96	0.98	1.00	1.00	0.98	1.00	1.00	1.06	1.14	1.25	1.45
x̄/Lo	-6.74	-6.30	-5.86	-5.42	-4.98	-4.55	-4.11	-3.67	-3.23	-2.79	-2.35	-1.69	-1.25	-0.81	-0.37	0.06	0.50	0.94	1.38

EXP.: 316D0.51N2.54 Q=0.51 cu.m/s Yo=1.04 m Yt/Yo= 2.54 So=0.15 Fo=0.503 N=2.171

Pool:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Δh (m)		0.43	0.40	0.46	0.48	0.46	0.48	0.44	0.48	0.44	0.44	0.42	0.44	0.36	0.32	0.25	0.19	0.13	0.11
y (m)	0.95	0.98	1.04	1.04	1.02	1.02	1.00	1.02	1.00	1.02	1.04	1.08	1.10	1.20	1.35	1.55	1.81	2.14	2.49
y/yo	0.91	0.94	1.00	1.00	0.98	0.98	0.96	0.98	0.96	0.98	1.00	1.04	1.06	1.16	1.29	1.49	1.74	2.05	2.39
x̄/Lo	-5.30	-4.86	-4.42	-3.98	-3.54	-3.10	-2.66	-2.22	-1.78	-1.34	-0.91	-0.25	0.19	0.63	1.07	1.51	1.95	2.39	2.83

TABLE 3: Rating Curve Constants for Various Designs

Design	Slope A	Intercept D	Correlation Coefficient
1	3.77	-1.11	0.998
2	3.75	-3.52	0.998
3	2.84	-1.62	0.998
4	5.85	+0.67	0.995
5	2.67	-0.52	0.999
6	----	-----	-----
7	2.91	-3.22	0.997

Table 4: Energy Dissipation Rates (kW/cu.m)

Experiment	Pool 1	Pool 2	Pool 3	Pool 4
105B1.67N0.00	0.423	0.552	0.649	1.021
105B1.67N0.44	0.378	0.490	0.557	0.786
105B1.67N0.62	0.364	0.442	0.459	0.583
105B1.67N0.92	0.283	0.306	0.309	0.331
105B1.20N0.00	0.356	0.395	0.515	0.778
105B1.20N0.43	0.331	0.364	0.451	0.645
105B1.20N0.76	0.301	0.325	0.366	0.412
105B1.20N1.14	0.221	0.232	0.219	0.196
105B1.20N1.37	0.177	0.163	0.152	0.138
105B0.66N0.00	0.253	0.296	0.333	0.474
105B0.66N0.39	0.264	0.283	0.327	0.414
105B0.66N1.20	0.207	0.183	0.167	0.134
105B0.66N2.23	0.065	0.047	0.039	0.025
105B0.33N0.00	0.203	0.257	0.257	0.289
105B0.33N1.97	0.172	0.151	0.094	0.058
105B0.33N3.40	0.054	0.026	0.014	0.011
205B1.67N0.05	0.546	0.744	0.929	1.322
205B1.67N0.42	0.561	0.730	0.843	1.107
205B1.67N0.58	0.509	0.658	0.681	0.860
205B1.67N0.87	0.440	0.495	0.525	0.504
205B1.20N0.04	0.350	0.462	0.559	0.841
205B1.20N0.37	0.341	0.470	0.525	0.834
205B1.20N0.66	0.327	0.446	0.462	0.564
205B1.20N0.99	0.267	0.305	0.303	0.302
205B1.20N1.18	0.207	0.214	0.201	0.182
205B0.66N0.03	0.185	0.235	0.246	0.332
205B0.66N0.34	0.182	0.234	0.234	0.332
205B0.66N1.04	0.153	0.156	0.157	0.142
205B0.66N1.93	0.051	0.049	0.041	0.036
205B0.33N0.05	0.105	0.134	0.129	0.168
205B0.33N1.52	0.093	0.093	0.064	0.044
205B0.33N2.63	0.029	0.019	0.012	0.007
305B1.41N0.36	0.480	0.478	0.673	0.898
305B1.41N0.60	0.458	0.407	0.584	0.659
305B1.41N0.93	0.370	0.251	0.378	0.340
305B1.20N0.36	0.345	0.374	0.501	0.644
305B1.20N0.62	0.303	0.357	0.387	0.469
305B1.20N0.94	0.253	0.229	0.282	0.226
305B1.20N1.05	0.232	0.183	0.247	0.175
305B0.66N0.32	0.171	0.204	0.240	0.297
305B0.66N0.97	0.141	0.148	0.146	0.131
305B0.66N1.91	0.053	0.047	0.037	0.024
305B0.33N1.45	0.083	0.075	0.066	0.037
305B0.33N2.65	0.029	0.022	0.013	0.007

Table 5: Experimental Results for Vertical Slot Fishway - Design 1

Experiment	Q (m^3/s)	Slot 1 $\bar{y}$ (m)	Slot 1 Δh (m)	Slot 1 C_d	Slot 2 $\bar{y}$ (m)	Slot 2 Δh (m)	Slot 2 C_d	Slot 3 $\bar{y}$ (m)	Slot 3 Δh (m)	Slot 3 C_d	Slot 4 $\bar{y}$ (m)	Slot 4 Δh (m)	Slot 4 C_d	Slot 5 $\bar{y}$ (m)	Slot 5 Δh (m)	Slot 5 C_d	y_t (m)
105B1.67N 0.00	1.67	2.52	0.437	0.742	2.47	0.533	0.685	2.31	0.571	0.707	2.13	0.732	0.678	1.76	1.761	0.530	-
0.44	1.67	2.69	0.419	0.710	2.61	0.510	0.664	2.48	0.540	0.677	2.32	0.660	0.682	2.04	0.993	0.609	1.21
0.62	1.67	2.73	0.415	0.704	2.71	0.483	0.657	2.59	0.478	0.691	2.48	0.562	0.665	2.32	0.725	0.626	1.69
0.92	1.67	2.91	0.353	0.716	2.94	0.379	0.684	2.89	0.377	0.697	2.86	0.400	0.682	2.85	0.432	0.659	2.53
105B1.20N 0.00	1.20	2.02	0.424	0.697	1.91	0.424	0.714	1.80	0.486	0.707	1.67	0.606	0.683	1.40	1.388	0.538	-
0.43	1.20	2.03	0.380	0.710	1.99	0.401	0.706	1.90	0.460	0.690	1.79	0.569	0.657	1.57	0.914	0.593	0.84
0.76	1.20	2.08	0.359	0.714	2.06	0.382	0.697	2.04	0.416	0.676	1.98	0.444	0.675	1.88	0.499	0.669	1.48
1.14	1.20	2.25	0.297	0.726	2.30	0.317	0.685	2.33	0.304	0.691	2.37	0.281	0.707	2.44	0.293	0.672	2.23
1.37	1.20	2.39	0.258	0.732	2.48	0.247	0.720	2.57	0.241	0.704	2.67	0.229	0.695	2.79	0.216	0.684	2.67
105B0.66N 0.00	0.656	1.29	0.327	0.659	1.27	0.364	0.633	1.22	0.384	0.643	1.16	0.463	0.617	1.00	0.914	0.510	-
0.39	0.656	1.29	0.341	0.644	1.28	0.354	0.637	1.23	0.382	0.638	1.17	0.429	0.634	1.05	0.677	0.560	0.47
1.20	0.656	1.36	0.293	0.659	1.38	0.268	0.680	1.42	0.254	0.681	1.48	0.218	0.705	1.56	0.206	0.685	1.45
2.23	0.656	1.88	0.140	0.689	2.01	0.112	0.724	2.26	0.104	0.668	2.50	0.075	0.709	2.74	0.075	0.646	2.70
105B0.33N 0.00	0.328	0.73	0.289	0.622	0.79	0.348	0.520	0.73	0.327	0.584	0.70	0.343	0.592	0.67	0.603	0.466	-
1.97	0.328	0.75	0.257	0.636	0.79	0.242	0.622	0.84	0.177	0.689	0.97	0.132	0.688	1.14	0.099	0.674	1.14
3.40	0.328	1.01	0.128	0.673	1.18	0.076	0.745	1.40	0.049	0.782	1.66	0.045	0.690	1.92	0.031	0.718	1.97

Table 6: Experimental Results for Vertical Slot Fishway - Design 2

Experiment	Q	Slot 1			Slot 2			Slot 3			Slot 4			Slot 5			y_t
	(m^3/s)	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	(m)
205B1.67N 0.05	1.67	2.66	0.416	0.721	2.62	0.533	0.645	2.48	0.601	0.643	2.25	0.714	0.650	1.91	1.863	0.474	0.13
0.42	1.67	2.71	0.434	0.694	2.67	0.530	0.637	2.50	0.562	0.659	2.32	0.642	0.666	2.03	1.179	0.562	1.21
0.58	1.67	2.74	0.405	0.708	2.71	0.496	0.647	2.57	0.483	0.693	2.45	0.559	0.676	2.26	0.806	0.608	1.69
0.87	1.67	2.87	0.371	0.707	2.88	0.411	0.670	2.83	0.426	0.668	2.77	0.402	0.704	2.73	0.491	0.646	2.53
205B1.20N 0.04	1.20	2.09	0.361	0.708	2.07	0.450	0.641	1.97	0.499	0.638	1.82	0.623	0.619	1.53	1.525	0.469	0.09
0.37	1.20	2.09	0.353	0.716	2.08	0.457	0.633	1.97	0.475	0.656	1.84	0.629	0.607	1.56	1.008	0.566	0.84
0.66	1.20	2.13	0.348	0.707	2.14	0.452	0.618	2.04	0.449	0.649	1.98	0.506	0.630	1.83	0.629	0.613	1.48
0.99	1.20	2.25	0.307	0.711	2.29	0.350	0.656	2.29	0.350	0.656	2.31	0.351	0.649	2.32	0.343	0.653	2.23
1.18	1.20	2.38	0.257	0.735	2.45	0.273	0.693	2.52	0.265	0.684	2.59	0.249	0.688	2.70	0.255	0.651	2.65
205B0.66N 0.03	0.656	1.28	0.312	0.679	1.30	0.380	0.604	1.25	0.377	0.632	1.19	0.445	0.614	1.06	1.119	0.432	0.04
0.34	0.656	1.28	0.307	0.686	1.30	0.377	0.609	1.24	0.362	0.650	1.20	0.450	0.602	1.07	0.851	0.491	0.47
1.04	0.656	1.37	0.284	0.665	1.42	0.299	0.627	1.46	0.307	0.601	1.48	0.284	0.618	1.50	0.286	0.605	1.45
1.93	0.656	1.83	0.141	0.708	2.00	0.148	0.632	2.18	0.135	0.606	2.37	0.130	0.570	2.56	0.104	0.588	2.70
205B0.33N 0.05	0.328	0.70	0.288	0.645	0.75	0.356	0.543	0.73	0.341	0.567	0.73	0.395	0.533	0.67	0.712	0.433	0.04
1.52	0.328	0.72	0.268	0.649	0.76	0.283	0.597	0.81	0.224	0.637	0.90	0.182	0.630	1.05	0.135	0.632	1.14
2.63	0.328	0.94	0.132	0.710	1.12	0.104	0.672	1.33	0.081	0.644	1.55	0.052	0.688	1.80	0.046	0.628	1.97

Table 7: Experimental Results for Vertical Slot Fishway - Design 3

Experiment	Q	Slot 1			Slot 2			Slot 3			Slot 4			Slot 5			y_t
	(m^3/s)	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	$\bar{y}$ (m)	Δh (m)	C_d	(m)
305B1.41N 0.36	1.41	2.78	0.444	0.563	2.65	0.423	0.605	2.54	0.540	0.558	2.32	0.619	0.572	2.01	1.157	0.482	1.01
0.60	1.41	2.81	0.431	0.566	2.69	0.374	0.634	2.63	0.497	0.563	2.45	0.512	0.595	2.25	0.693	0.557	1.69
0.93	1.41	2.99	0.380	0.566	2.93	0.263	0.696	2.98	0.385	0.565	2.91	0.343	0.613	2.88	0.328	0.634	2.63
305B1.20N 0.36	1.20	2.44	0.410	0.568	2.3[illegible]	0.423	0.582	2.24	0.512	0.555	2.04	0.569	0.578	1.78	0.948	0.511	0.91
0.62	1.20	2.47	0.372	0.589	2.42	0.418	0.569	2.31	0.429	0.587	2.20	0.478	0.585	2.03	0.579	0.574	1.55
0.94	1.20	2.59	0.332	0.595	2.57	0.302	0.628	2.59	0.364	0.570	2.54	0.294	0.646	2.56	0.309	0.625	2.36
1.05	1.20	2.66	0.315	0.595	2.66	0.254	0.663	2.72	0.340	0.560	2.69	0.247	0.664	2.76	0.252	0.641	2.63
305B0.66N 0.32	0.656	1.57	0.350	0.524	1.53	0.393	0.506	1.45	0.423	0.514	1.34	0.460	0.533	1.20	0.762	0.464	0.47
0.97	0.656	1.64	0.312	0.530	1.64	0.325	0.518	1.63	0.320	0.525	1.63	0.291	0.553	1.65	0.296	0.540	1.45
1.91	0.656	2.10	0.166	0.568	2.25	0.156	0.547	2.41	0.132	0.555	2.59	0.094	0.612	2.81	0.080	0.611	2.84
305B0.33N 1.45	0.328	0.90	0.296	0.499	0.91	0.281	0.501	0.95	0.262	0.500	1.00	0.172	0.596	1.14	0.146	0.557	1.09
2.65	0.328	1.12	0.154	0.553	1.28	0.135	0.516	1.46	0.096	0.537	1.73	0.062	0.563	1.98	0.049	0.553	1.99

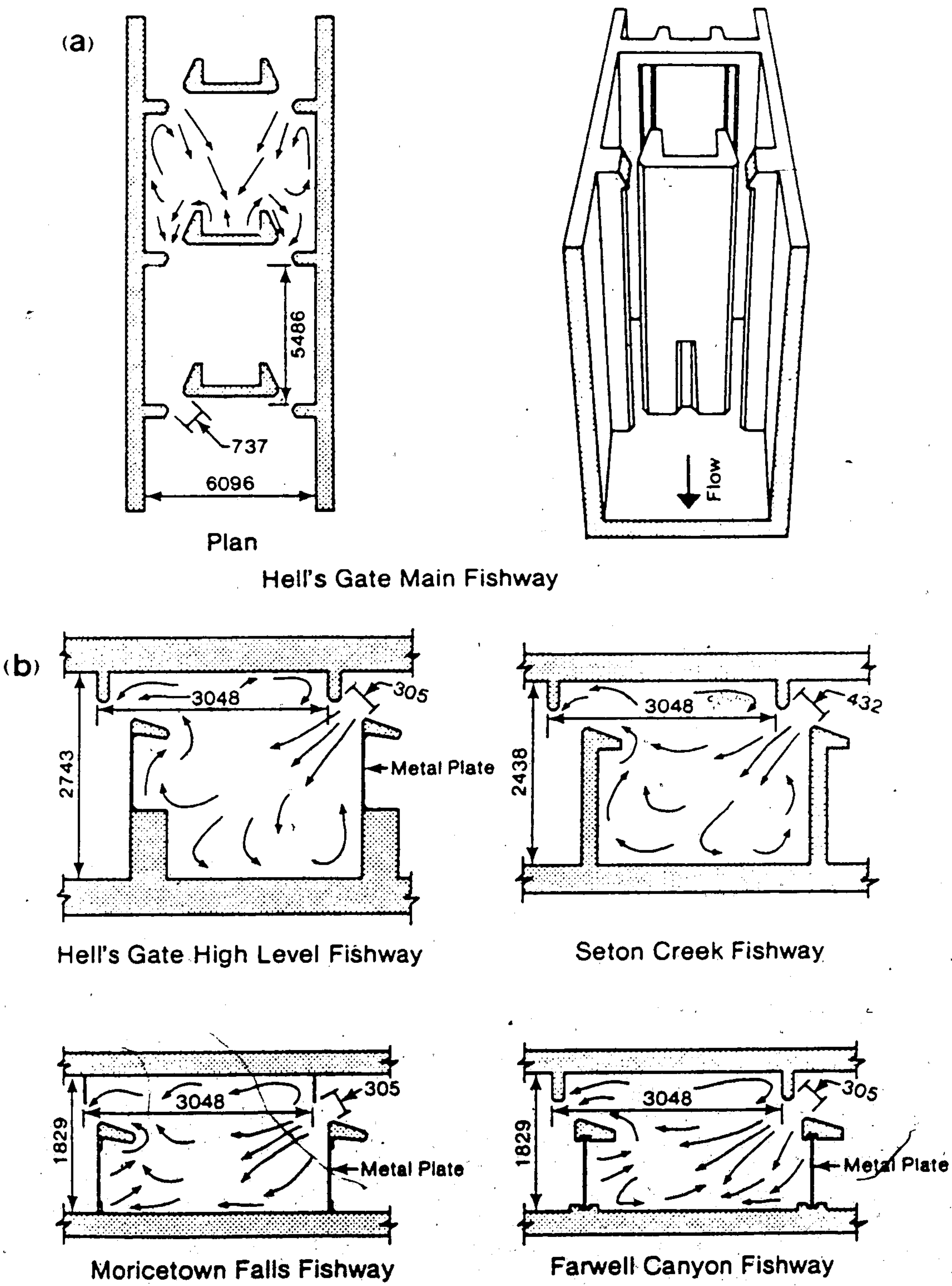
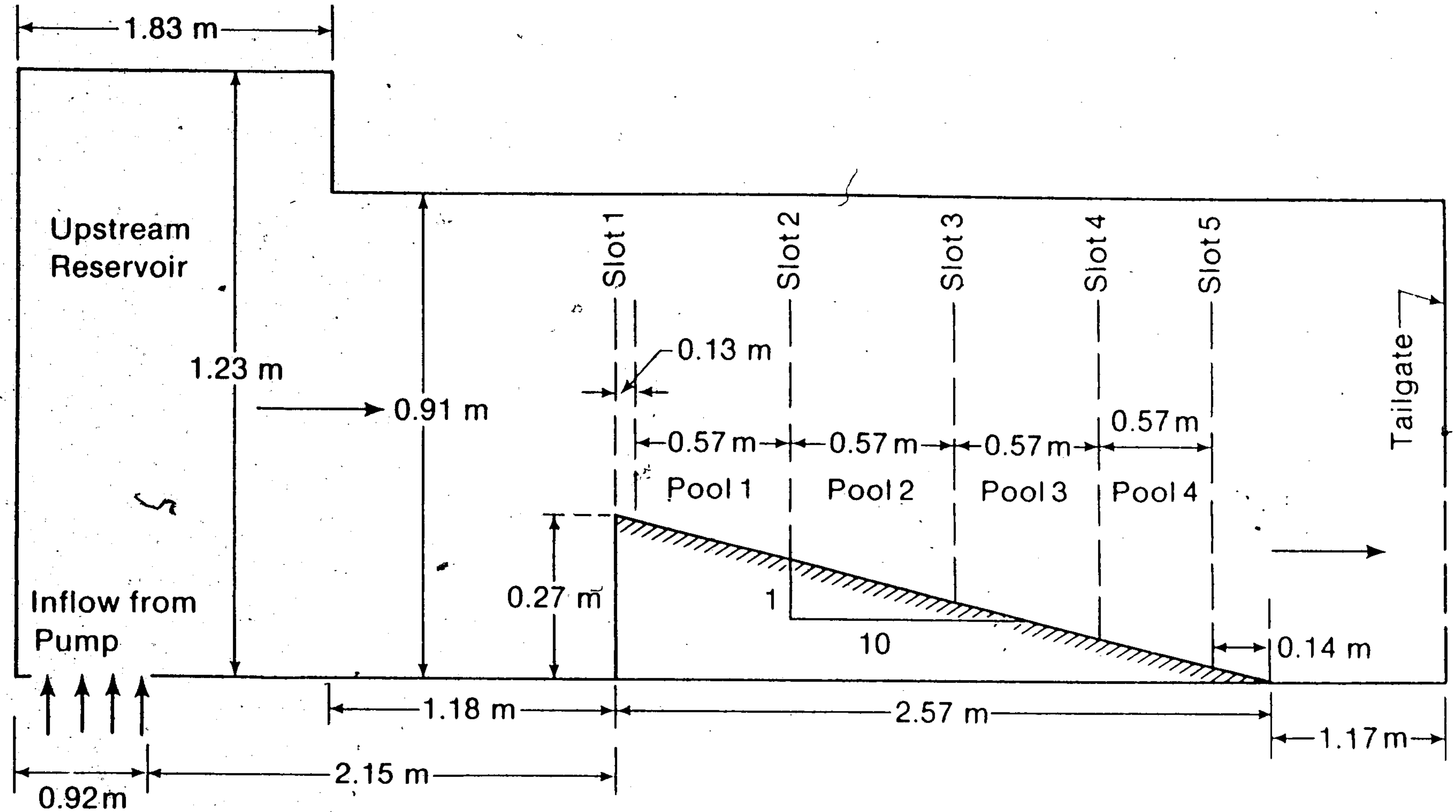


Fig. 1 Hell's Gate type vertical slot fishways



width of flume = 0.46 m (18 in)
all model dimensions
(scale 5.33)

Fig. 2 Details of experimental arrangement (Design 1).

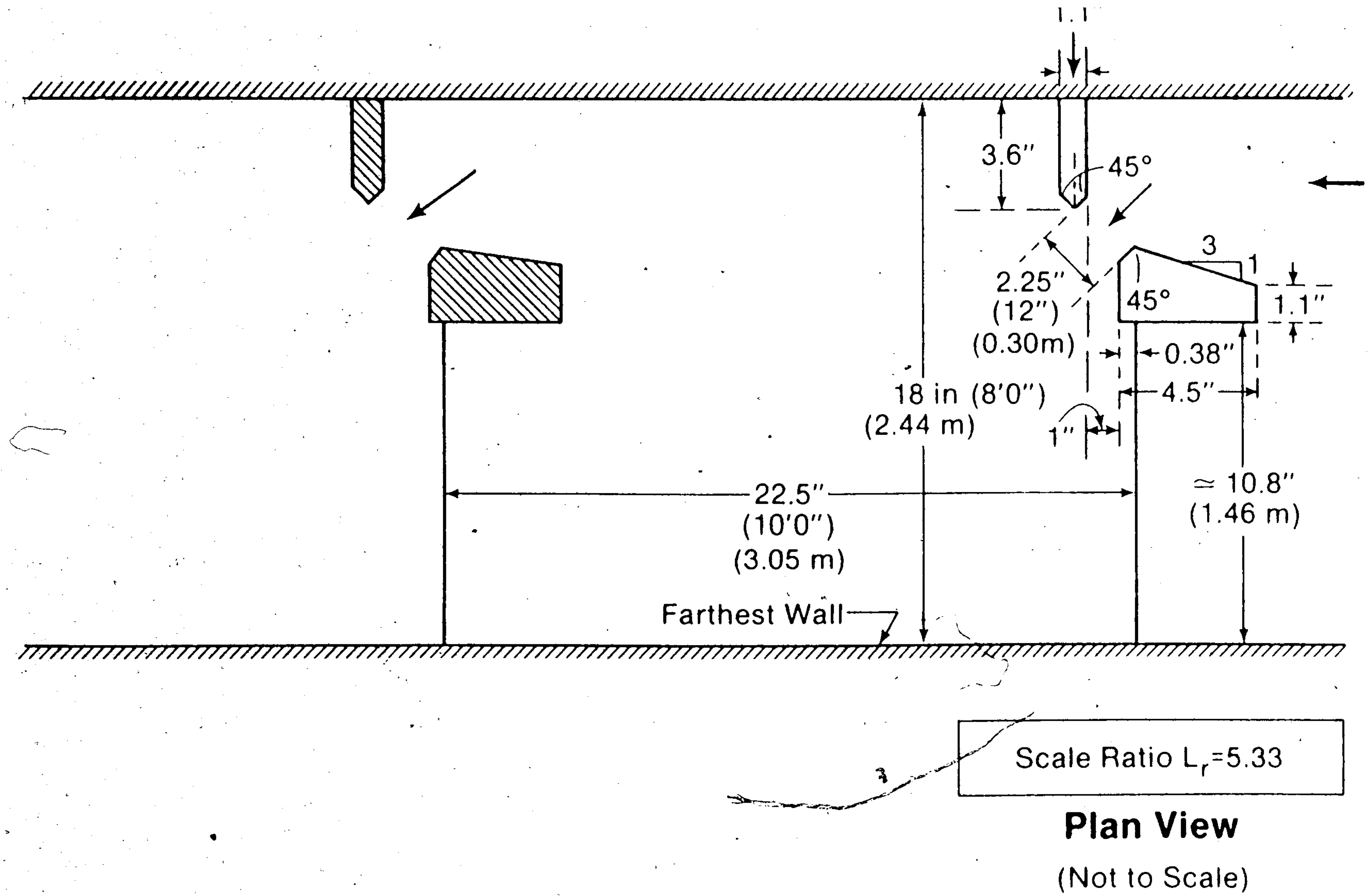


Fig. 3 Details of Design 1.

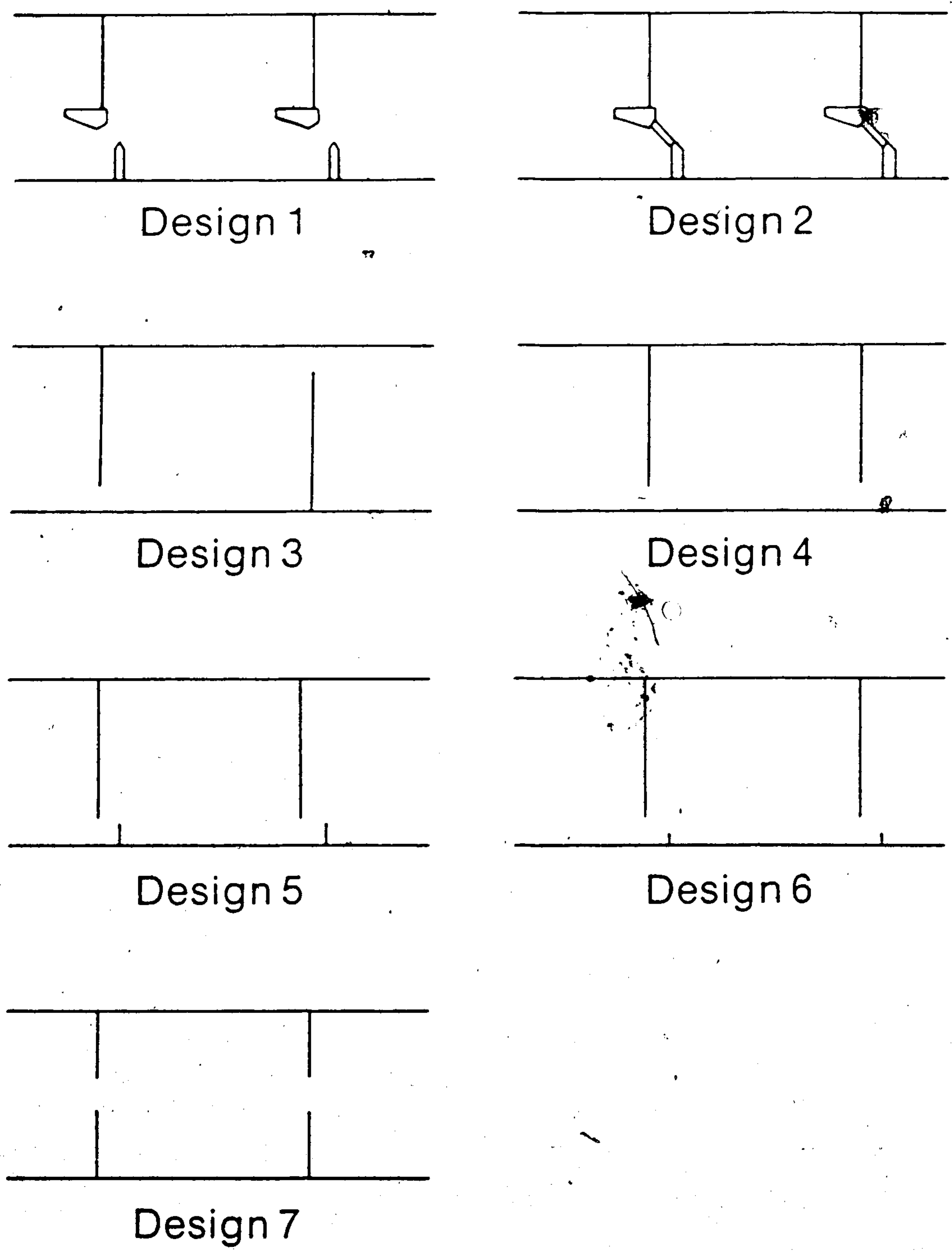


Fig. 4 Baffle geometry - all designs.

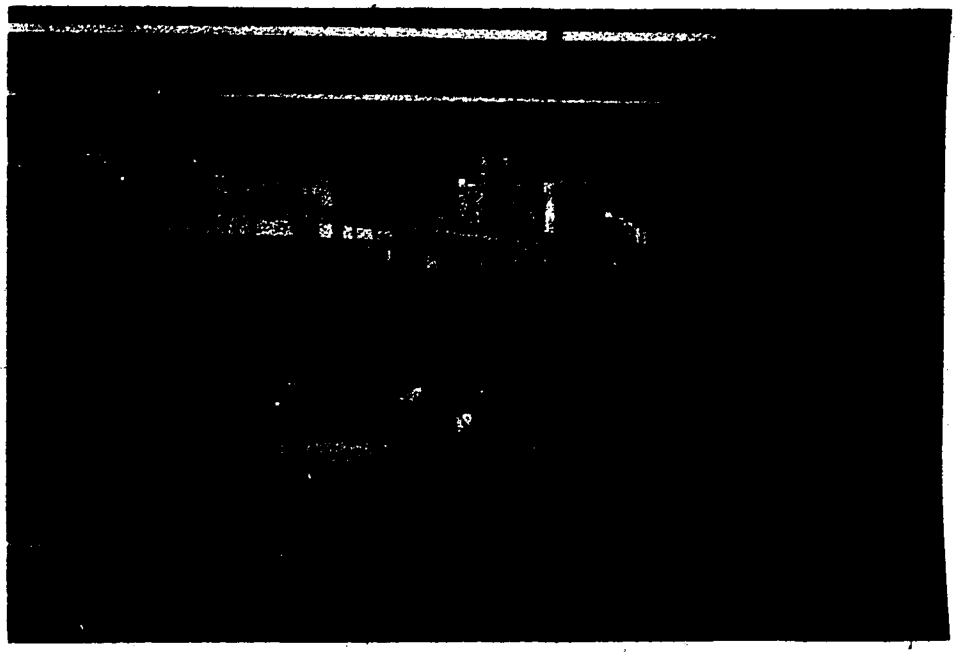


Fig. 5 Experiment 316B2.56N1.04.

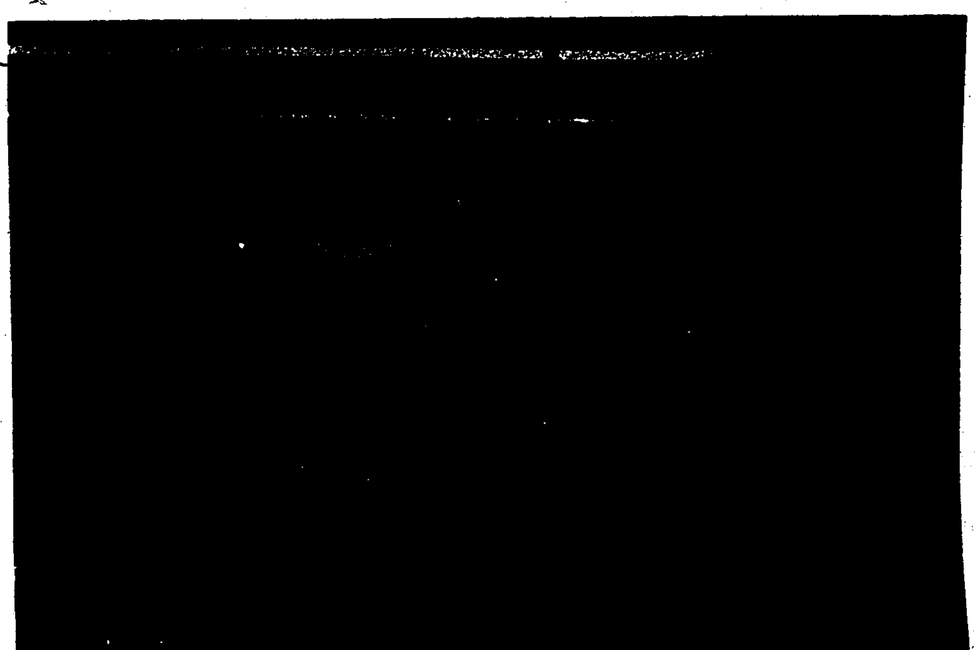


Fig. 6 Experiment 316B0.51N2.05.

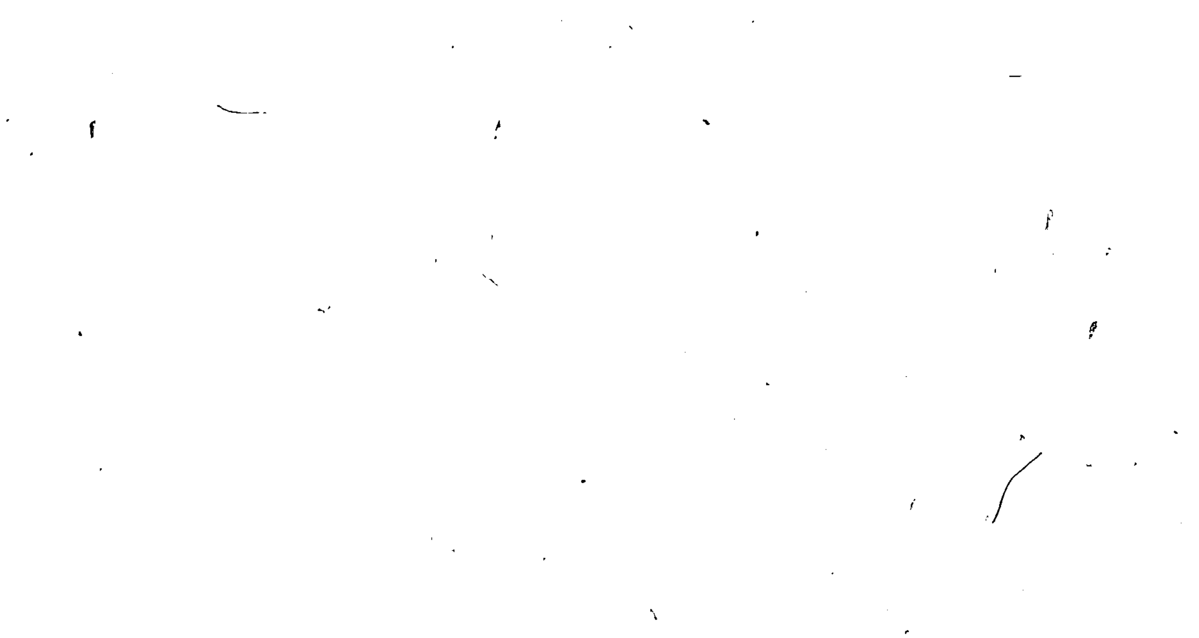
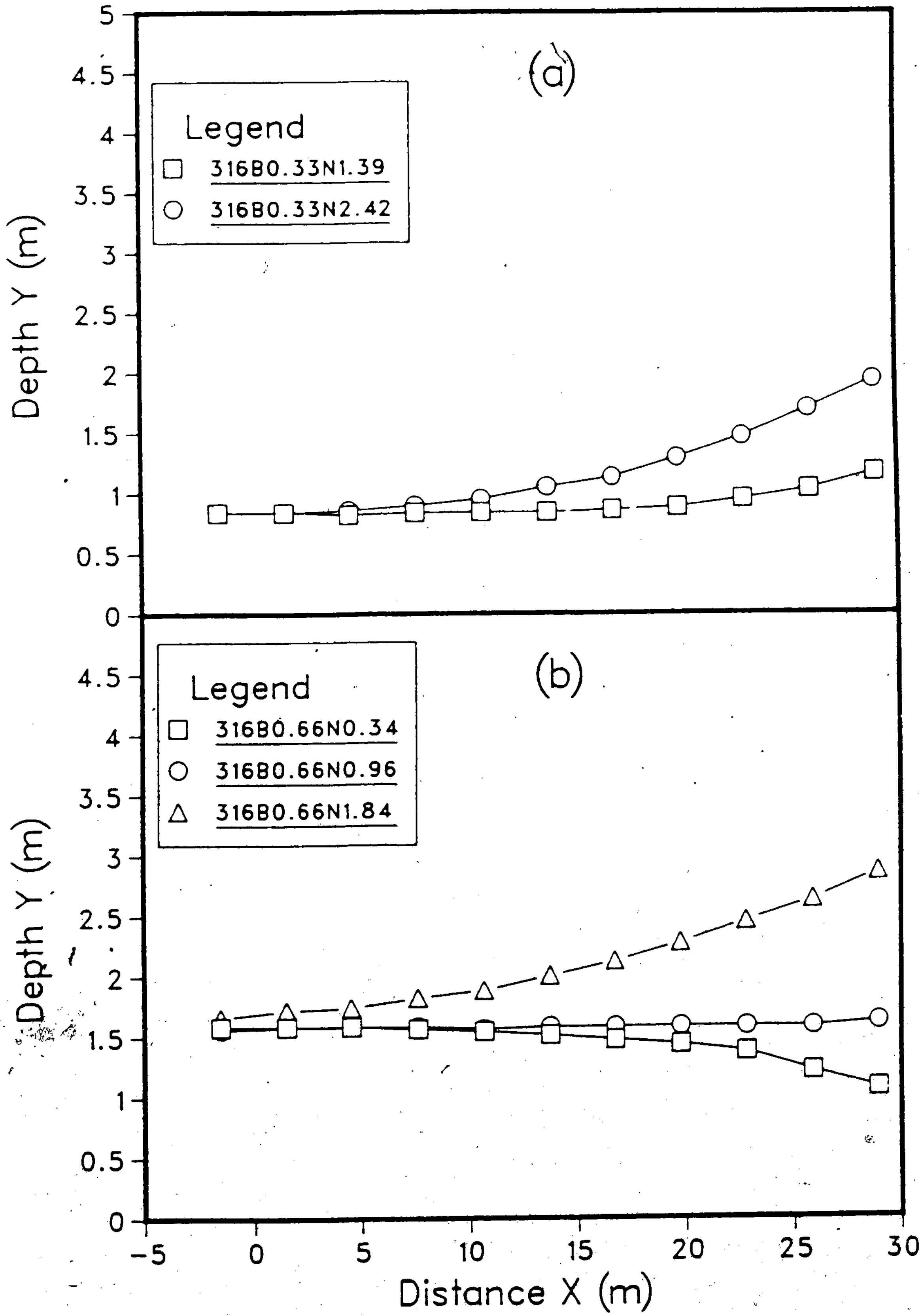
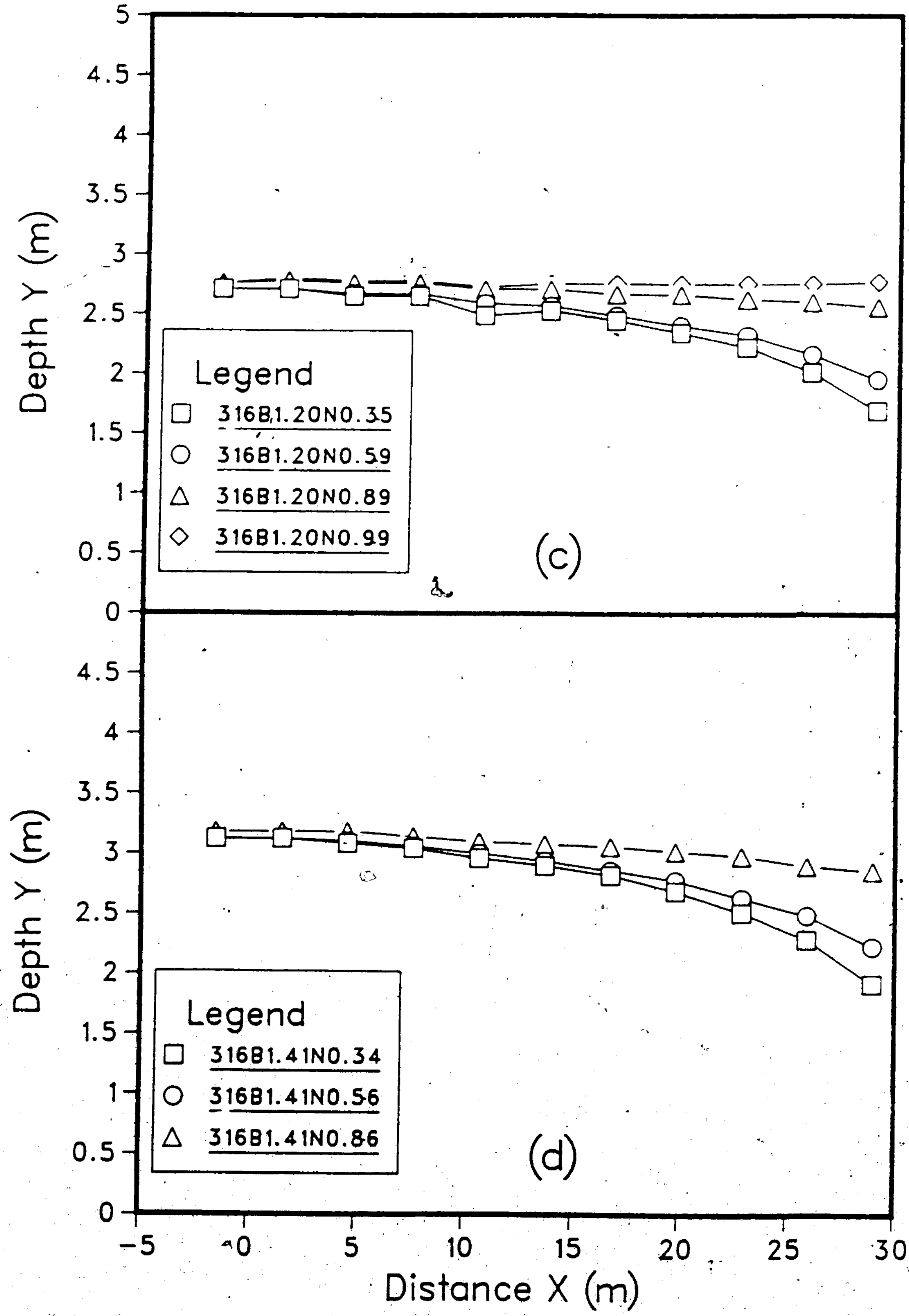
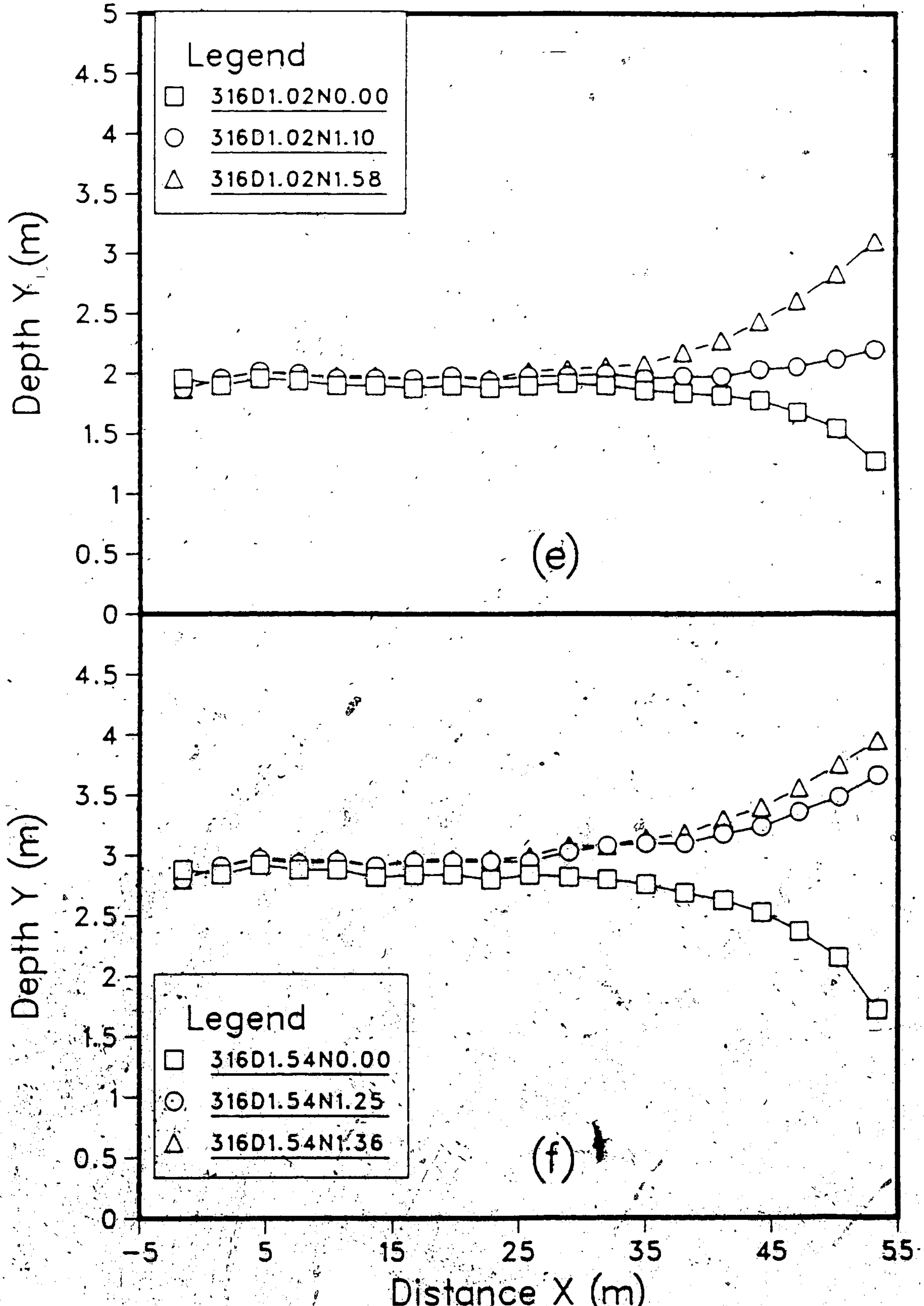


Fig. 7 Variation of pool depth with distance.


(a)
Legend
316B0.33N1.39
316B0.33N2.42
Depth Y (m)
(b)
Legend
316B0.66N0.34
316B0.66N0.96
316B0.66N1.84
Depth Y (m)
Distance X (m)



Depth Y (m)
Legend
316B1.20N0.35
316B1.20N0.59
316B1.20N0.89
316B1.20N0.99
(c)
Depth Y (m)
Legend
316B1.41N0.34
316B1.41N0.56
316B1.41N0.86
(d)
Distance X (m)



Legend
316D1.02N0.00
316D1.02N1.10
316D1.02N1.58
Depth Y (m)
(e)
Legend
316D1.54N0.00
316D1.54N1.25
316D1.54N1.36
Depth Y (m)
(f)
Distance X (m)

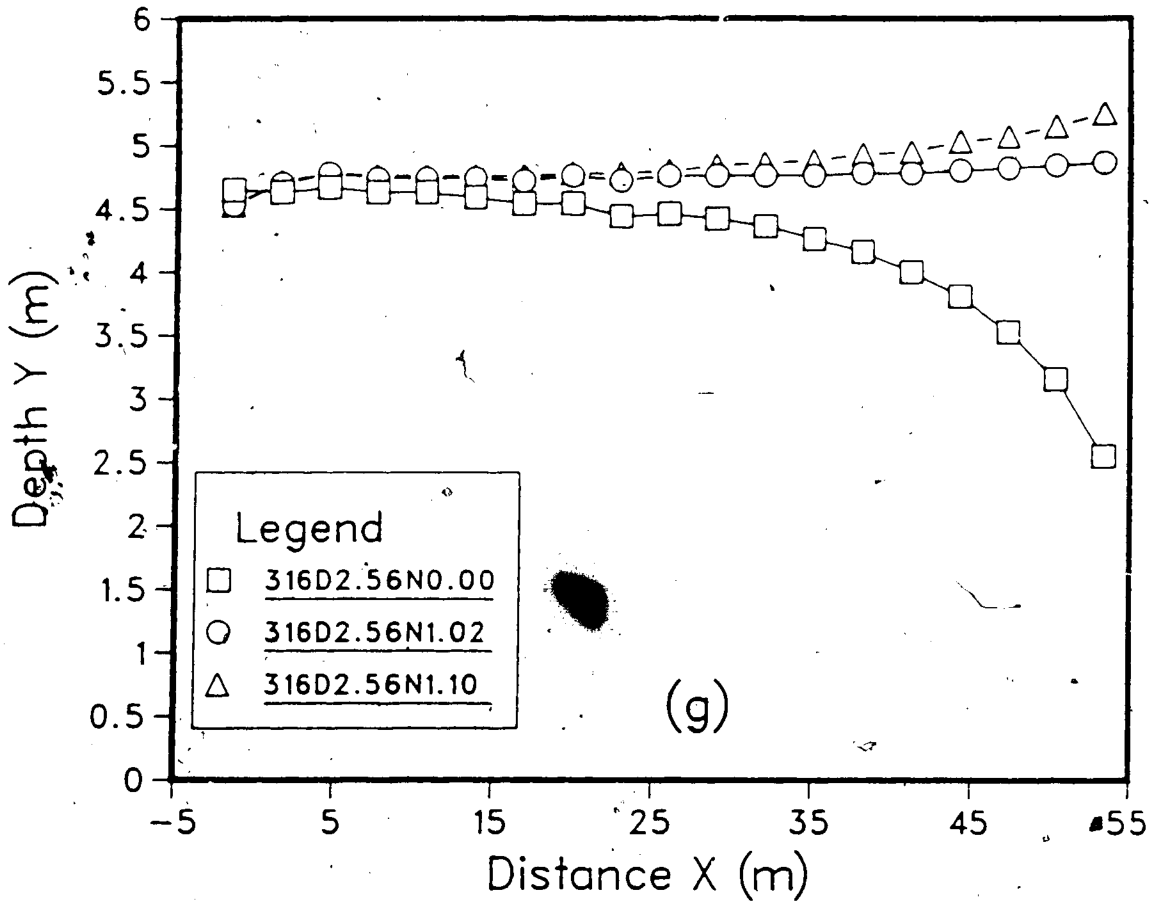
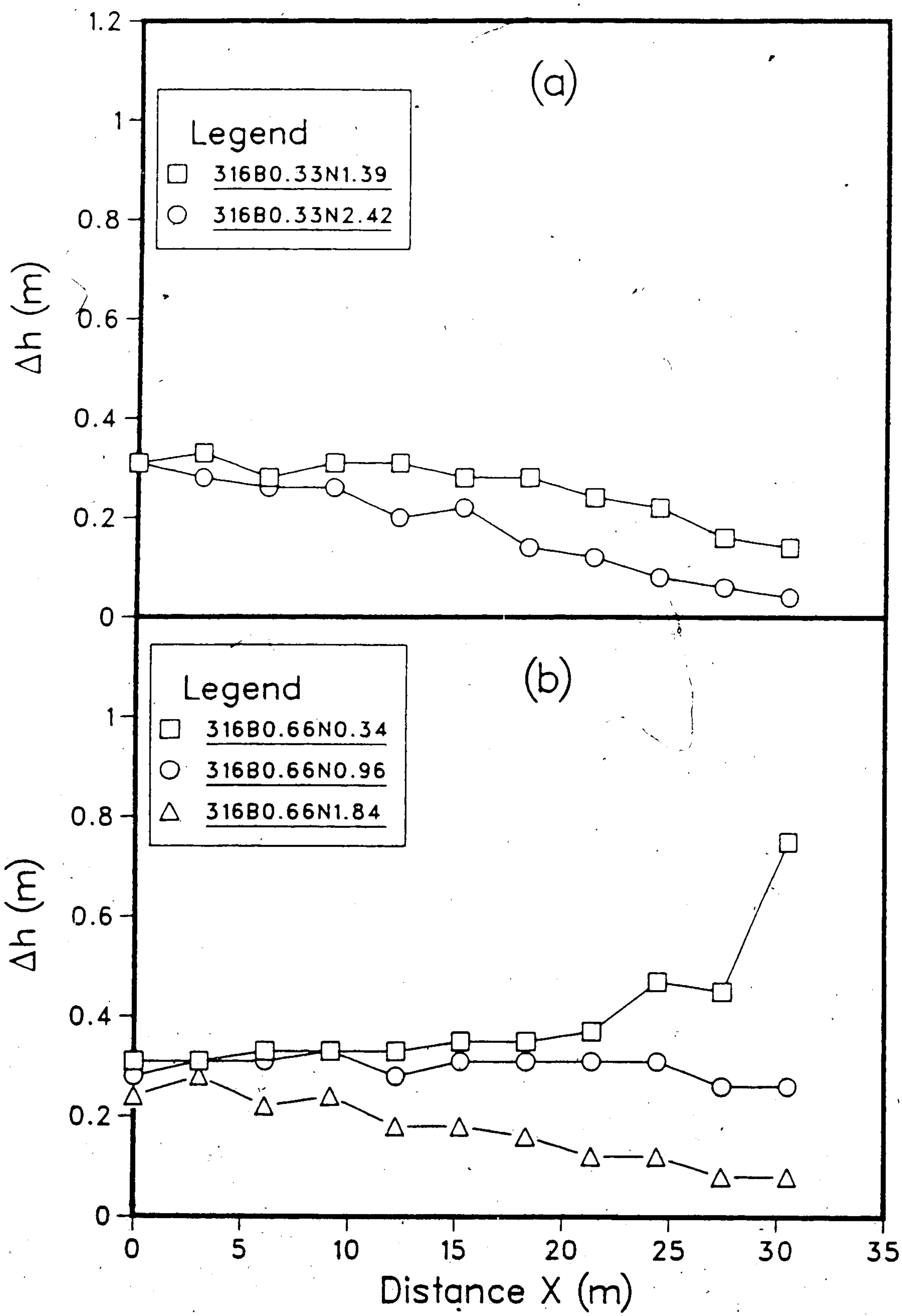
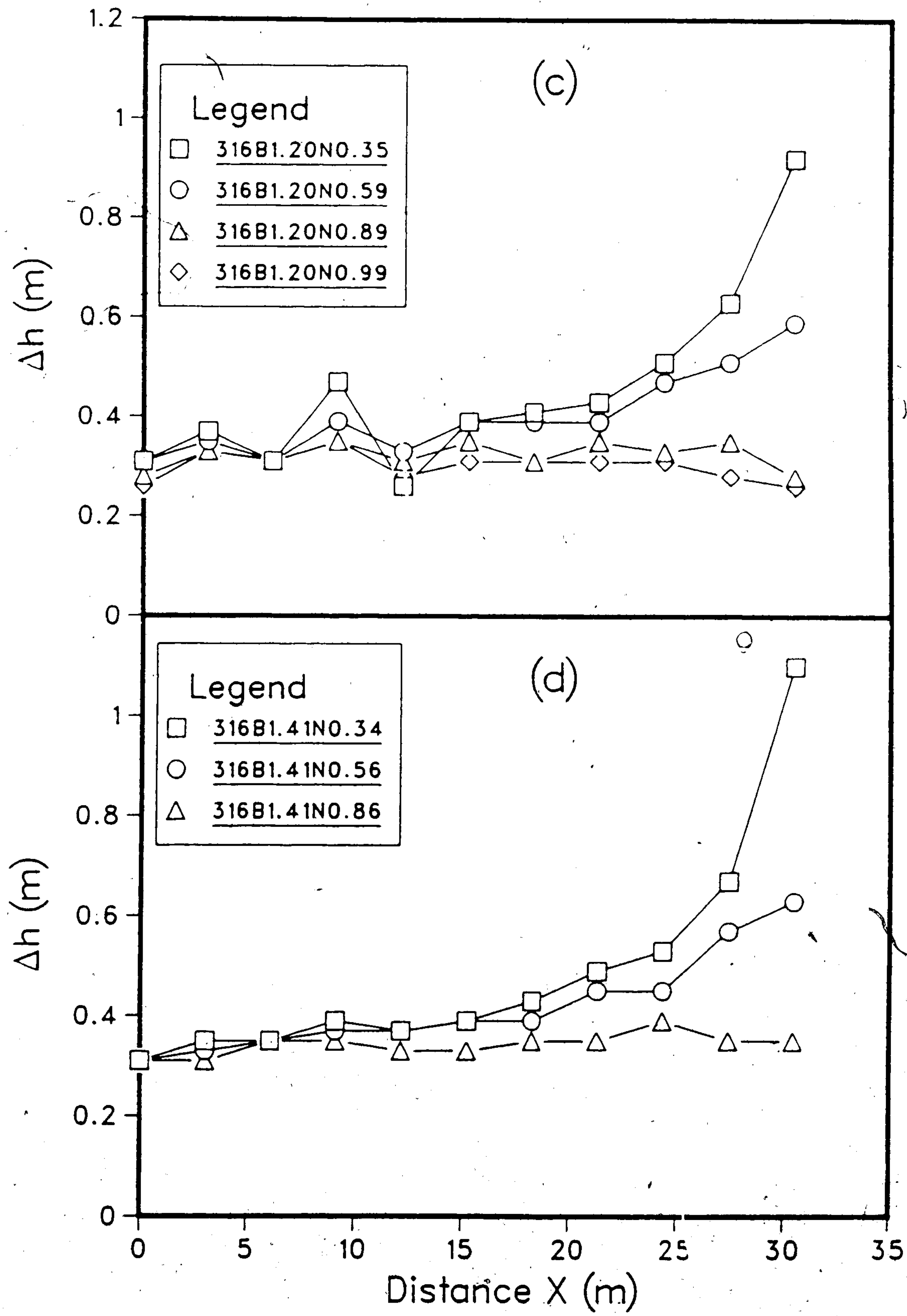
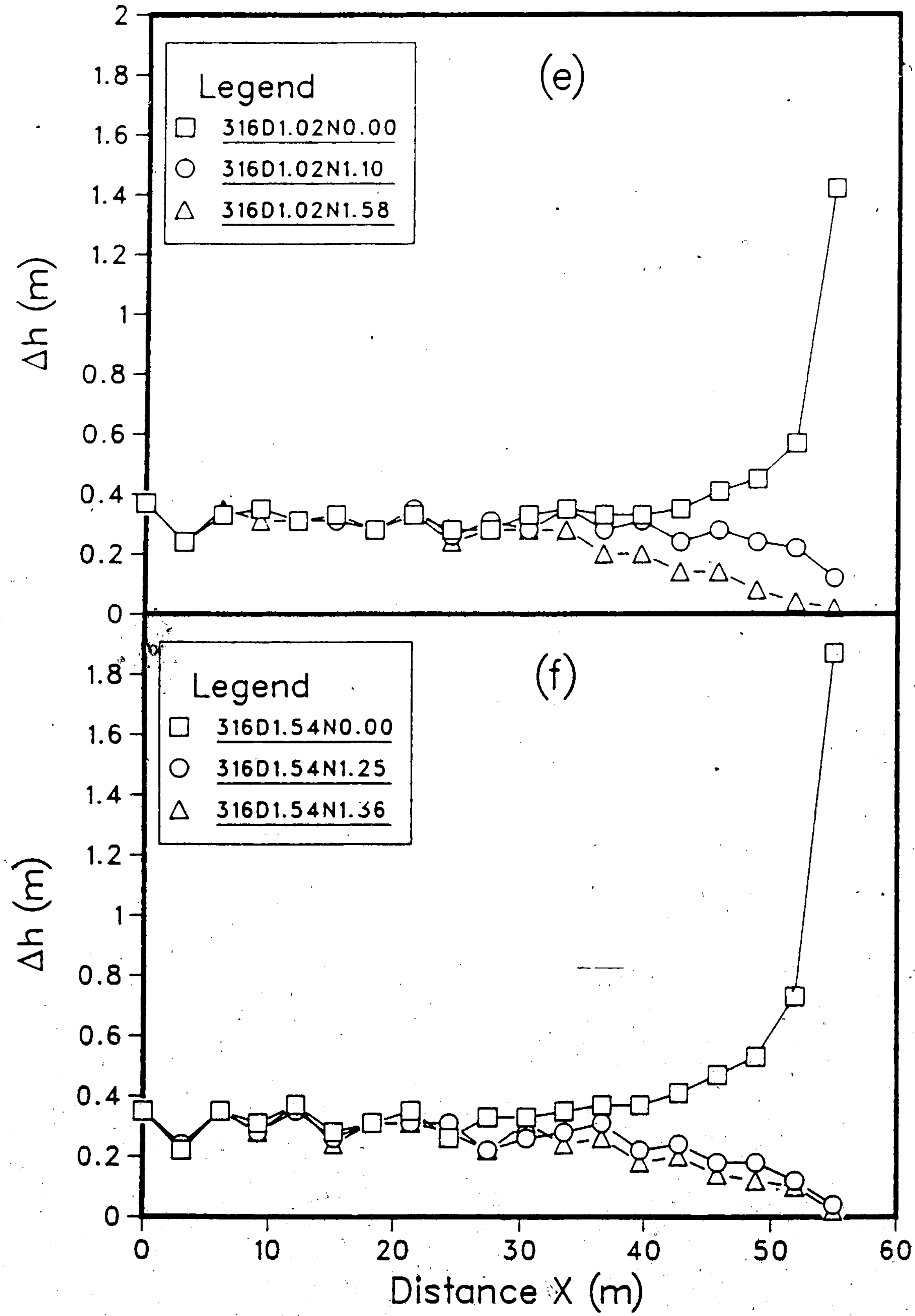

6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Depth Y (m)
−5
5
15
25
35
45
55
Distance X (m)
Legend
316D2.56N0.00
316D2.56N1.02
316D2.56N1.10
(g)

Fig. 8 Variation of Δh with distance.


(a)
Legend
316B0.33N1.39
316B0.33N2.42
(b)
Legend
316B0.66N0.34
316B0.66N0.96
316B0.66N1.84
Δh (m)
Δh (m)
Distance X (m)
0
0.2
0.4
0.6
0.8
1
1.2
0
5
10
15
20
25
30
35


(c)
Legend
316B1.20N0.35
316B1.20N0.59
316B1.20N0.89
316B1.20N0.99
Δh (m)
1.2
1
0.8
0.6
0.4
0.2
0
(d)
Legend
316B1.41N0.34
316B1.41N0.56
316B1.41N0.86
Δh (m)
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
Distance X (m)


(e)
Legend
316D1.02N0.00
316D1.02N1.10
316D1.02N1.58
(f)
Legend
316D1.54N0.00
316D1.54N1.25
316D1.54N1.36
Δh (m)
Distance X (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
10
20
30
40
50
60

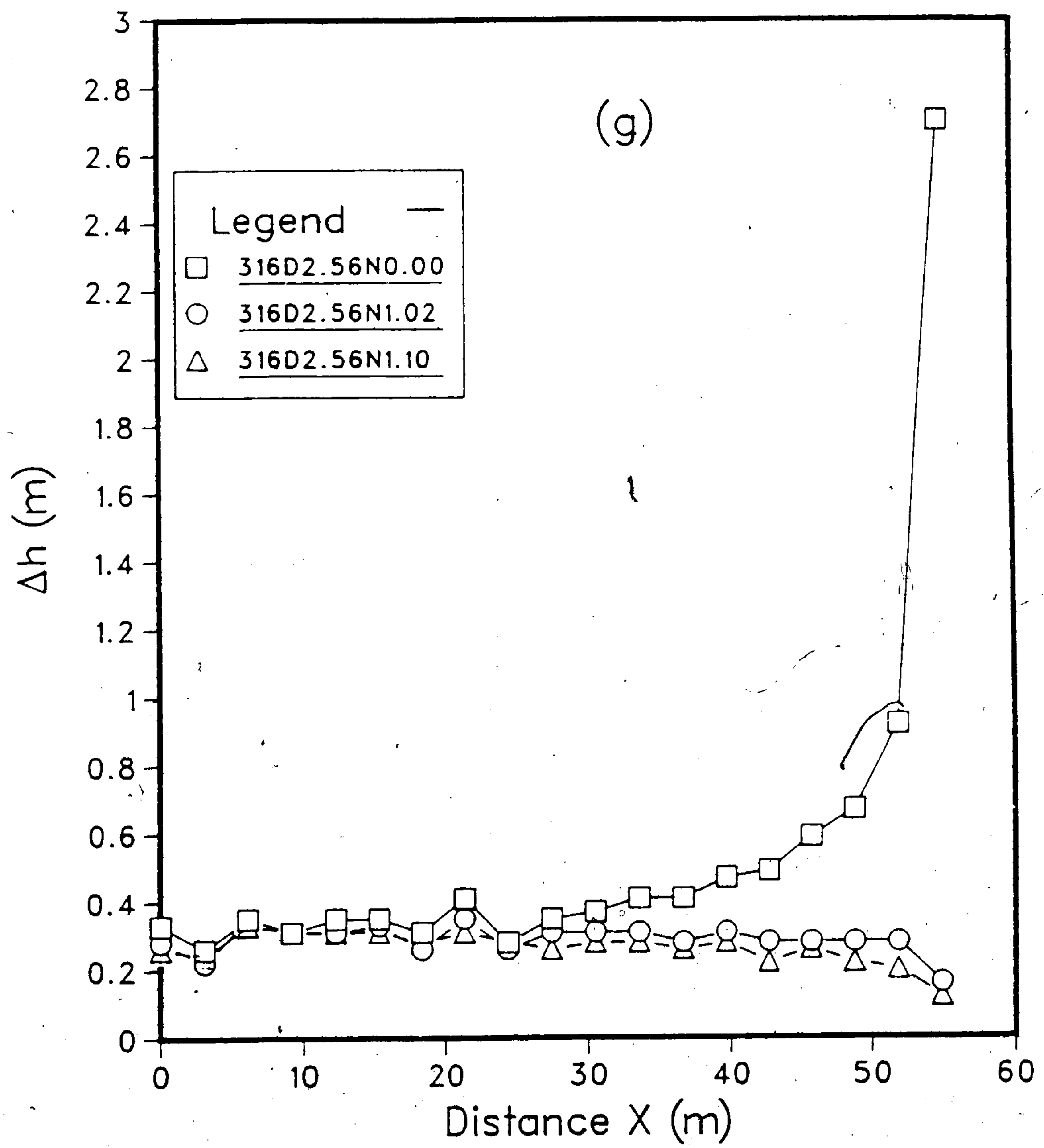
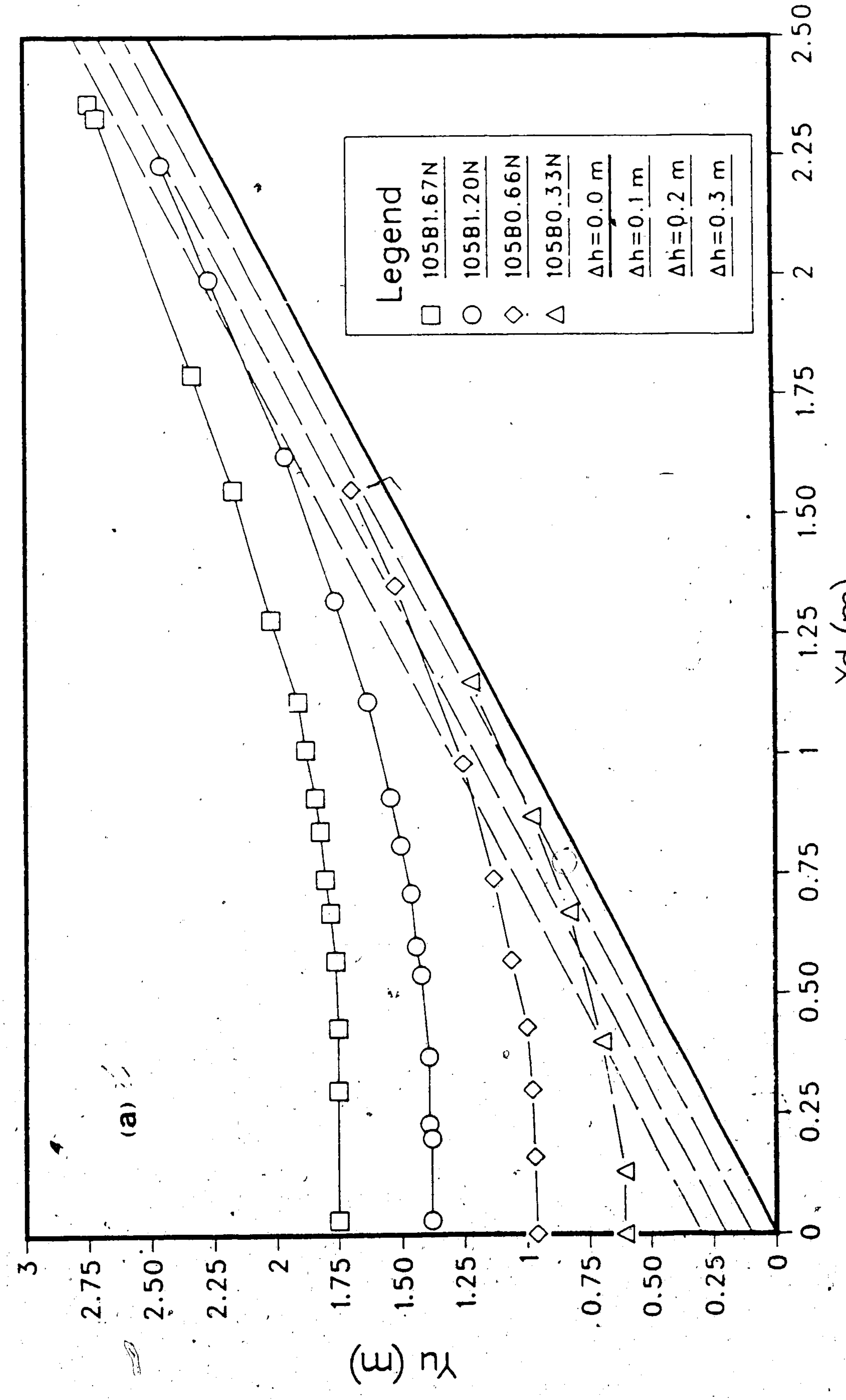
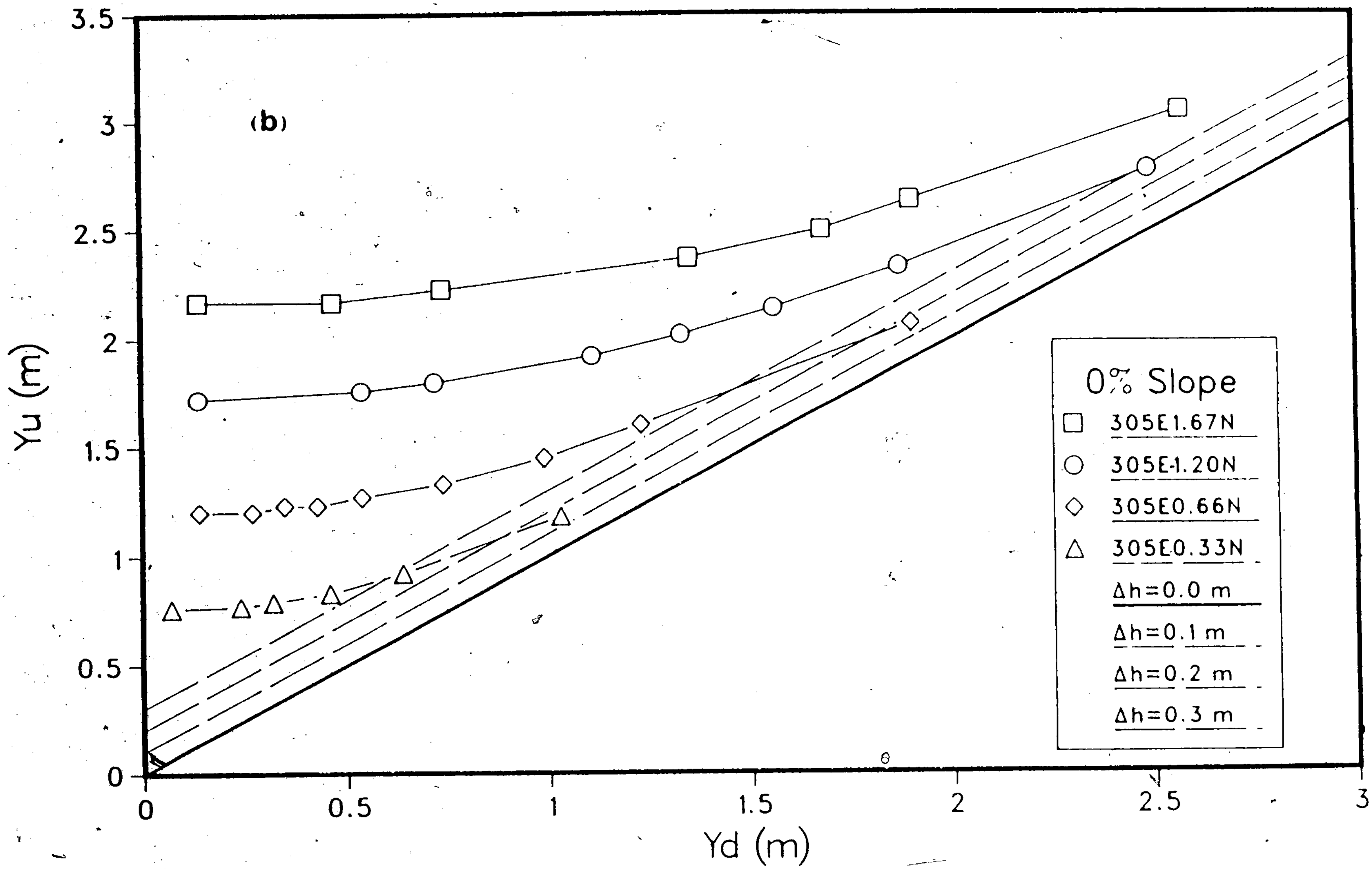
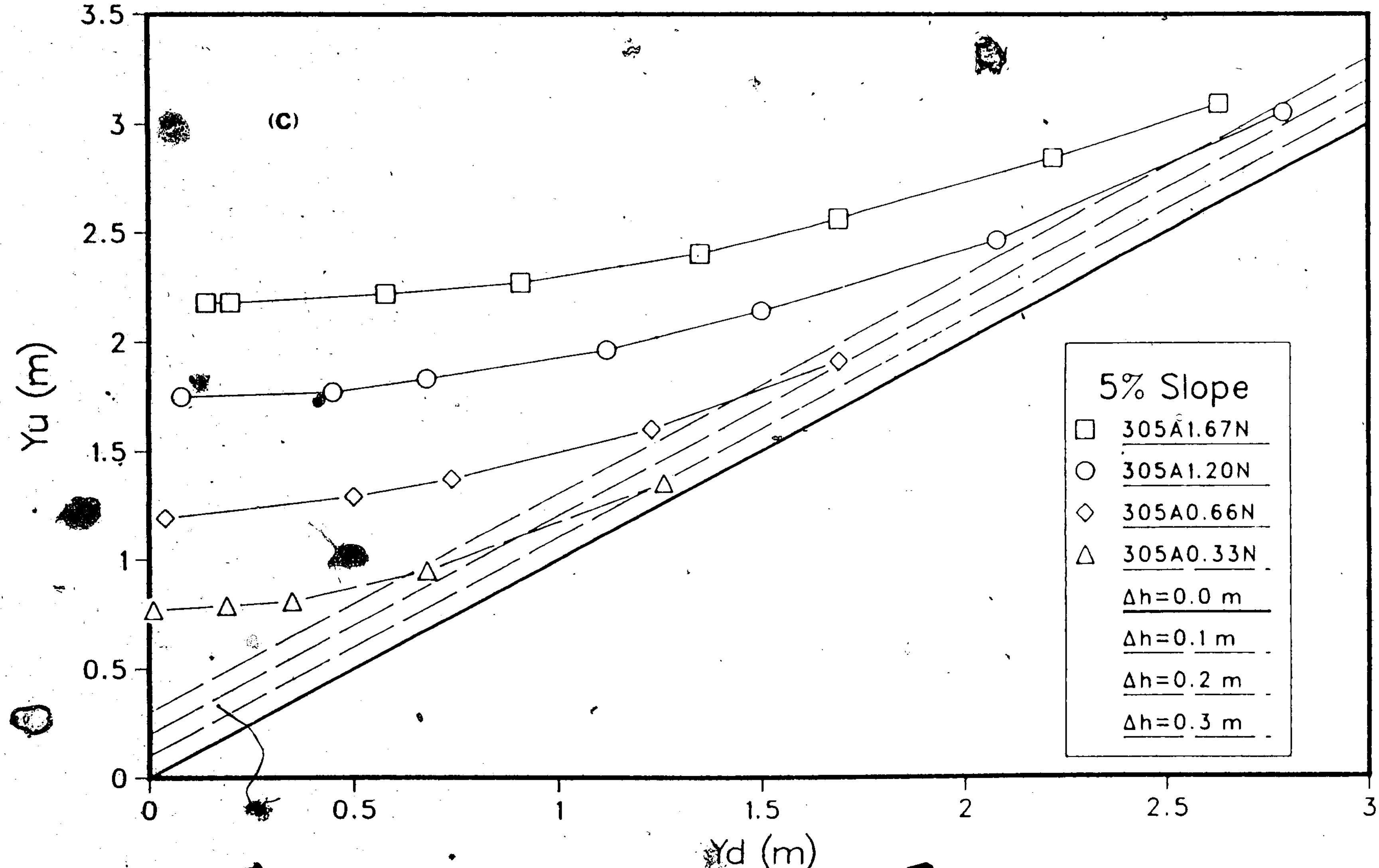

(g)
Legend
316D2.56N0.00
316D2.56N1.02
316D2.56N1.10
Δh (m)
Distance X (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
0
10
20
30
40
50
60

Fig. 9 Effect of tailwater on pool submergence.


(a)
Legend
105B1.67N
105B1.20N
105B0.66N
105B0.33N
Δh=0.0 m
Δh=0.1 m
Δh=0.2 m
Δh=0.3 m
Yd (m)
Yu (m)
0
0.25
0.50
0.75
1
1.25
1.50
1.75
2
2.25
2.50
2.75
3



(b)
0% Slope
305E1.67N
305E1.20N
305E0.66N
305E0.33N
Δh=0.0 m
Δh=0.1 m
Δh=0.2 m
Δh=0.3 m
Yu (m)
Yd (m)
0
0.5
1
1.5
2
2.5
3
3.5



(C)
5% Slope
305A1.67N
305A1.20N
305A0.66N
305A0.33N
Δh=0.0 m
Δh=0.1 m
Δh=0.2 m
Δh=0.3 m
Yu (m)
Yd (m)
0
0.5
1
1.5
2
2.5
3
3.5

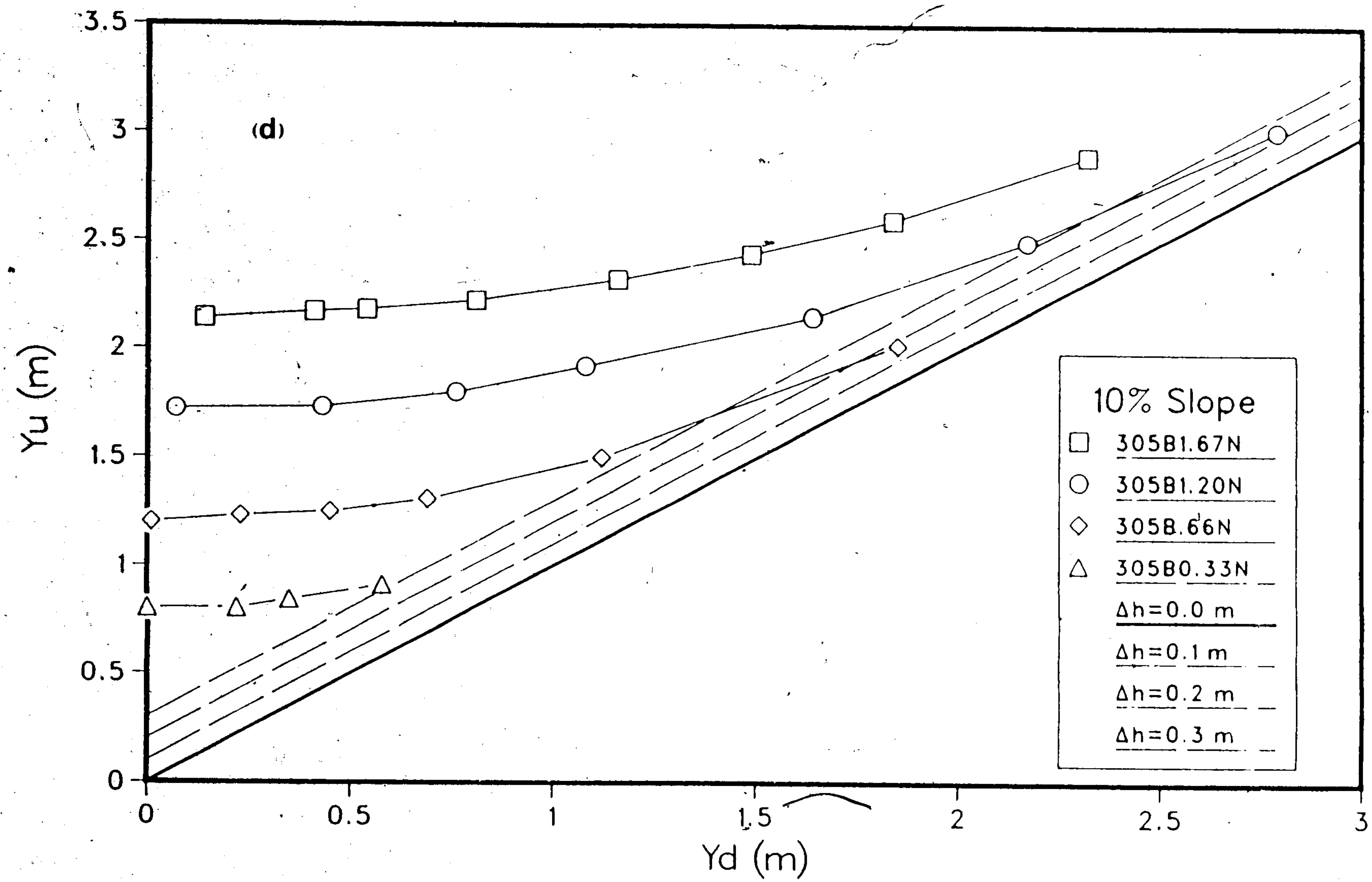
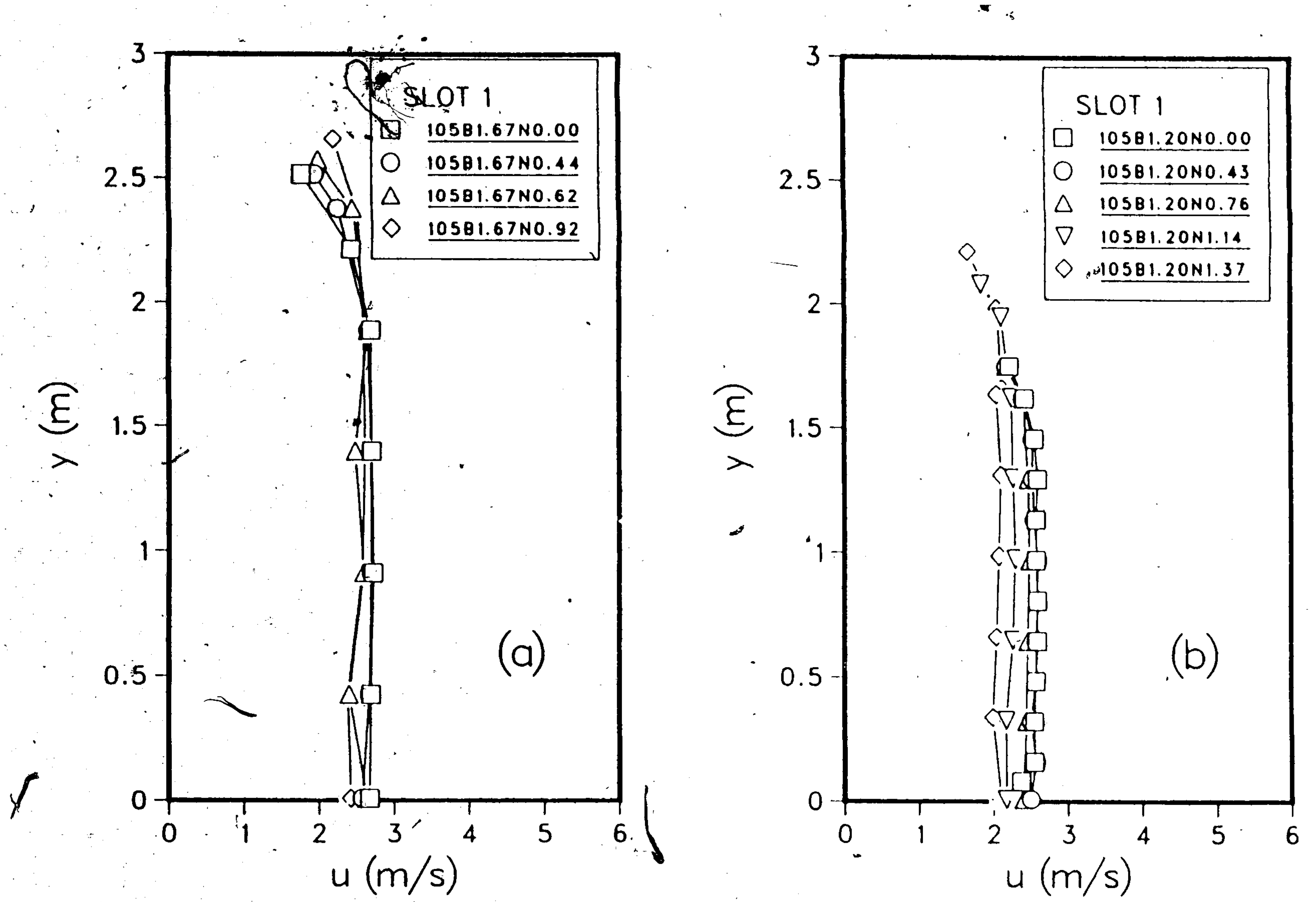
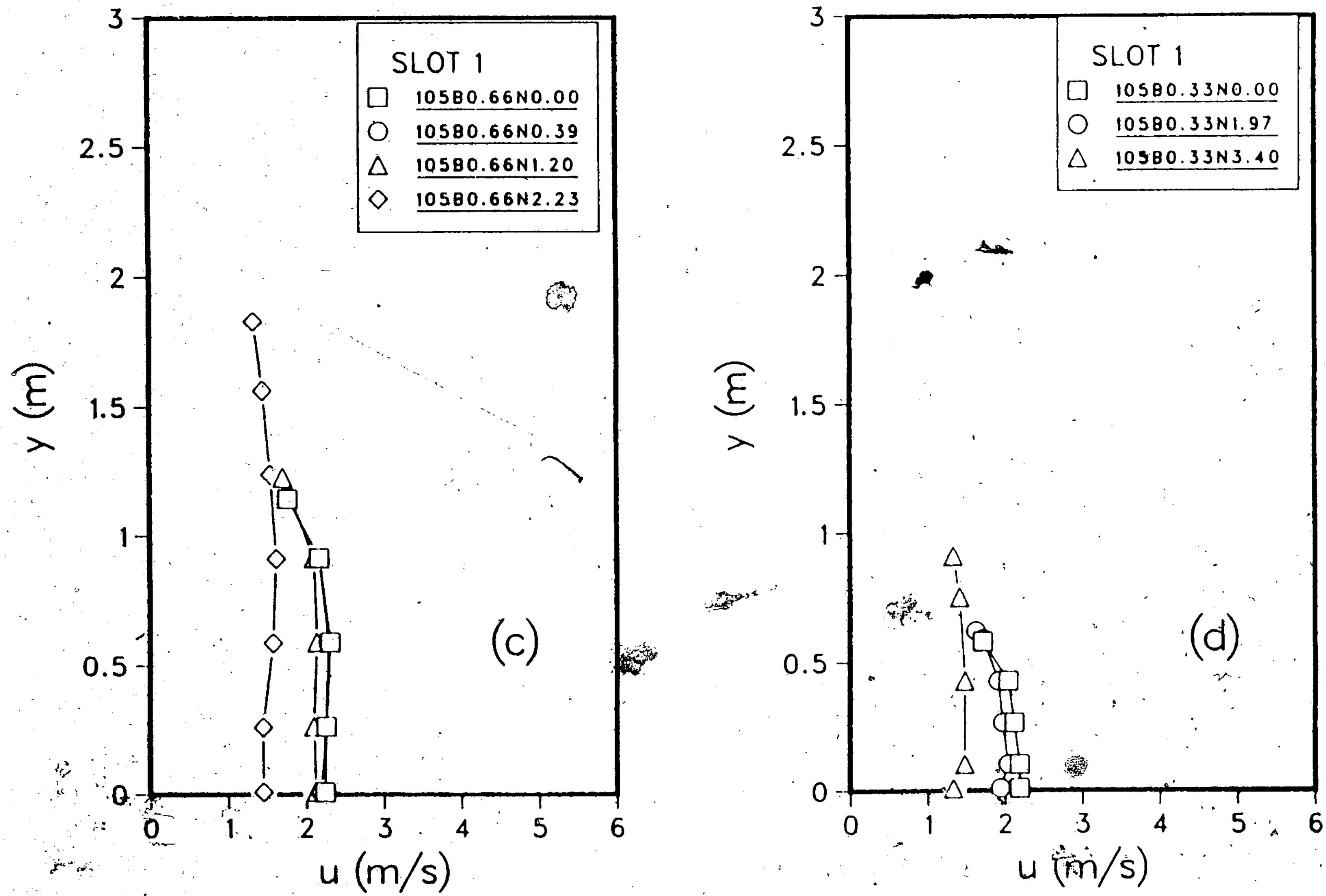
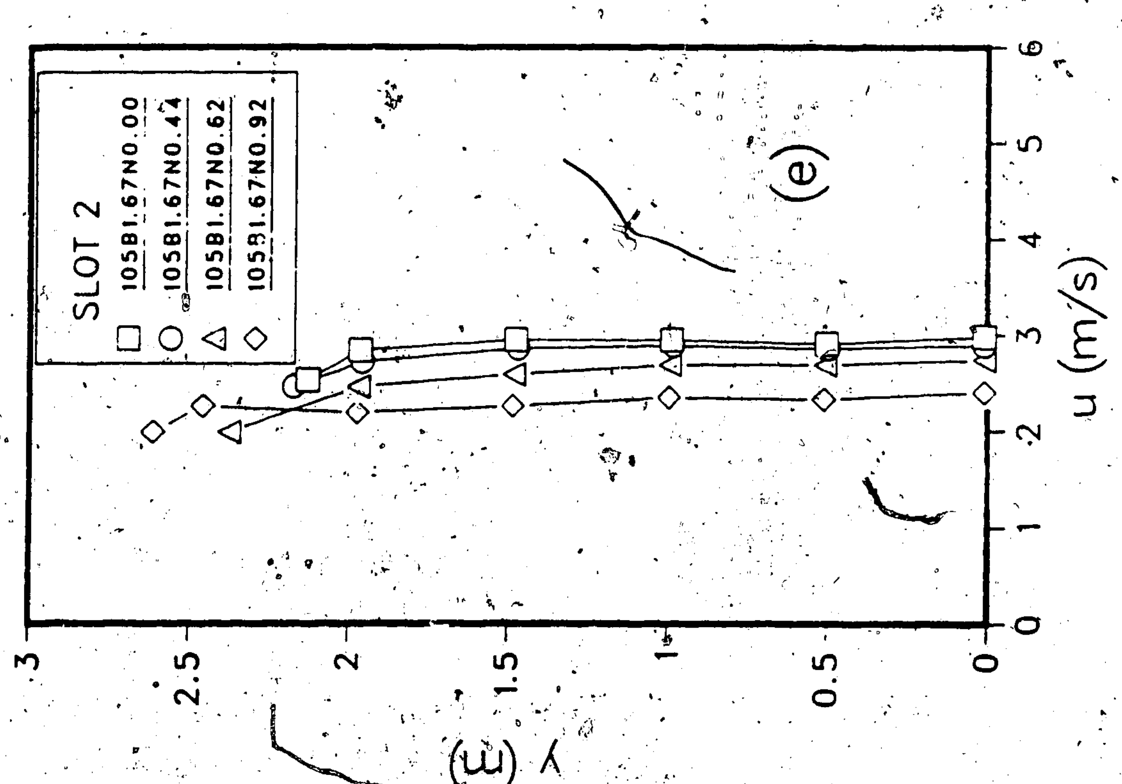
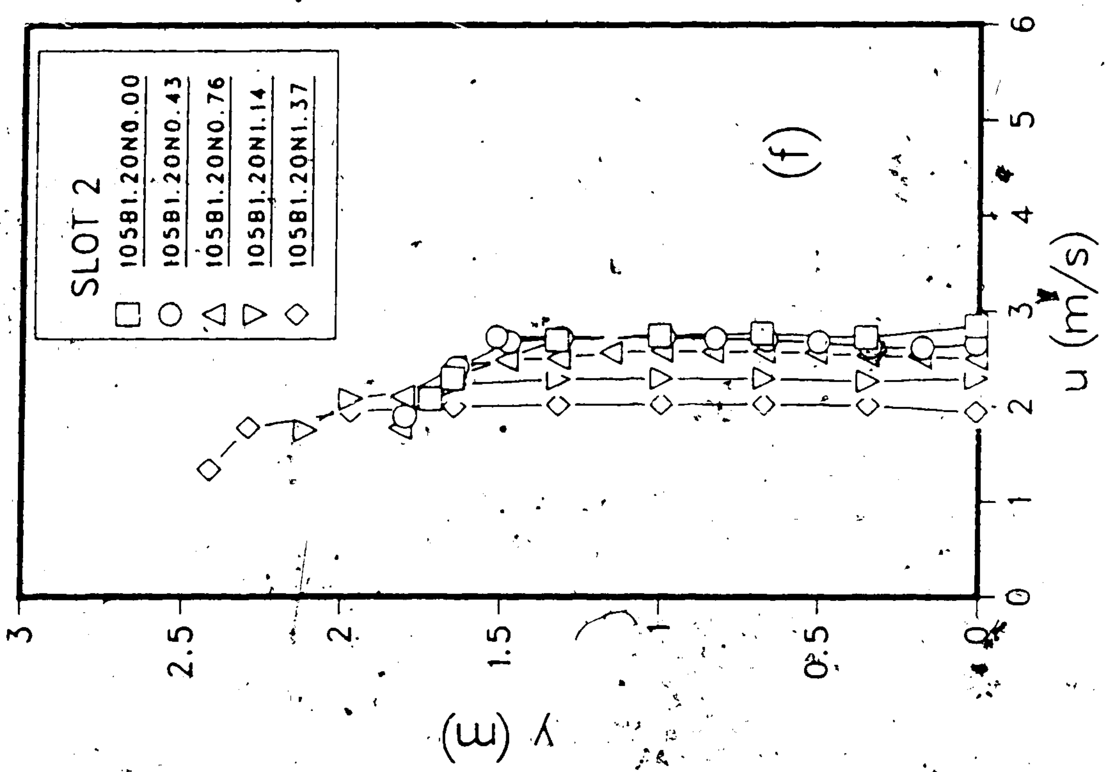

(d)
10% Slope
305B1.67N
305B1.20N
305B.66N
305B0.33N
Δh=0.0 m
Δh=0.1 m
Δh=0.2 m
Δh=0.3 m
Yu (m)
Yd (m)
0
0.5
1
1.5
2
2.5
3
3.5

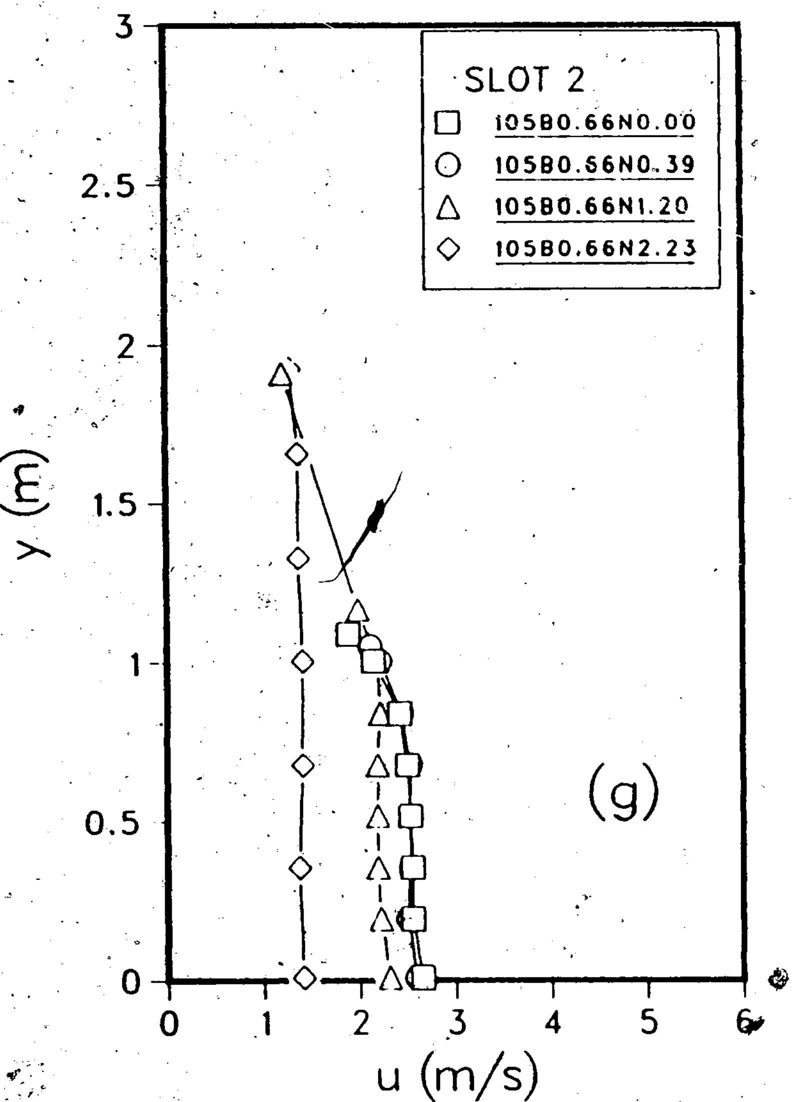
Fig. 10 Velocity profiles in the slots - Design 1.

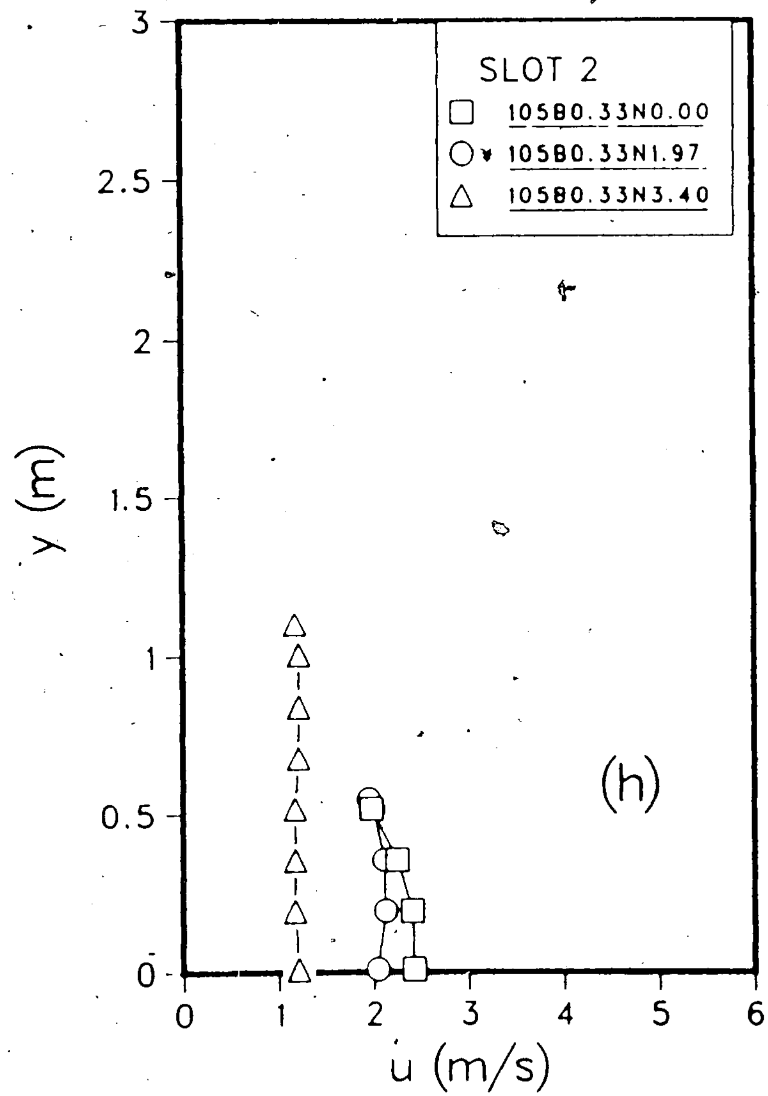

SLOT 1
105B1.67N0.00
105B1.67N0.44
105B1.67N0.62
105B1.67N0.92
y (m)
u (m/s)
(a)
SLOT 1
105B1.20N0.00
105B1.20N0.43
105B1.20N0.76
105B1.20N1.14
105B1.20N1.37
y (m)
u (m/s)
(b)

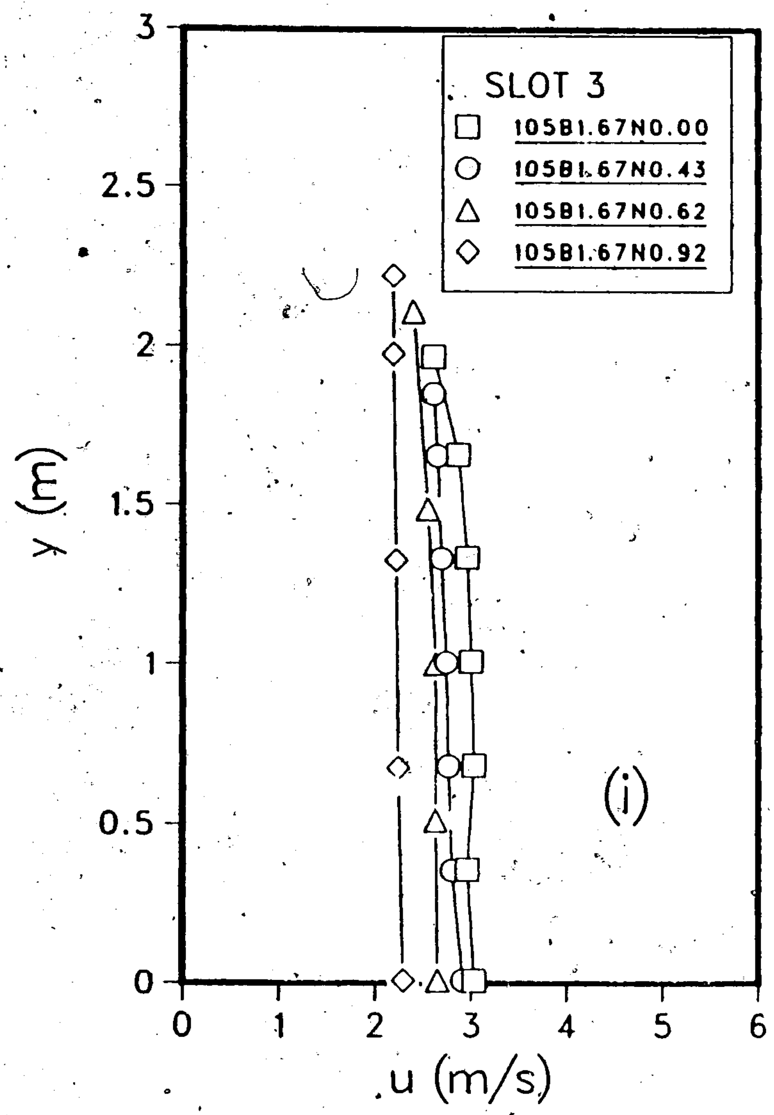

SLOT 1
105B0.66N0.00
105B0.66N0.39
105B0.66N1.20
105B0.66N2.23
(c)
y (m)
u (m/s)
SLOT 1
105B0.33N0.00
105B0.33N1.97
105B0.33N3.40
(d)
y (m)
u (m/s)

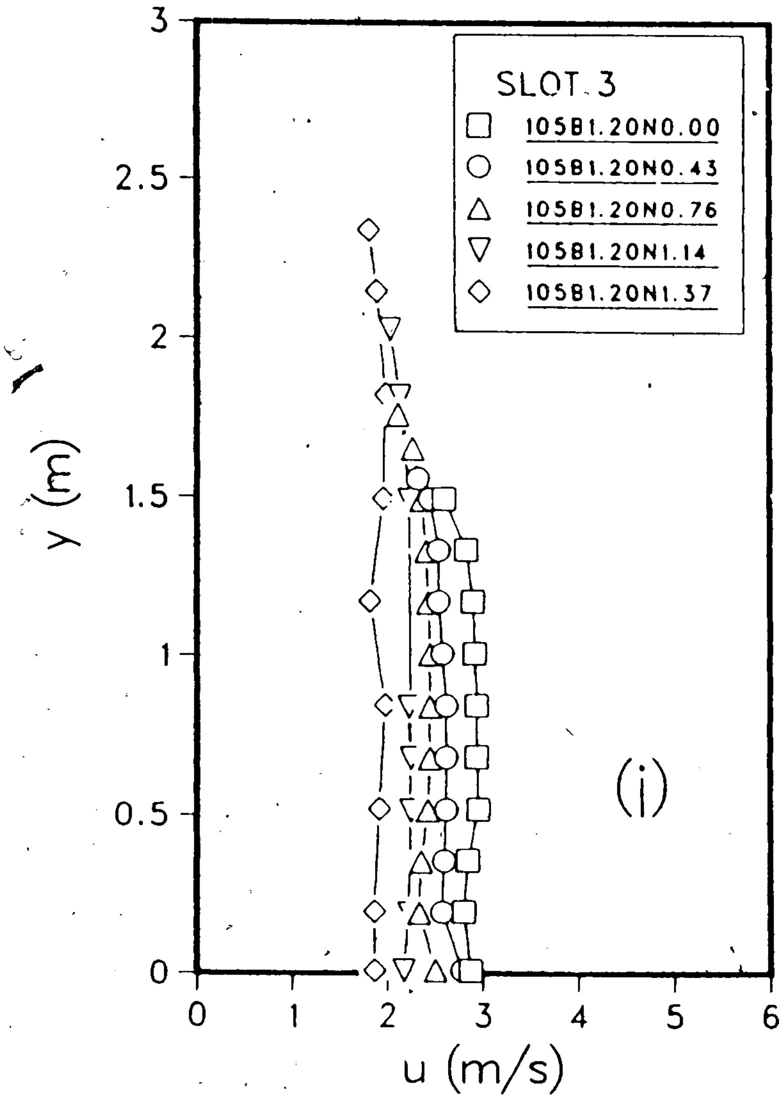

SLOT 2
105BI.67N0.00
105BI.67N0.44
105BI.67N0.62
105BI.67N0.92
(e)
u (m/s)
y (m)

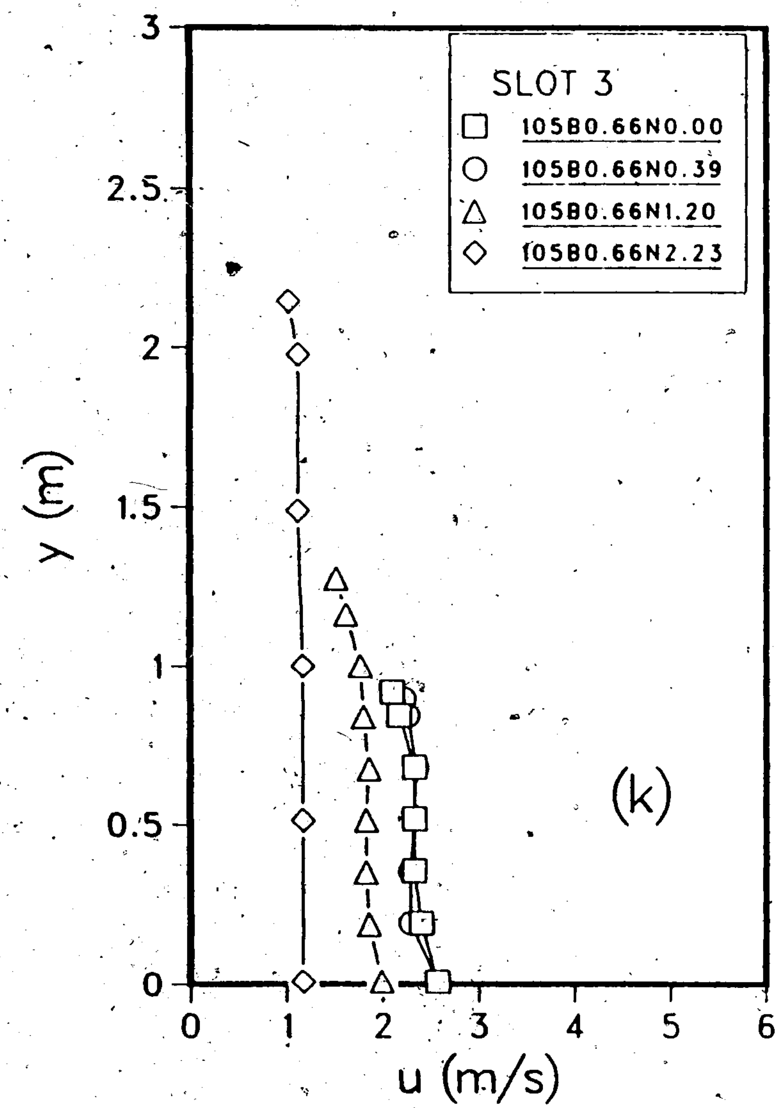

SLOT 2
105BI.20N0.00
105BI.20N0.43
105BI.20N0.76
105BI.20N1.14
105BI.20N1.37
(f)
u (m/s)
y (m)

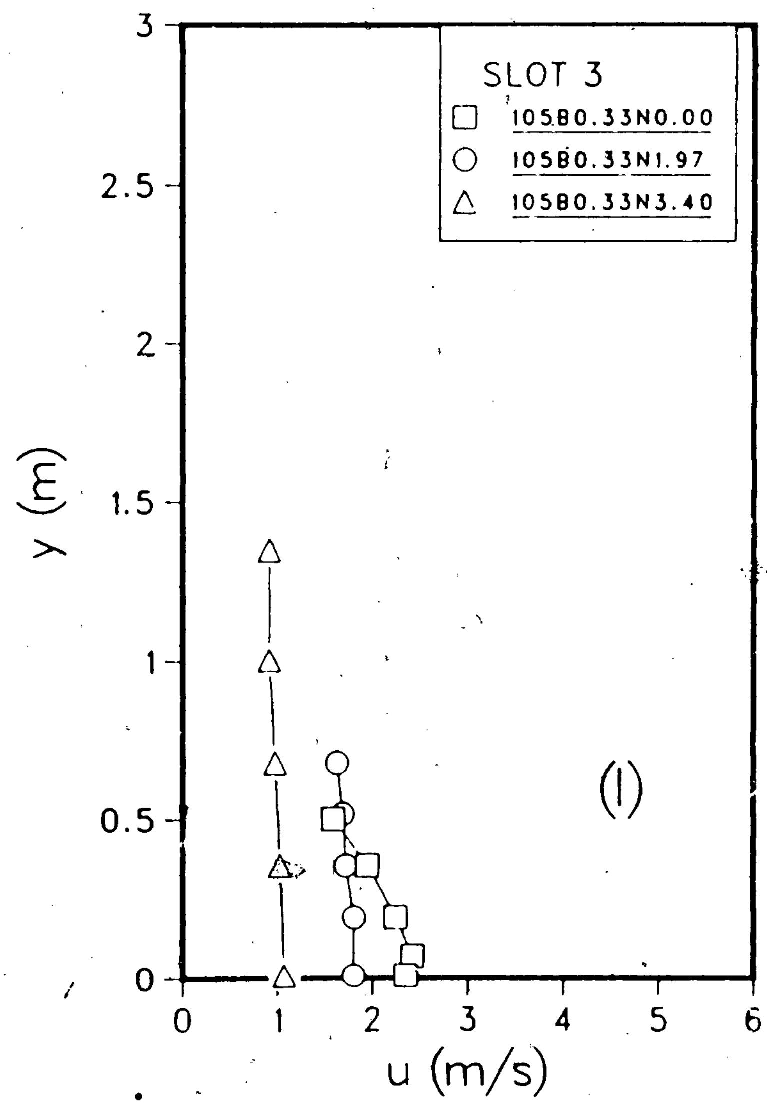

SLOT 2
105B0.66N0.00
105B0.66N0.39
105B0.66N1.20
105B0.66N2.23
(g)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6

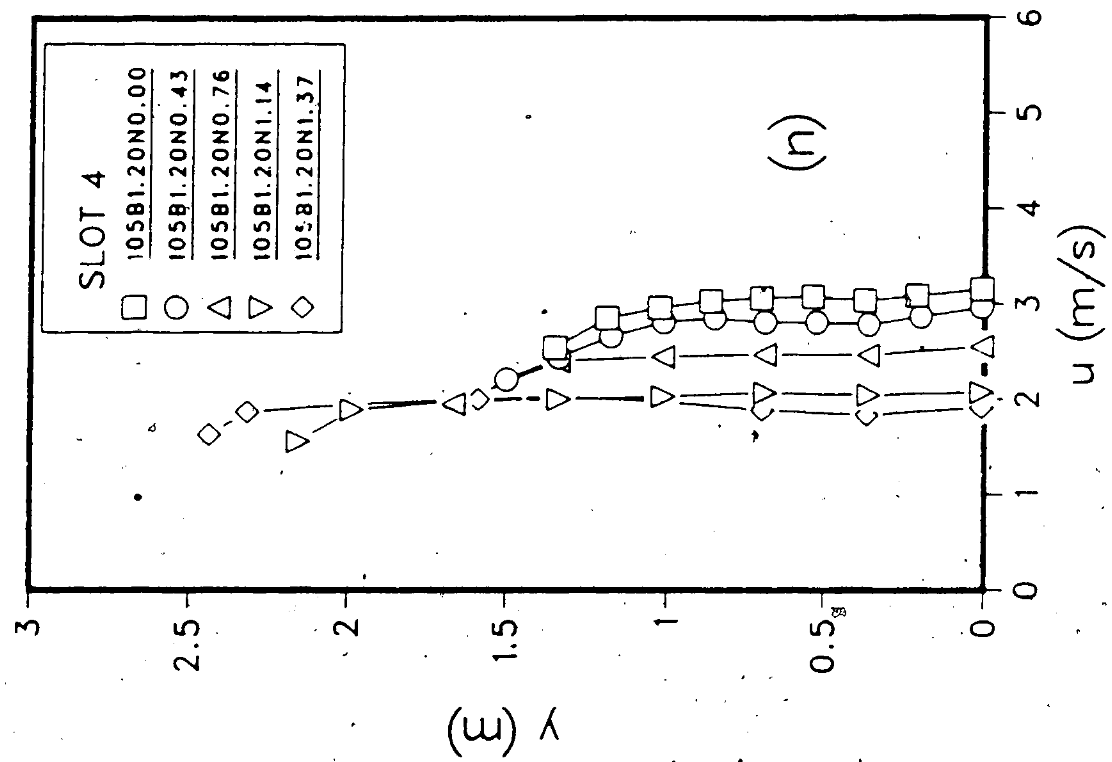

SLOT 2
105B0.33N0.00
105B0.33N1.97
105B0.33N3.40
(h)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6

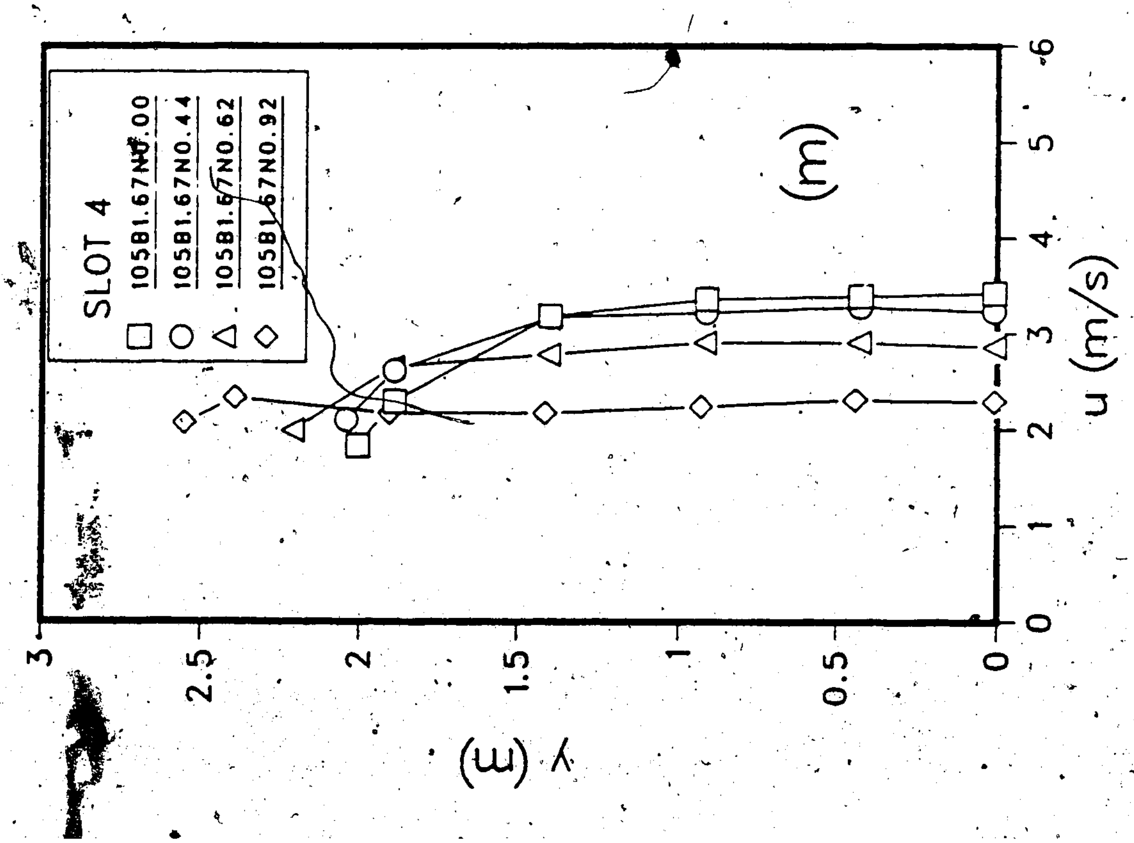

SLOT 3
105B1.67N0.00
105B1.67N0.43
105B1.67N0.62
105B1.67N0.92
(i)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6

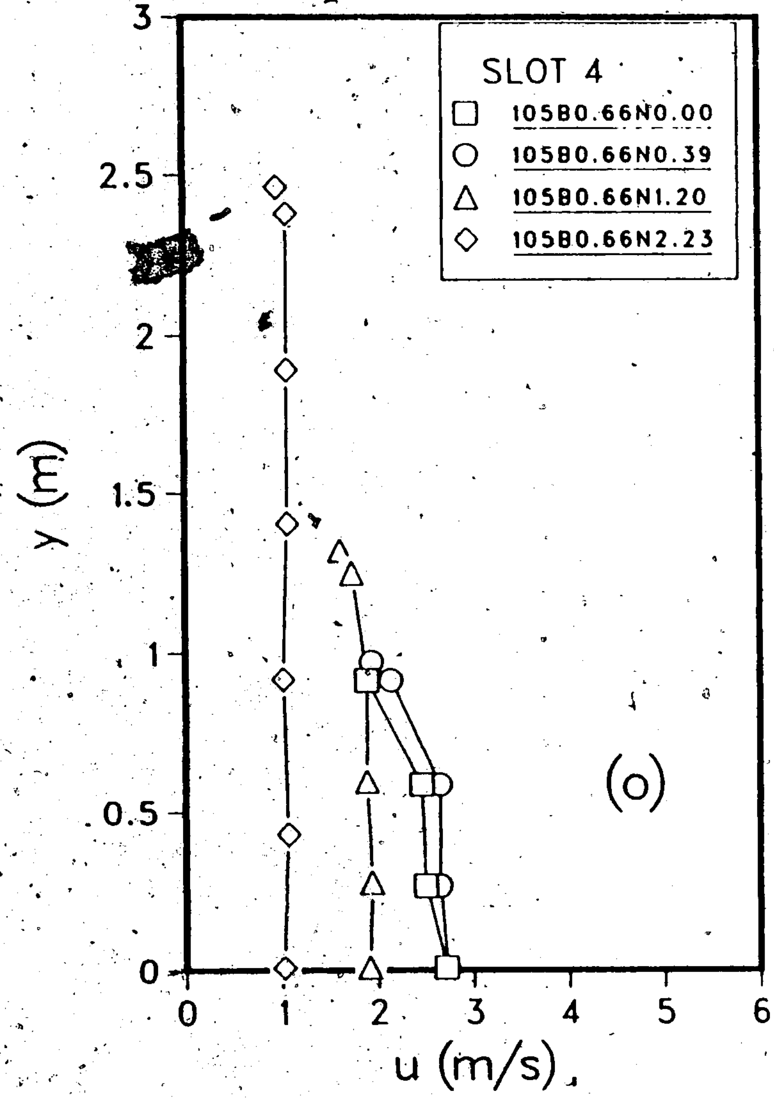

SLOT 3
105B1.20N0.00
105B1.20N0.43
105B1.20N0.76
105B1.20N1.14
105B1.20N1.37
(j)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6

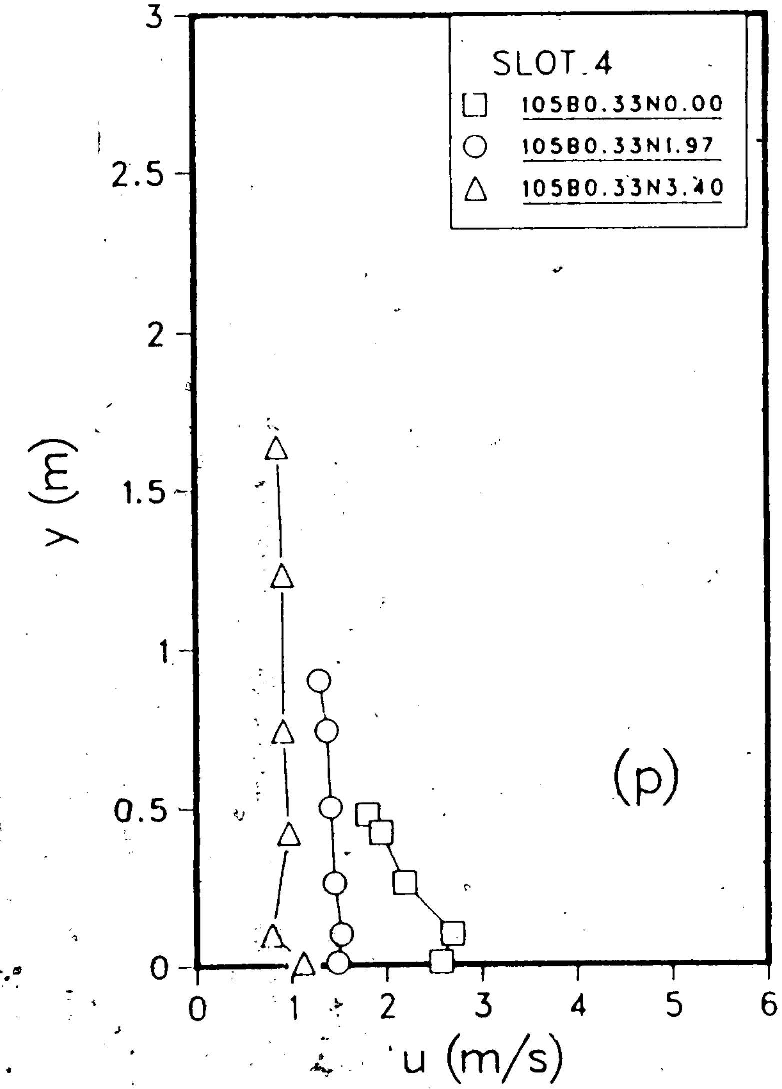

SLOT 3
105B0.66N0.00
105B0.66N0.39
105B0.66N1.20
105B0.66N2.23
(k)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
4
5
6

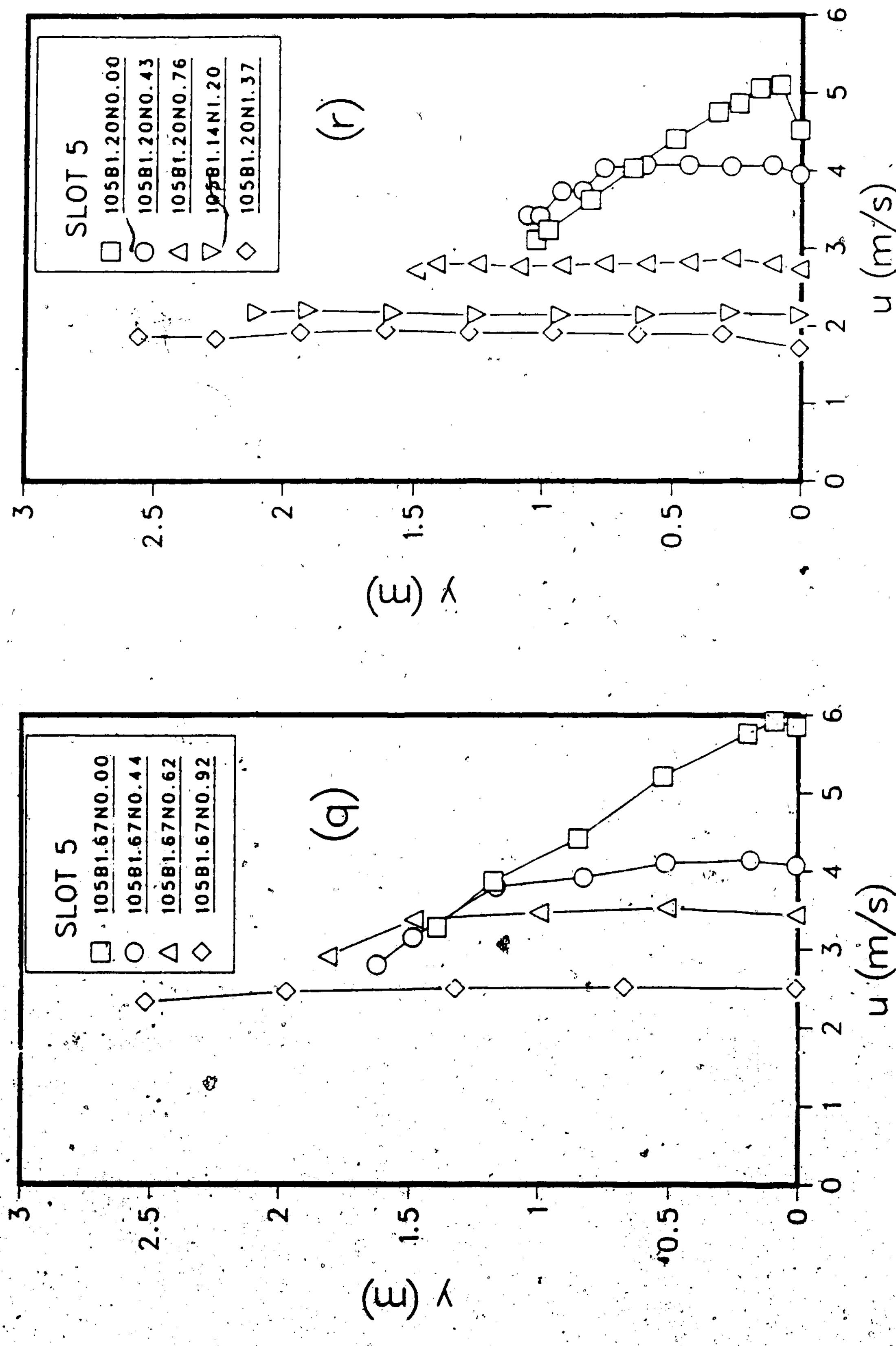

SLOT 3
105B0.33N0.00
105B0.33N1.97
105B0.33N3.40
(l)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
4
5
6

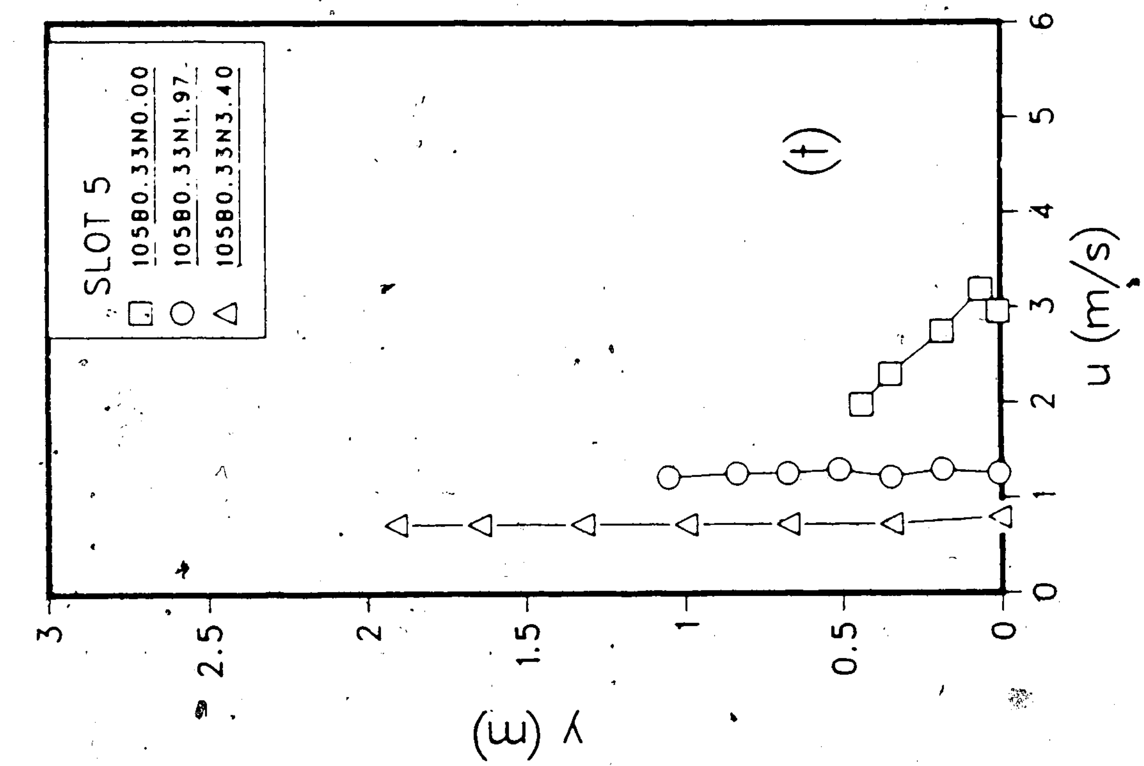

SLOT 4
105B1.20N0.00
105B1.20N0.43
105B1.20N0.76
105B1.20N1.14
105B1.20N1.37
(n)
y (m)
u (m/s)


SLOT 4
105B1.67N0.00
105B1.67N0.44
105B1.67N0.62
105B1.67N0.92
(m)
y (m)
u (m/s)


SLOT 4
105B0.66N0.00
105B0.66N0.39
105B0.66N1.20
105B0.66N2.23
(o)
y (m)
u (m/s)


SLOT 4
105B0.33N0.00
105B0.33N1.97
105B0.33N3.40
(p)
y (m)
u (m/s)


SLOT 5
105B1.20N0.00
105B1.20N0.43
105B1.20N0.76
105B1.14N1.20
105B1.20N1.37
(r)
u (m/s)
y (m)
SLOT 5
105B1.67N0.00
105B1.67N0.44
105B1.67N0.62
105B1.67N0.92
(q)
u (m/s)
y (m)


SLOT 5
105B0.33N0.00
105B0.33N1.97
105B0.33N3.40
(t)
u (m/s)
y (m)

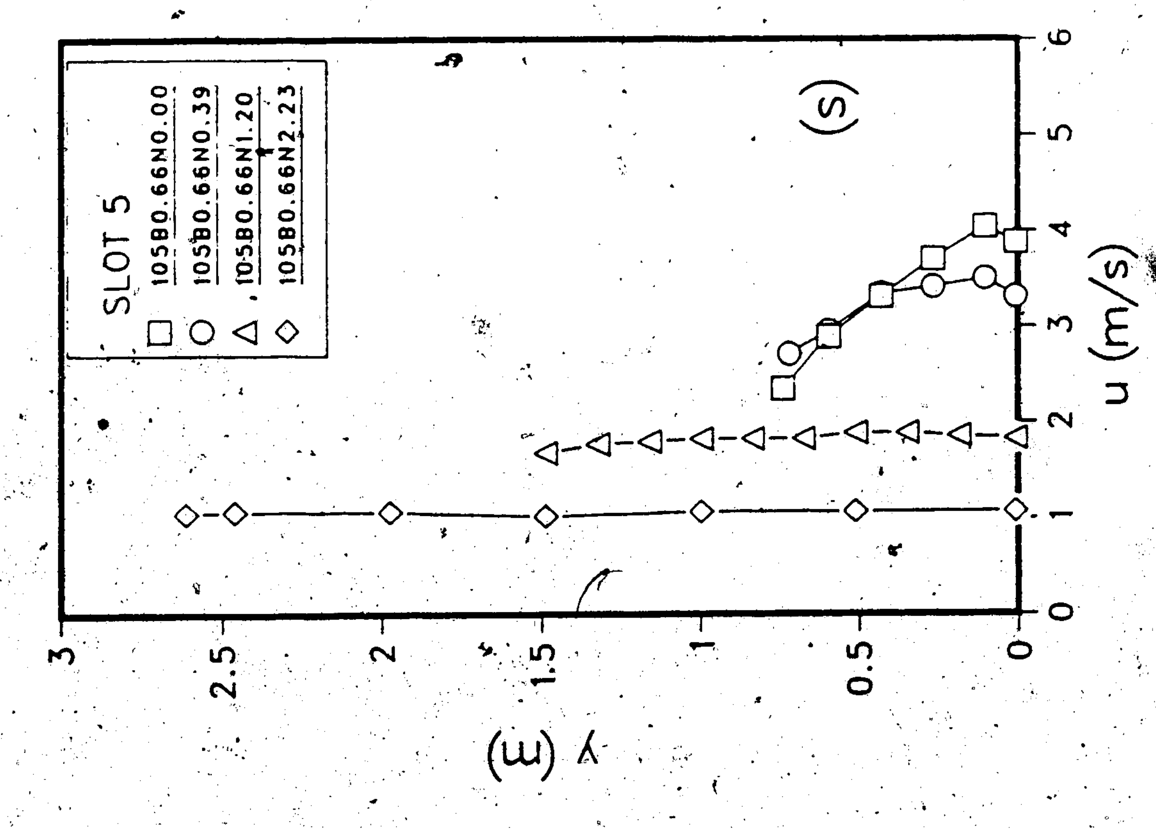
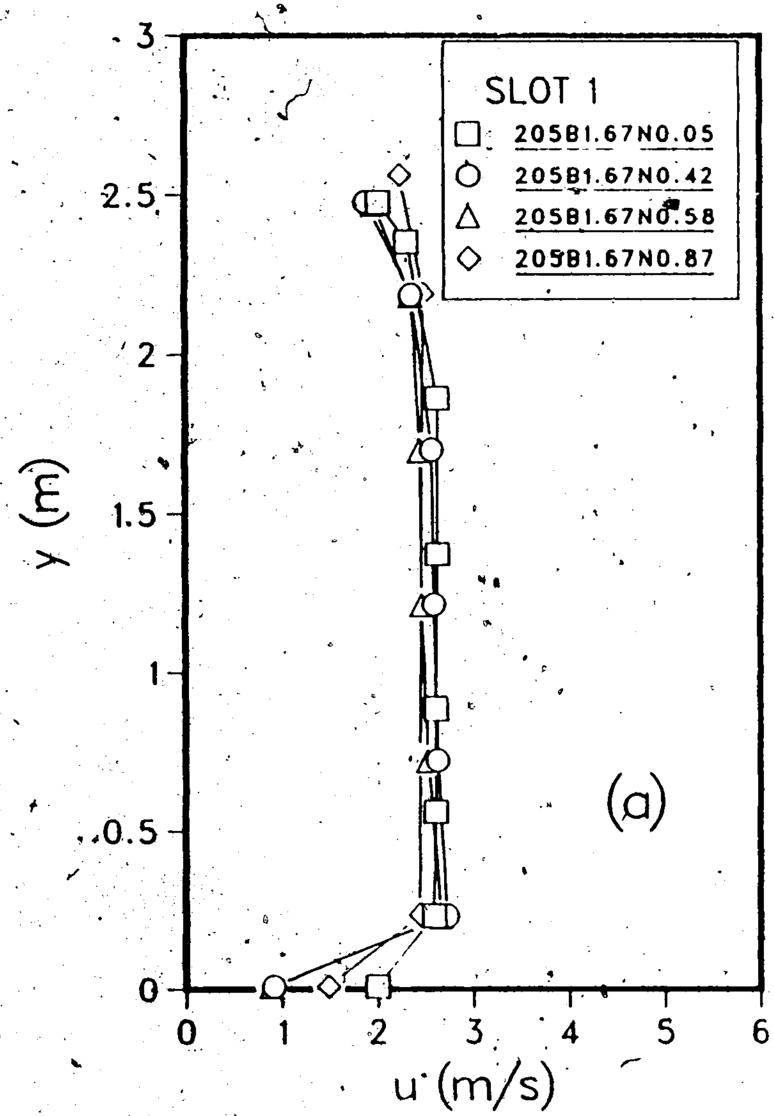
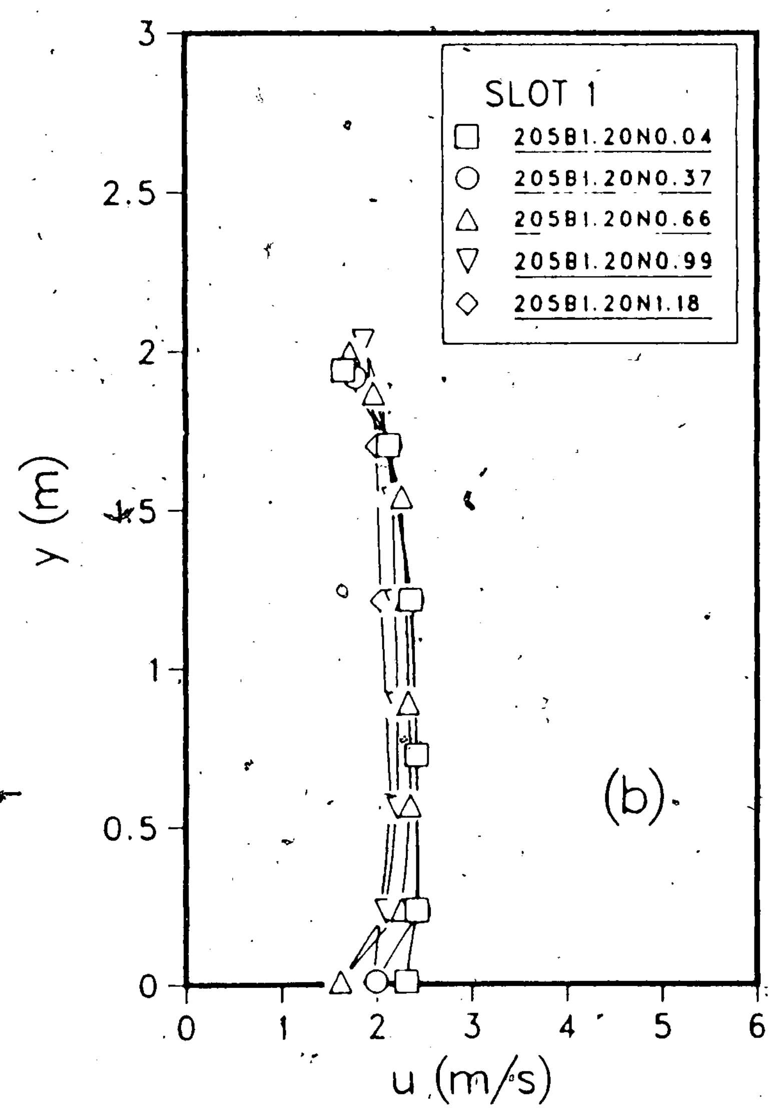
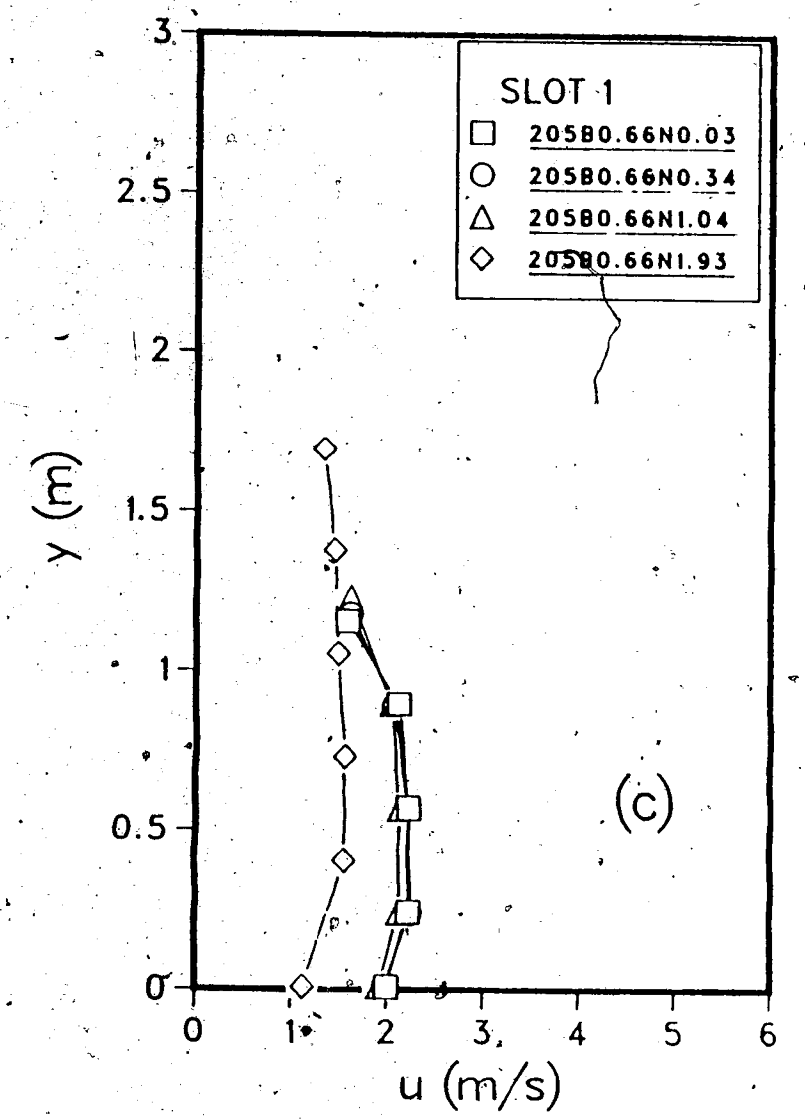
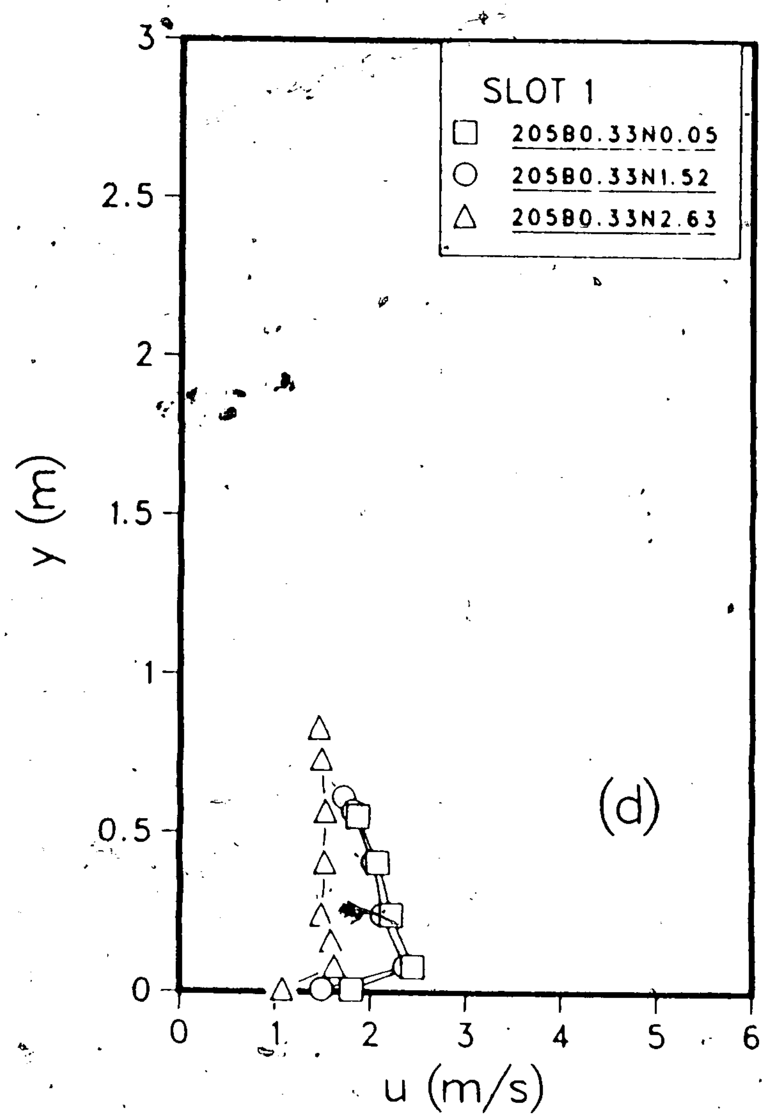

SLOT 5
105B0.66N0.00
105B0.66N0.39
105B0.66N1.20
105B0.66N2.23
(s)
u (m/s)
y (m)

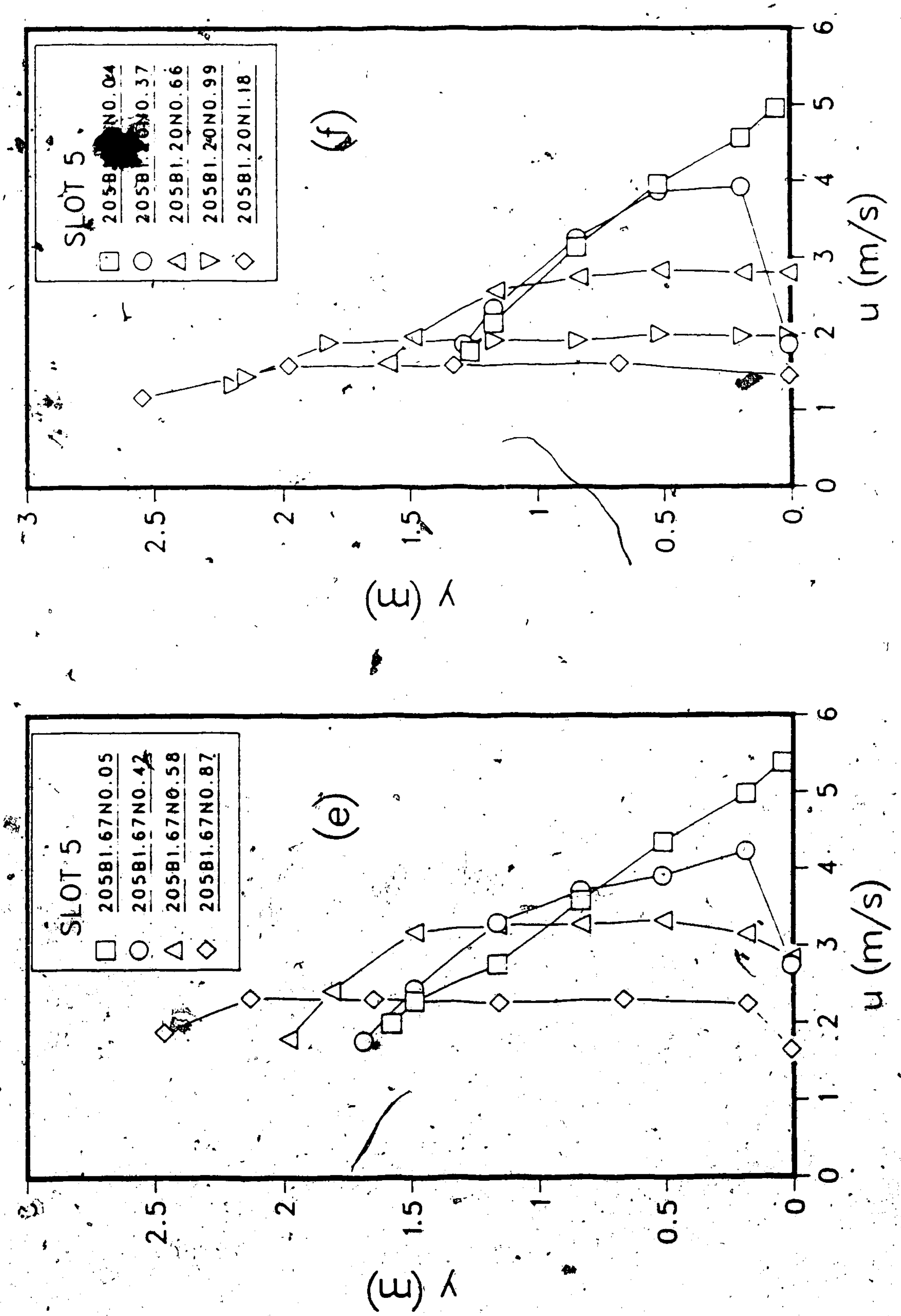
Fig. 11 Velocity profiles in the slots - Design 2.


SLOT 1
205B1.67N0.05
205B1.67N0.42
205B1.67N0.58
205B1.67N0.87
(a)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6


SLOT 1
205B1.20N0.04
205B1.20N0.37
205B1.20N0.66
205B1.20N0.99
205B1.20N1.18
(b)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6


SLOT 1
205B0.66N0.03
205B0.66N0.34
205B0.66N1.04
205B0.66N1.93
(c)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6


SLOT 1
205B0.33N0.05
205B0.33N1.52
205B0.33N2.63
(d)
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5
6


(f)
SLOT 5
205BI.20N0.66
205BI.20N0.99
205BI.20NI.18
u (m/s)
y (m)
(e)
SLOT 5
205BI.67N0.05
205BI.67N0.42
205BI.67N0.58
205BI.67N0.87
u (m/s)
y (m)

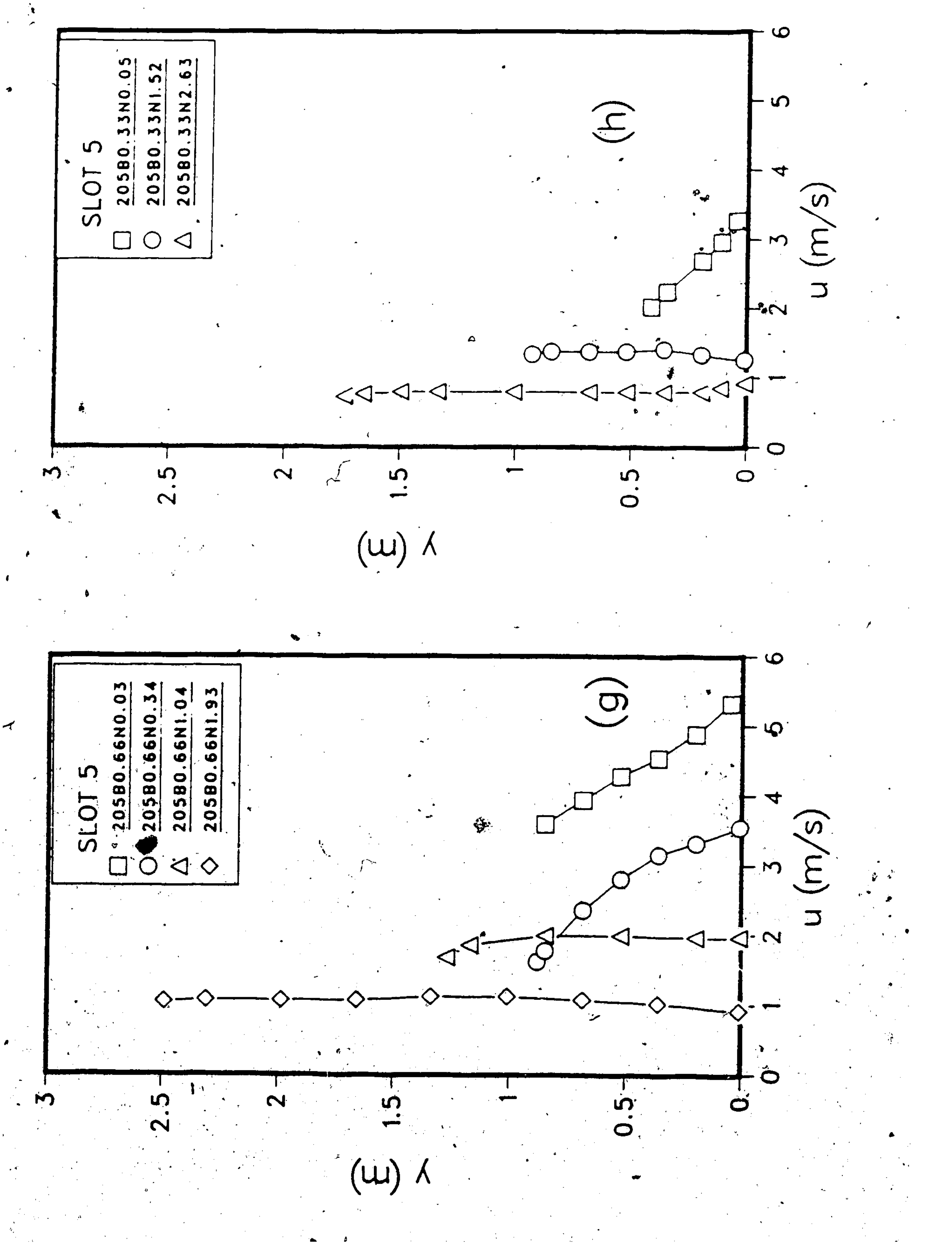
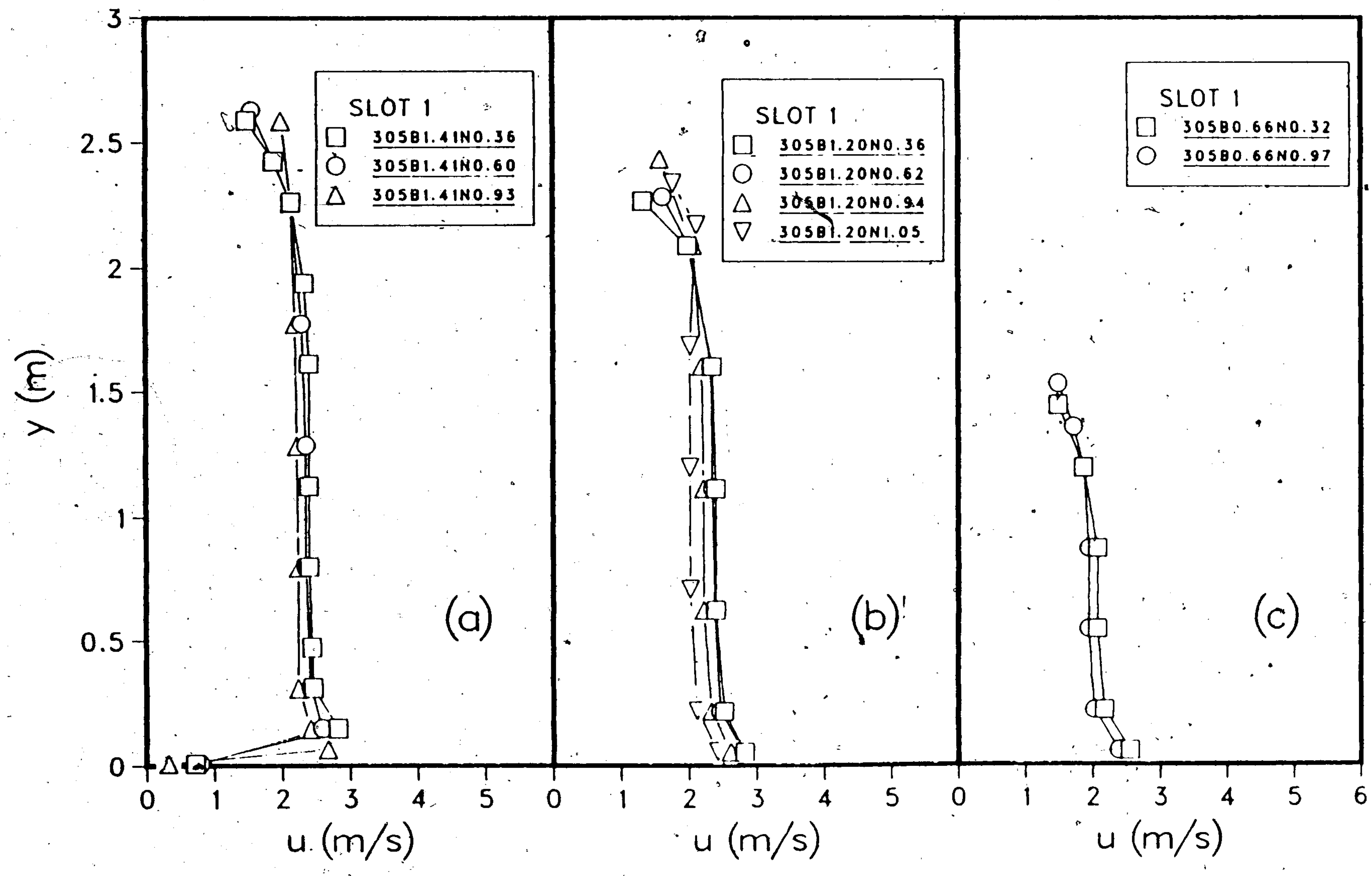
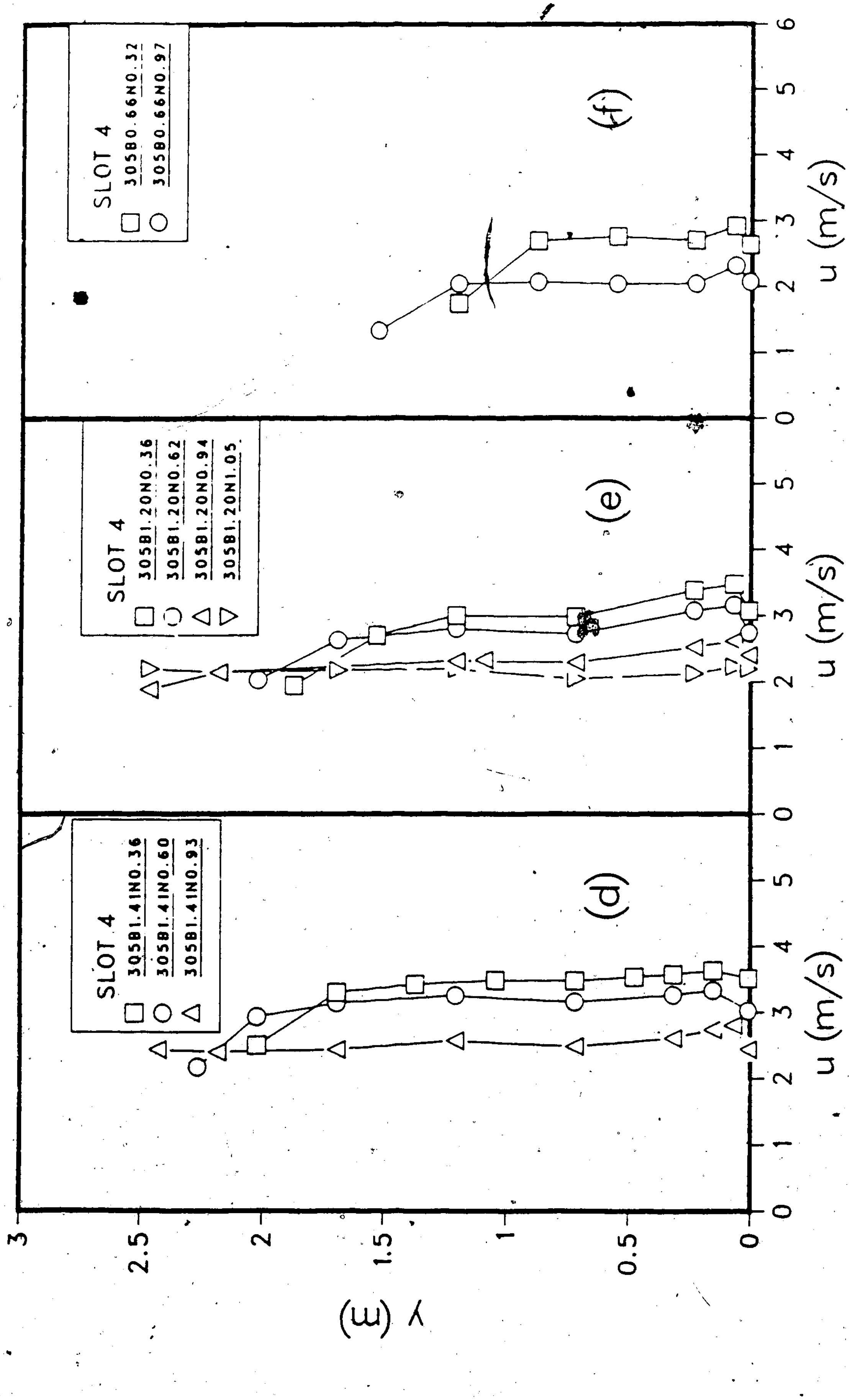

SLOT 5
205B0.33N0.05
205B0.33N1.52
205B0.33N2.63
(h)
y (m)
u (m/s)
SLOT 5
205B0.66N0.03
205B0.66N0.34
205B0.66N1.04
205B0.66N1.93
(g)
y (m)
u (m/s)

Fig. 12 Velocity profiles in the slots - Design 3.



SLOT 1
305B1.41N0.36
305B1.41N0.60
305B1.41N0.93
(a)
SLOT 1
305B1.20N0.36
305B1.20N0.62
305B1.20N0.94
305B1.20N1.05
(b)
SLOT 1
305B0.66N0.32
305B0.66N0.97
(c)
u (m/s)
y (m)



(d)
SLOT 4
305B1.41N0.36
305B1.41N0.60
305B1.41N0.93
(e)
SLOT 4
305B1.20N0.36
305B1.20N0.62
305B1.20N0.94
305B1.20N1.05
(f)
SLOT 4
305B0.66N0.32
305B0.66N0.97
u (m/s)
y (m)

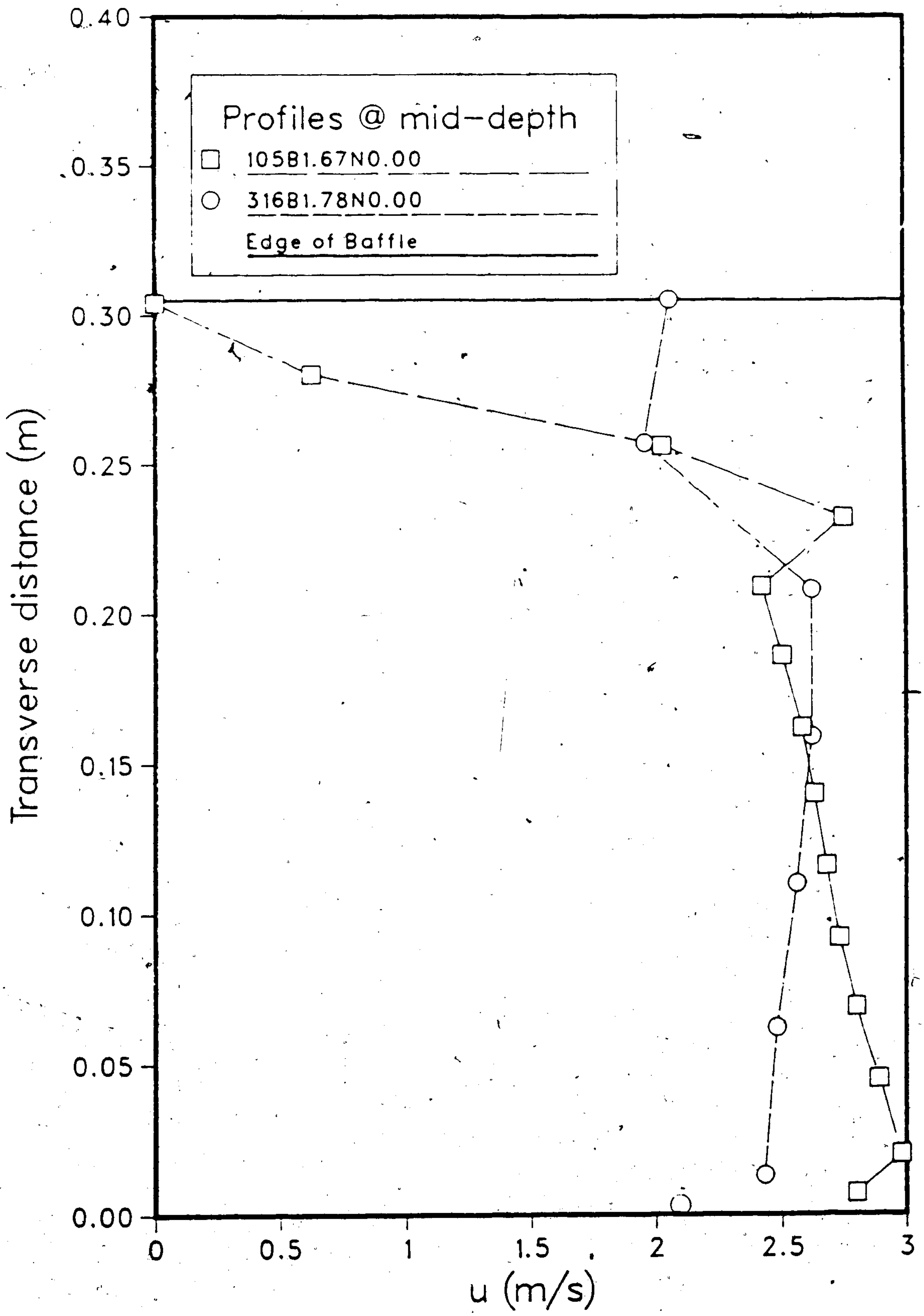


Fig. 13 Transverse velocity profiles.

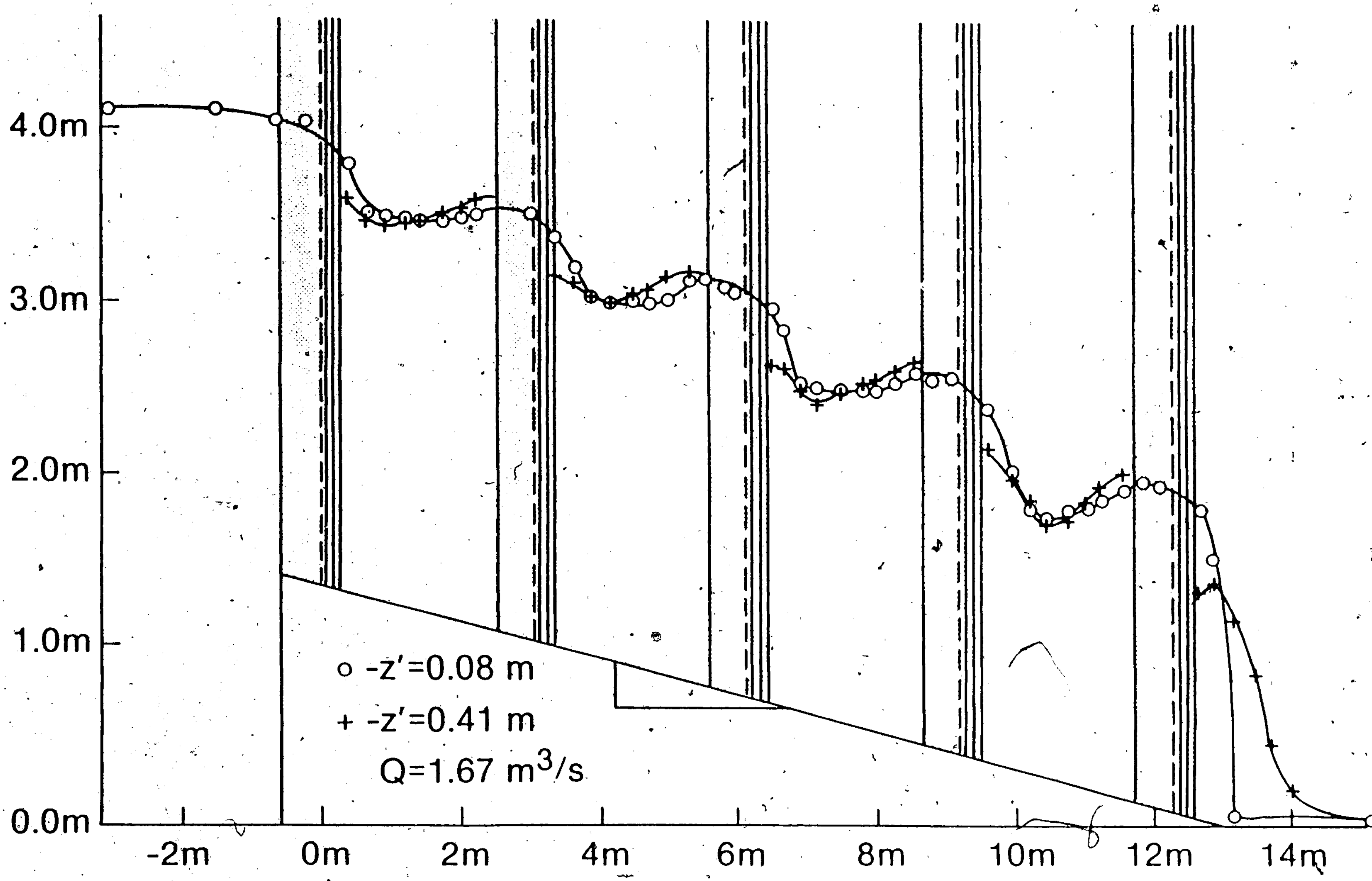
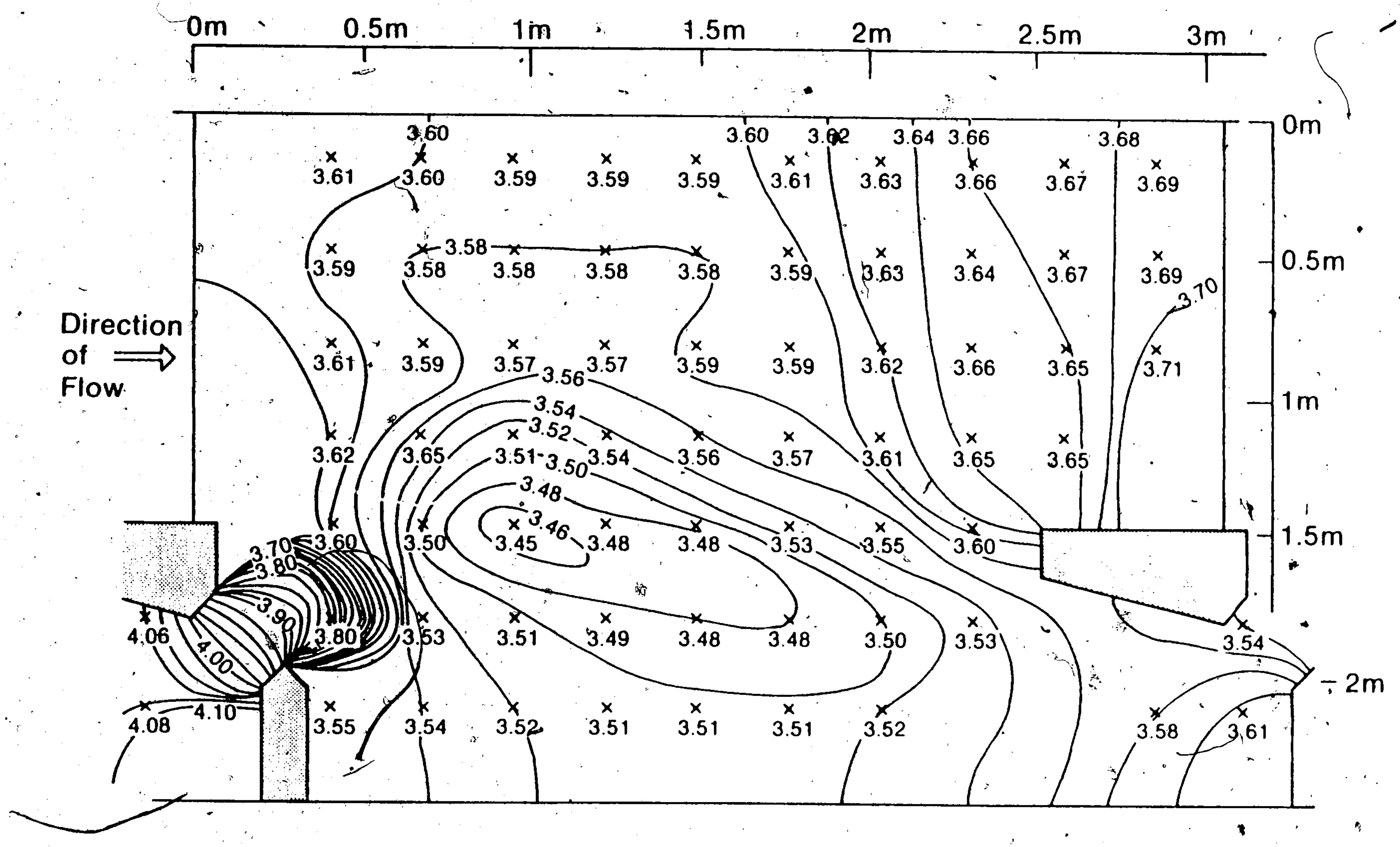


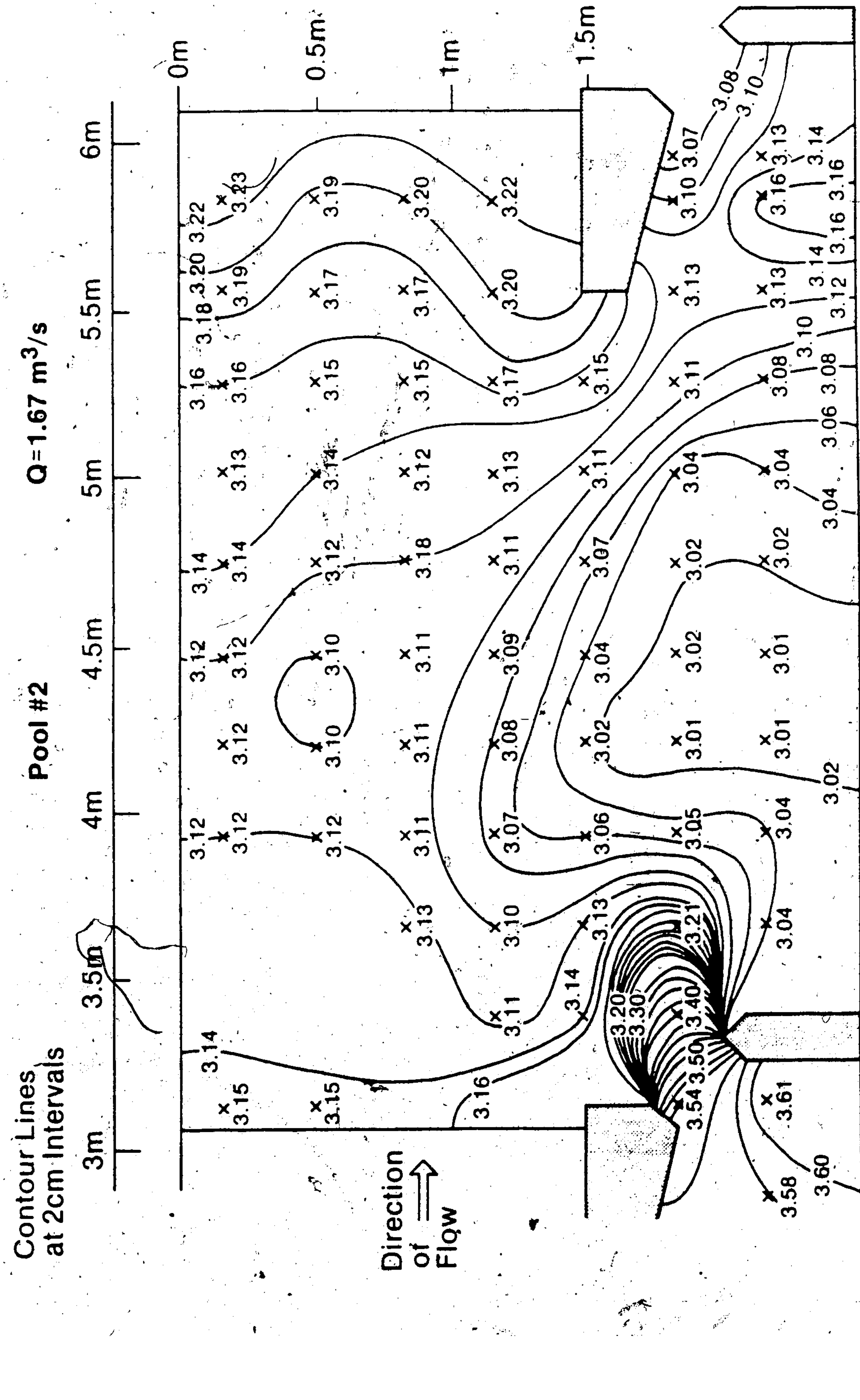
Fig. 14 Longitudinal water surface profiles.

Fig. 15 Water surface contours.

at 2cm intervals   Pool #1   Q=1.67 m³/s

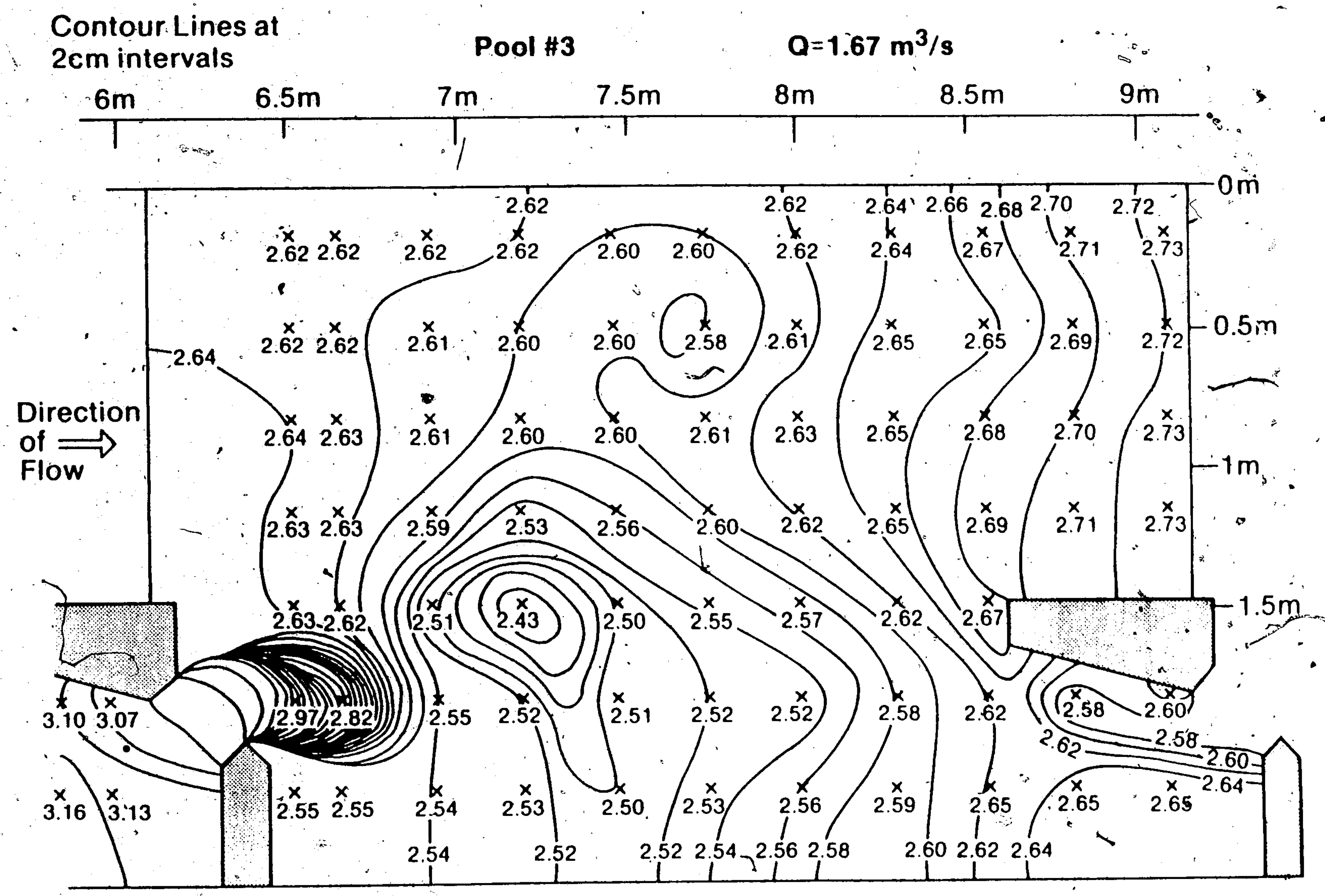


(a)

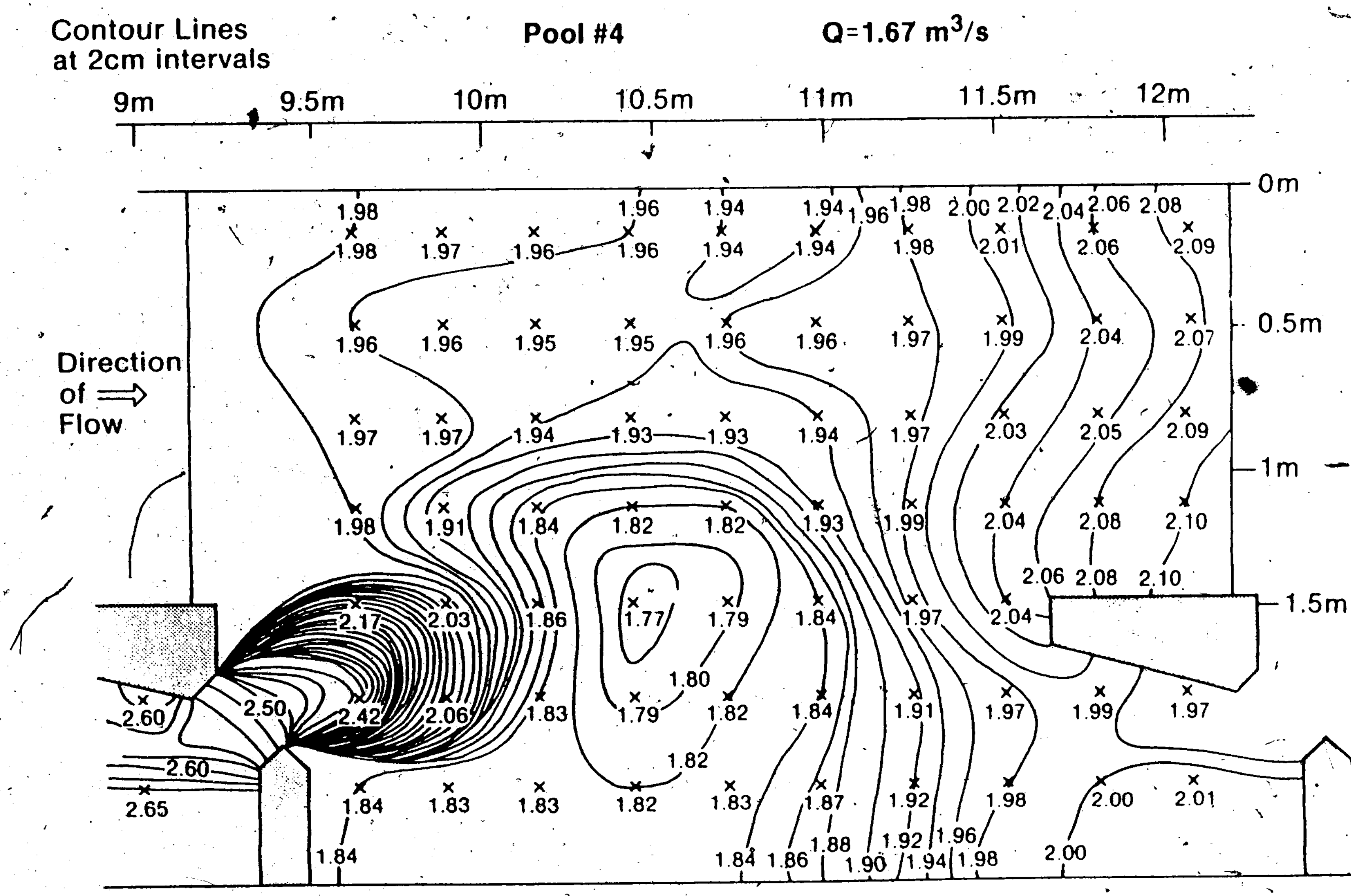


Contour Lines at 2cm Intervals
Pool #2
Q=1.67 m^3/s
Direction of Flow
0m
0.5m
1m
1.5m
3m
3.5m
4m
4.5m
5m
5.5m
6m

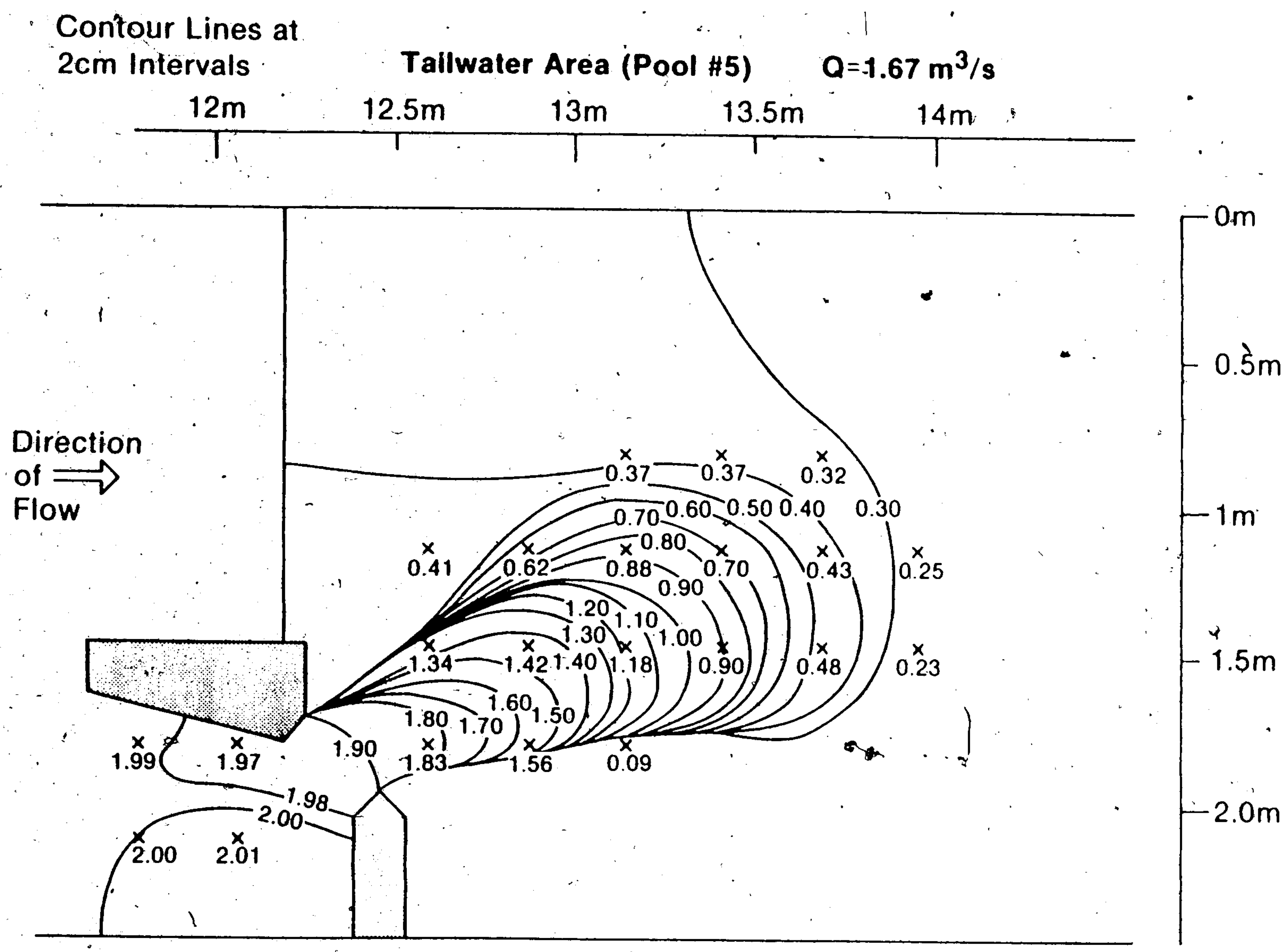
(b)


Contour Lines at
2cm intervals
Pool #3
Q=1.67 m³/s
6m
6.5m
7m
7.5m
8m
8.5m
9m
0m
0.5m
1m
1.5m
Direction
of
Flow
2.62
2.62
2.64 2.66 2.68 2.70
2.72
2.62 2.62 2.62 2.62 2.60 2.60 2.62 2.64 2.67 2.71 2.73
2.64
2.62 2.62 2.61 2.60 2.60 2.58 2.61 2.65 2.65 2.69 2.72
2.64 2.63 2.61 2.60 2.60 2.61 2.63 2.65 2.68 2.70 2.73
2.63 2.63 2.59 2.53 2.56 2.60 2.62 2.65 2.69 2.71 2.73
2.63 2.62 2.51 2.43 2.50 2.55 2.57 2.62 2.67
3.10 3.07 2.97 2.82 2.55 2.52 2.51 2.52 2.52 2.58 2.62 2.58 2.60
2.62
2.58
2.60
2.64
3.16 3.13 2.55 2.55 2.54 2.53 2.50 2.53 2.56 2.59 2.65 2.65 2.65
2.54 2.52 2.52 2.54 2.56 2.58 2.60 2.62 2.64

(c)


Contour Lines
at 2cm intervals
Pool #4
Q=1.67 m³/s
9m
9.5m
10m
10.5m
11m
11.5m
12m
0m
0.5m
1m
1.5m
Direction
of ⟹
Flow

(d)



Contour Lines at
2cm Intervals
Tailwater Area (Pool #5)
Q=1.67 m3/s
12m
12.5m
13m
13.5m
14m
0m
0.5m
1m
1.5m
2.0m
Direction
of
Flow
0.37
0.37
0.32
0.70
0.60
0.50
0.40
0.30
0.41
0.62
0.80
0.88
0.70
0.43
0.25
0.90
1.20
1.10
1.30
1.00
1.34
1.42
1.40
1.18
0.90
0.48
0.23
1.60
1.50
1.80
1.70
1.90
1.99
1.97
1.83
1.56
0.09
1.98
2.00
2.00
2.01

(e)

Fig. 16 Circulation patterns (horizontal) for Design 1.

Symbols for Flow Direction

(observation of string direction in water)

•—— / ——• indicates direction in horizontal plane

⊙ upward flow

⊗ downward flow

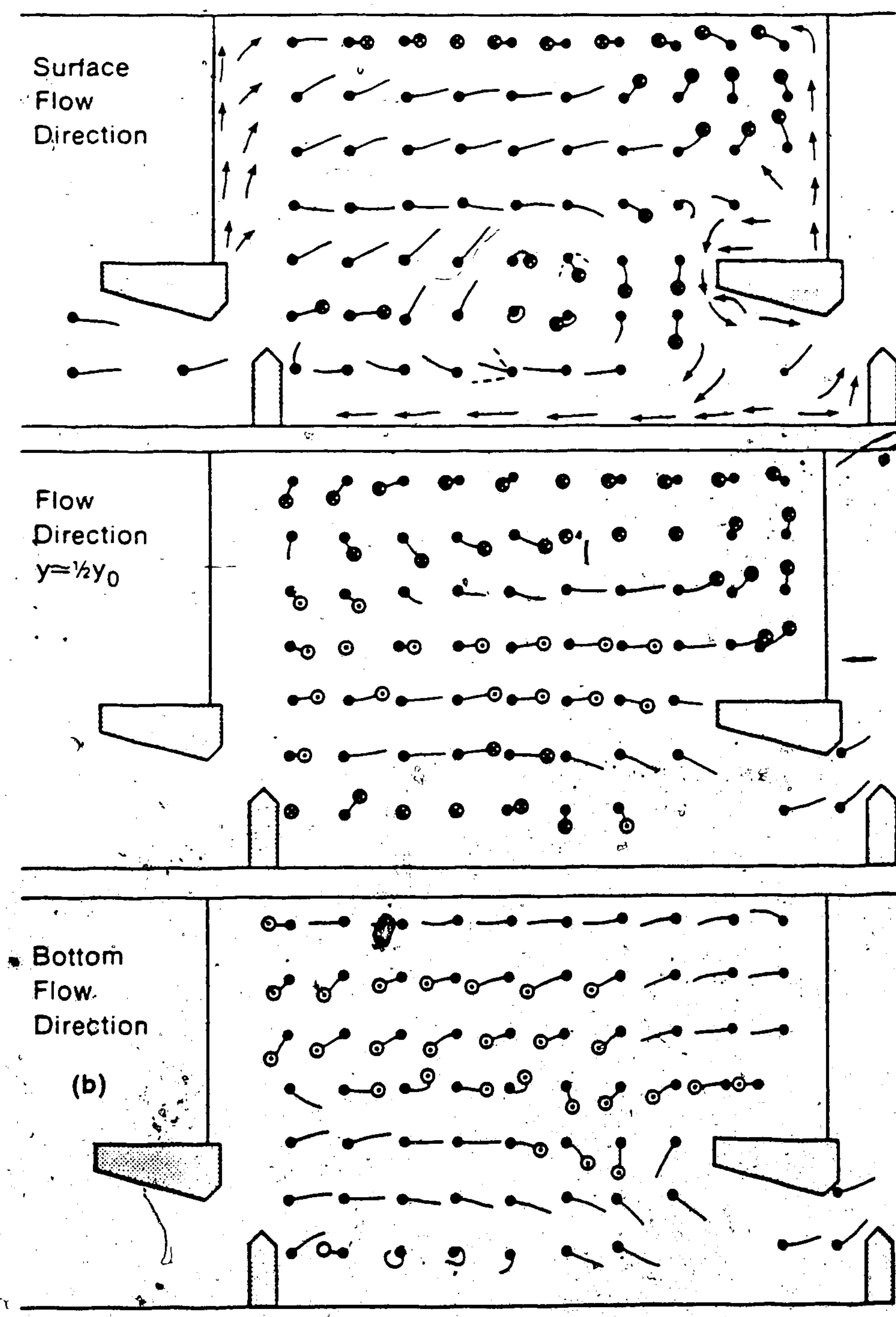
•–⊙ flow not directly upwards

•——⊙ flow closer to horizontal plane with upward flow

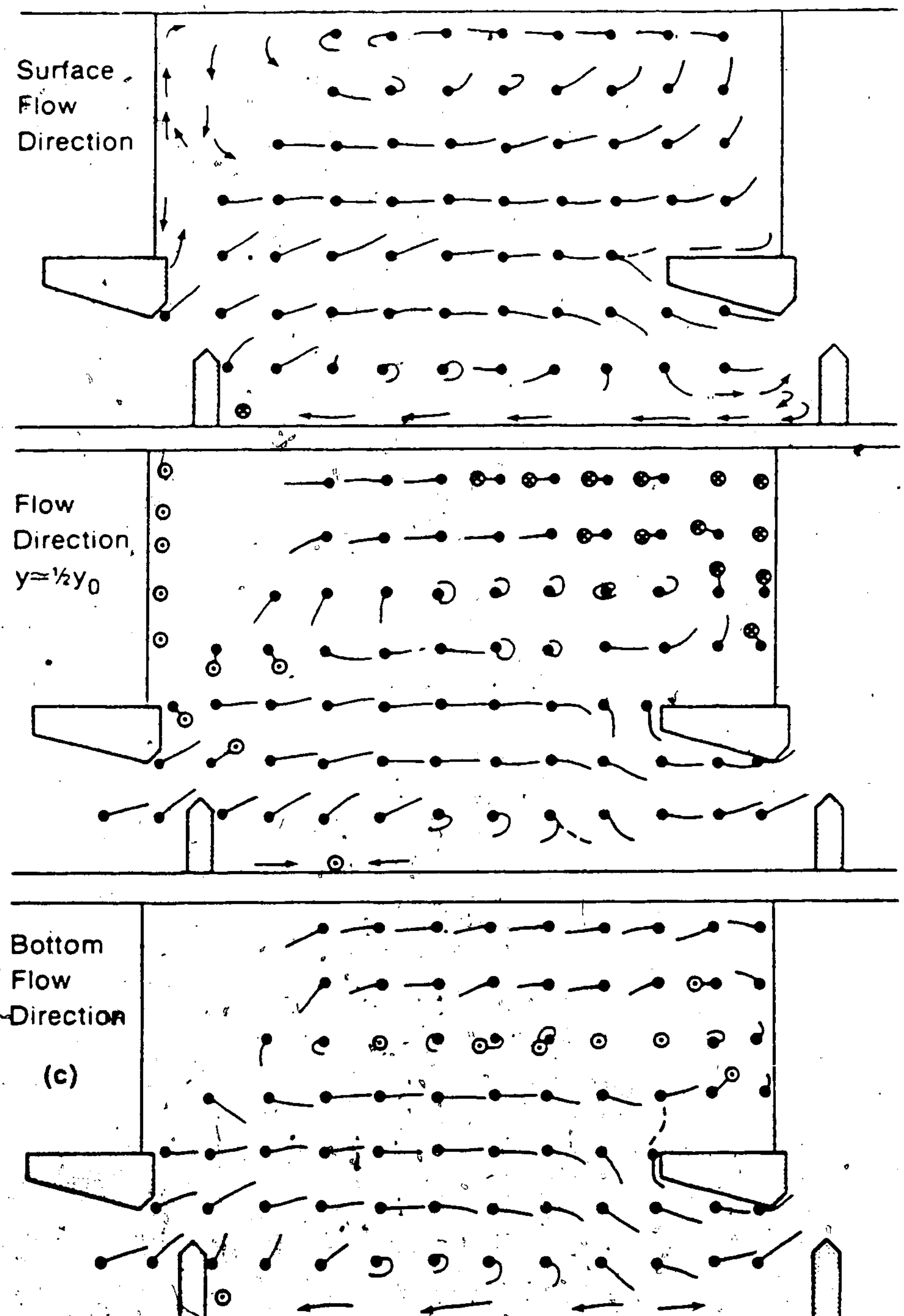
flow changes direction frequently
(near center of rotation)

→ / ← flow observed by injecting dye into water
(used to fill in details)

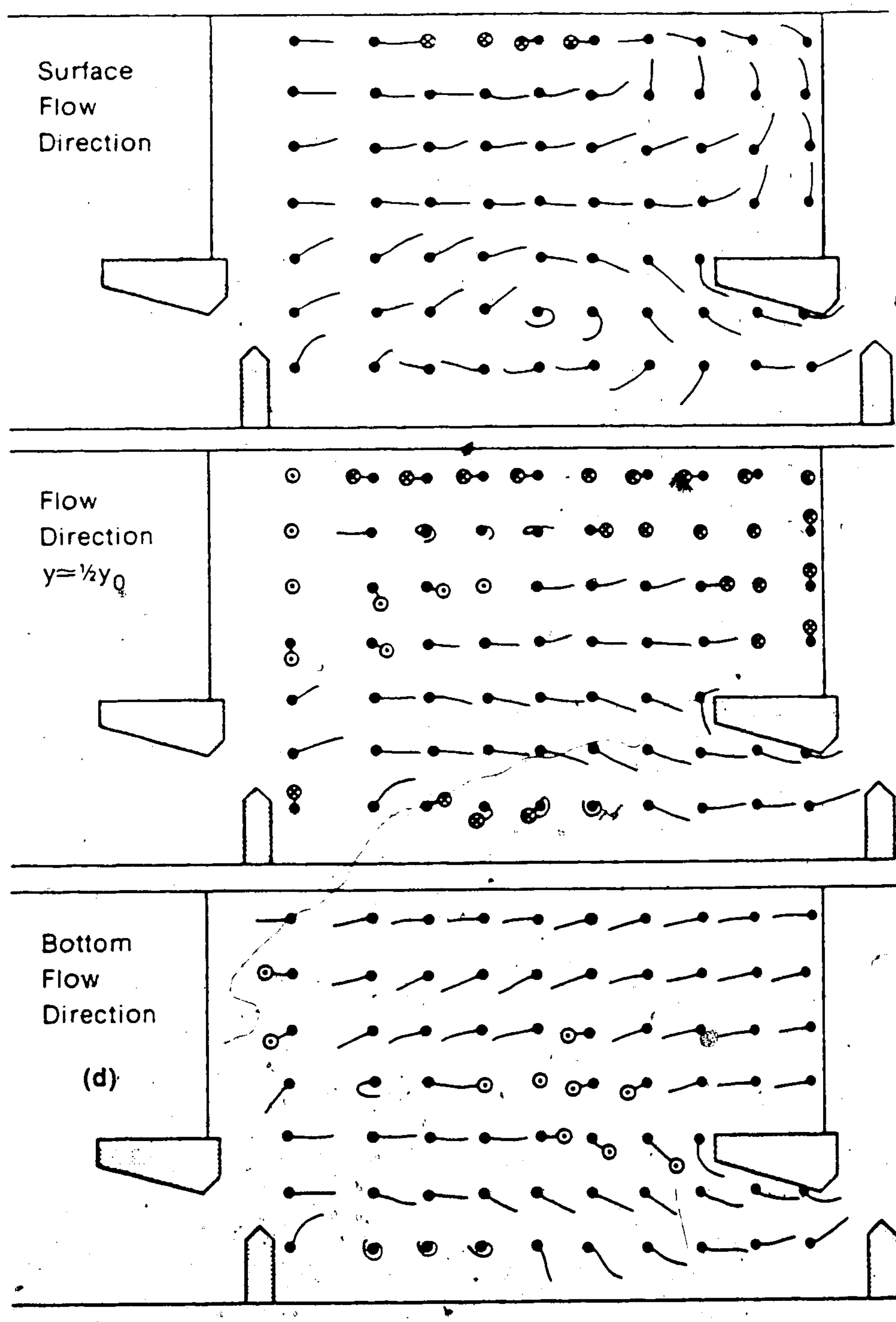
(a)



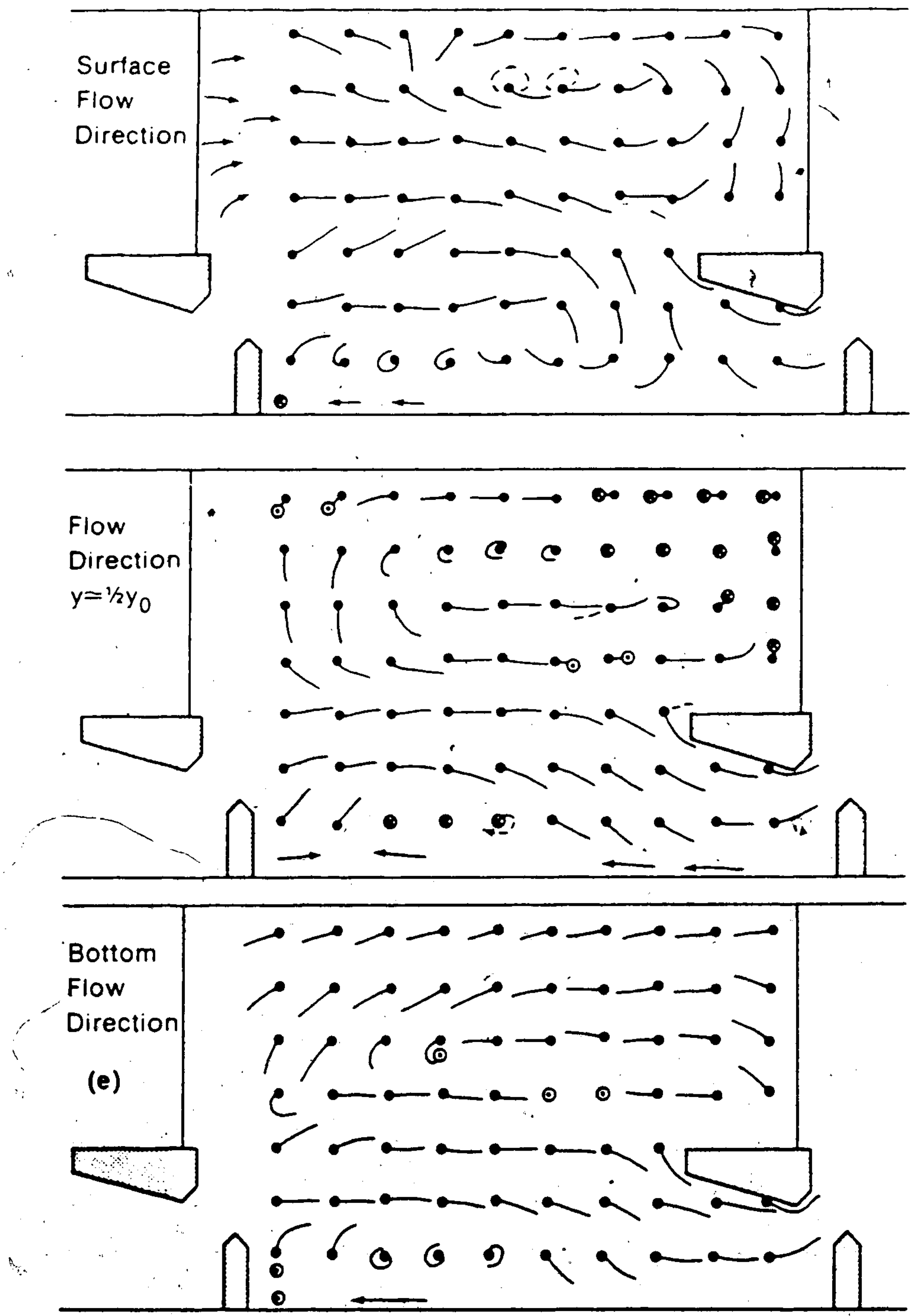
Pool 1 Q = 1.67 m³/s (No Tailwater Control)



Pool 2 Q = 1.67 m^3/s (No Tailwater Control)

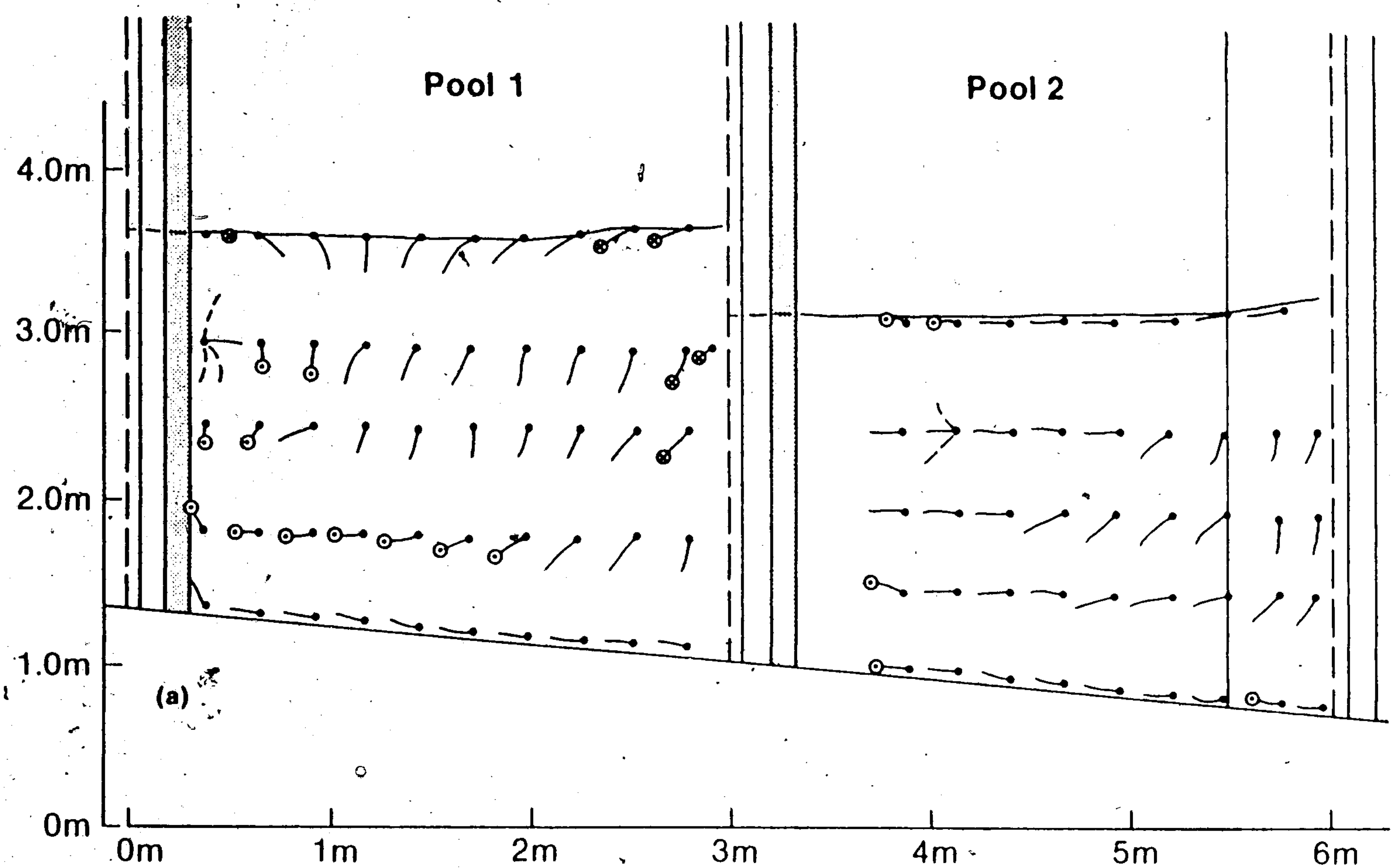


Pool 3 Q = 1.67 m³/s (No Tailwater Control)

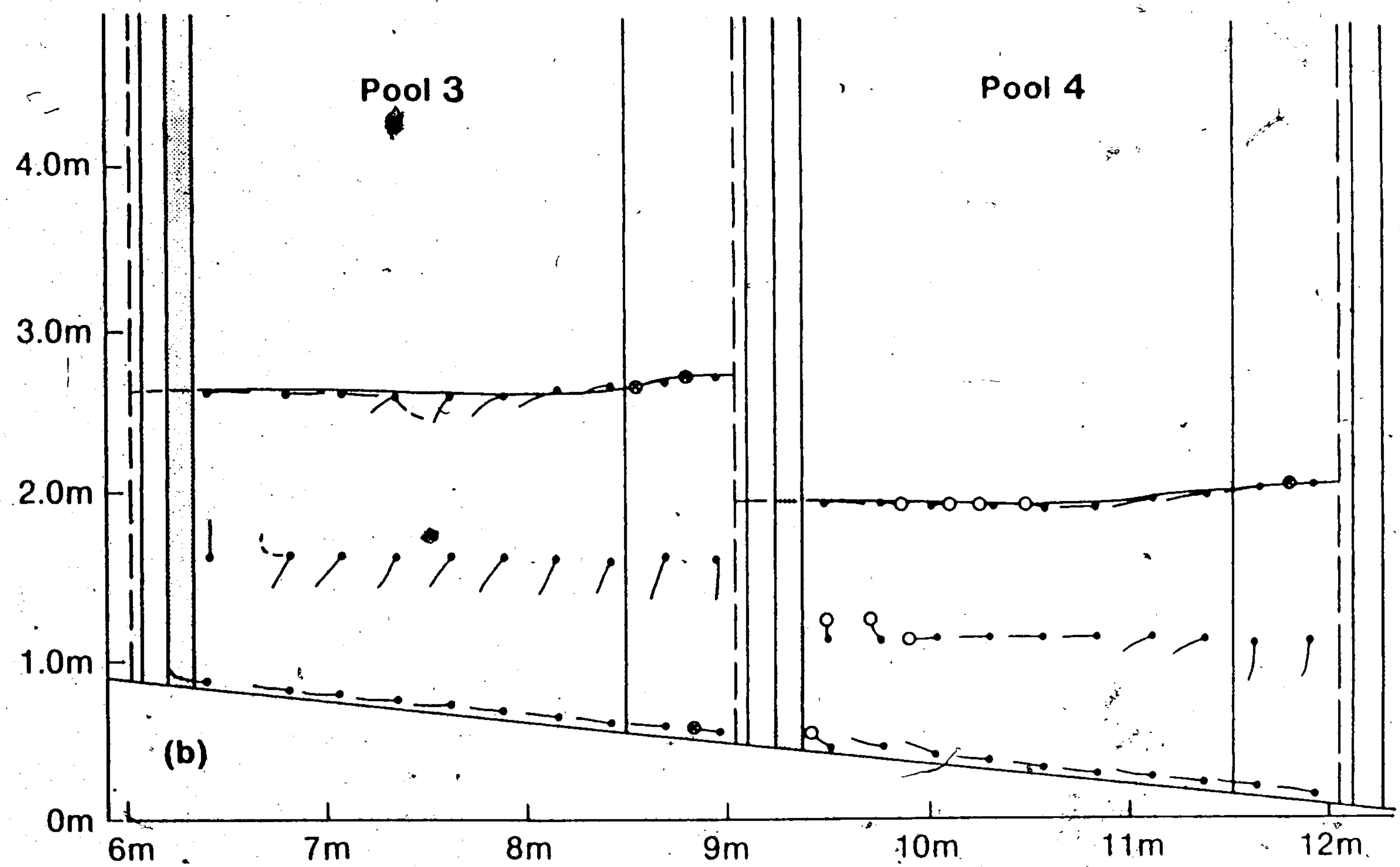


Pool 4 Q = 1.67 m^3/s (No Tailwater Control)

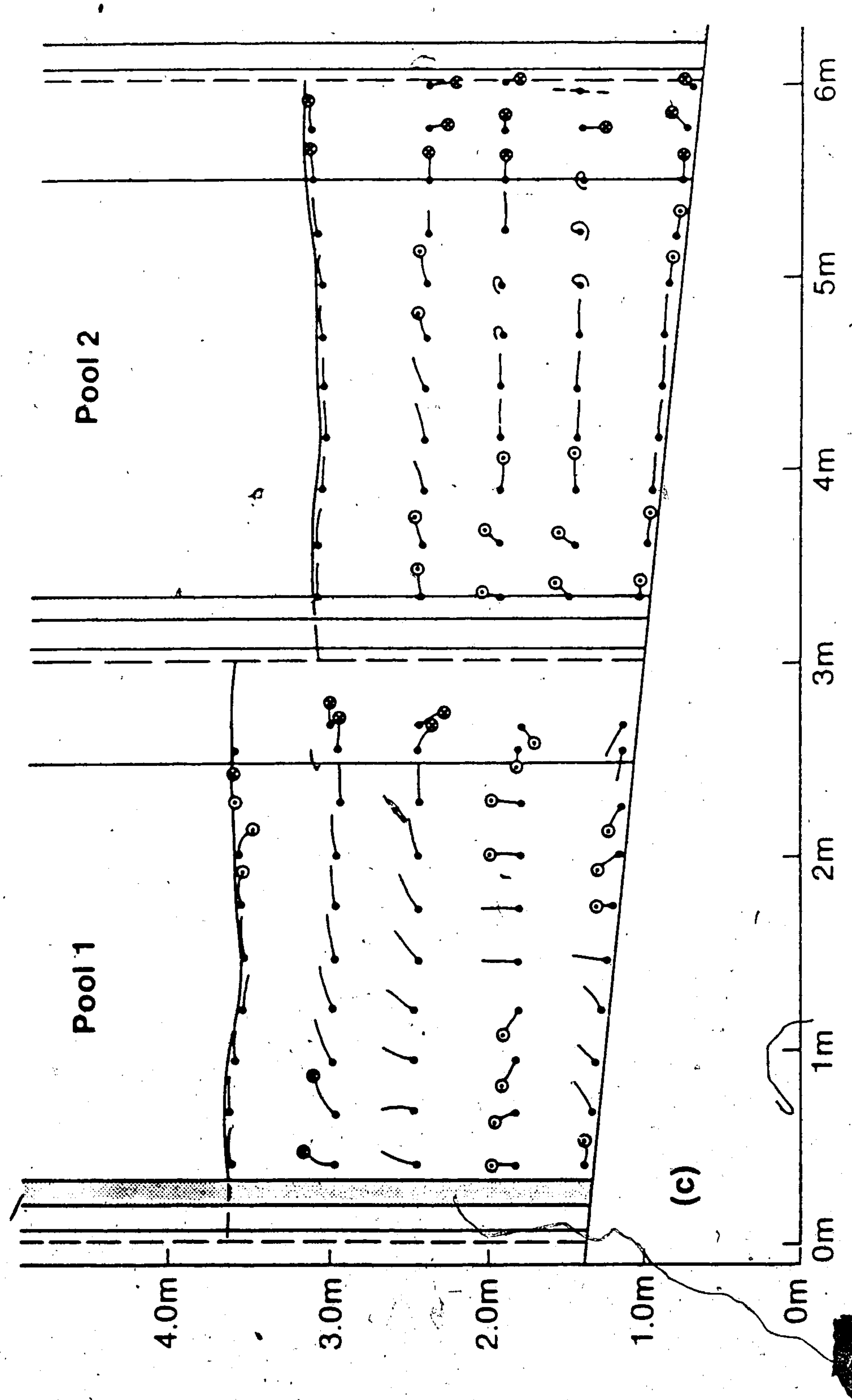
Fig. 17 Circulation patterns (vertical) for Design 1.



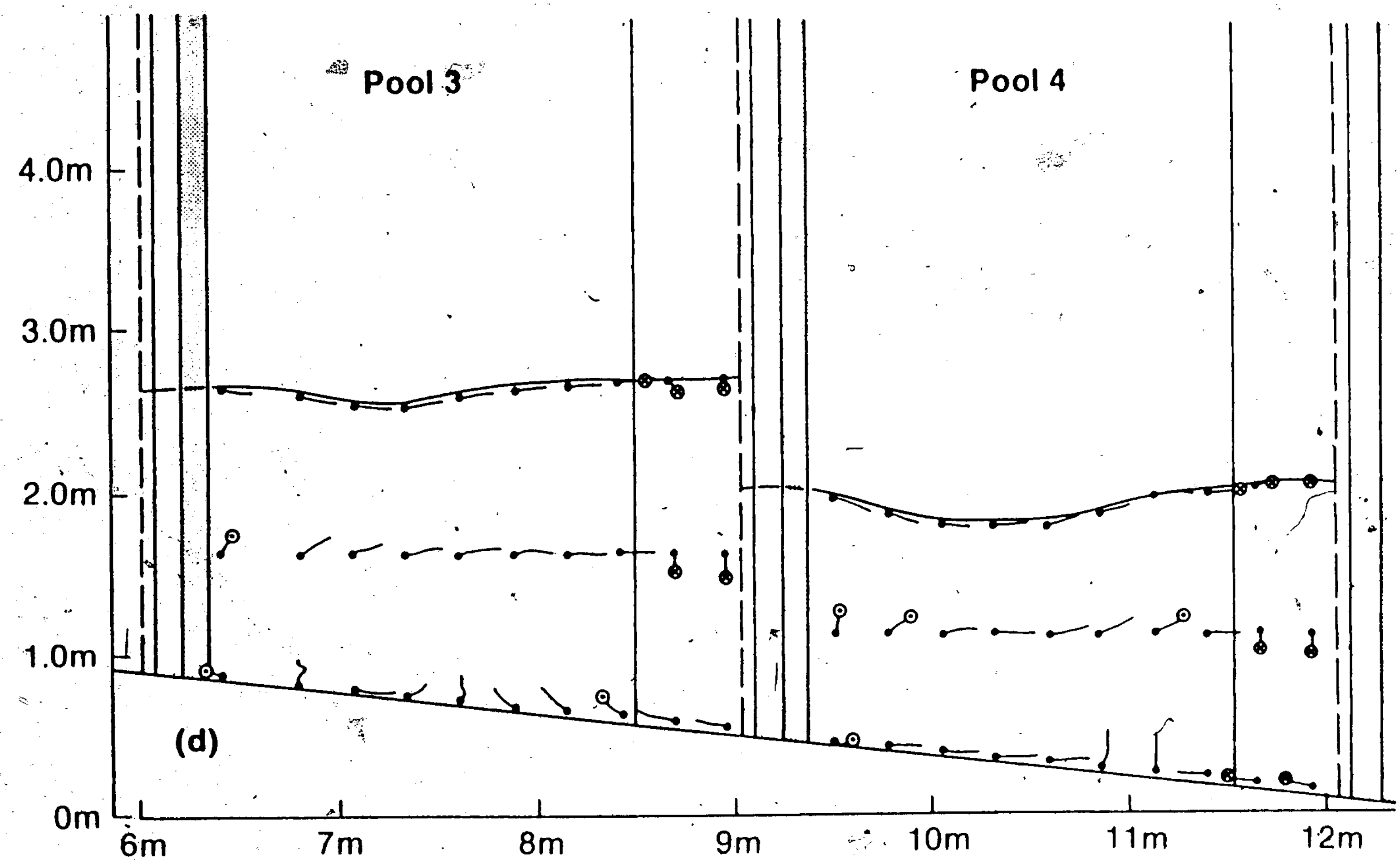
z'=1.71 m Q = 1.67 m^3/s (No Tailwater Control)



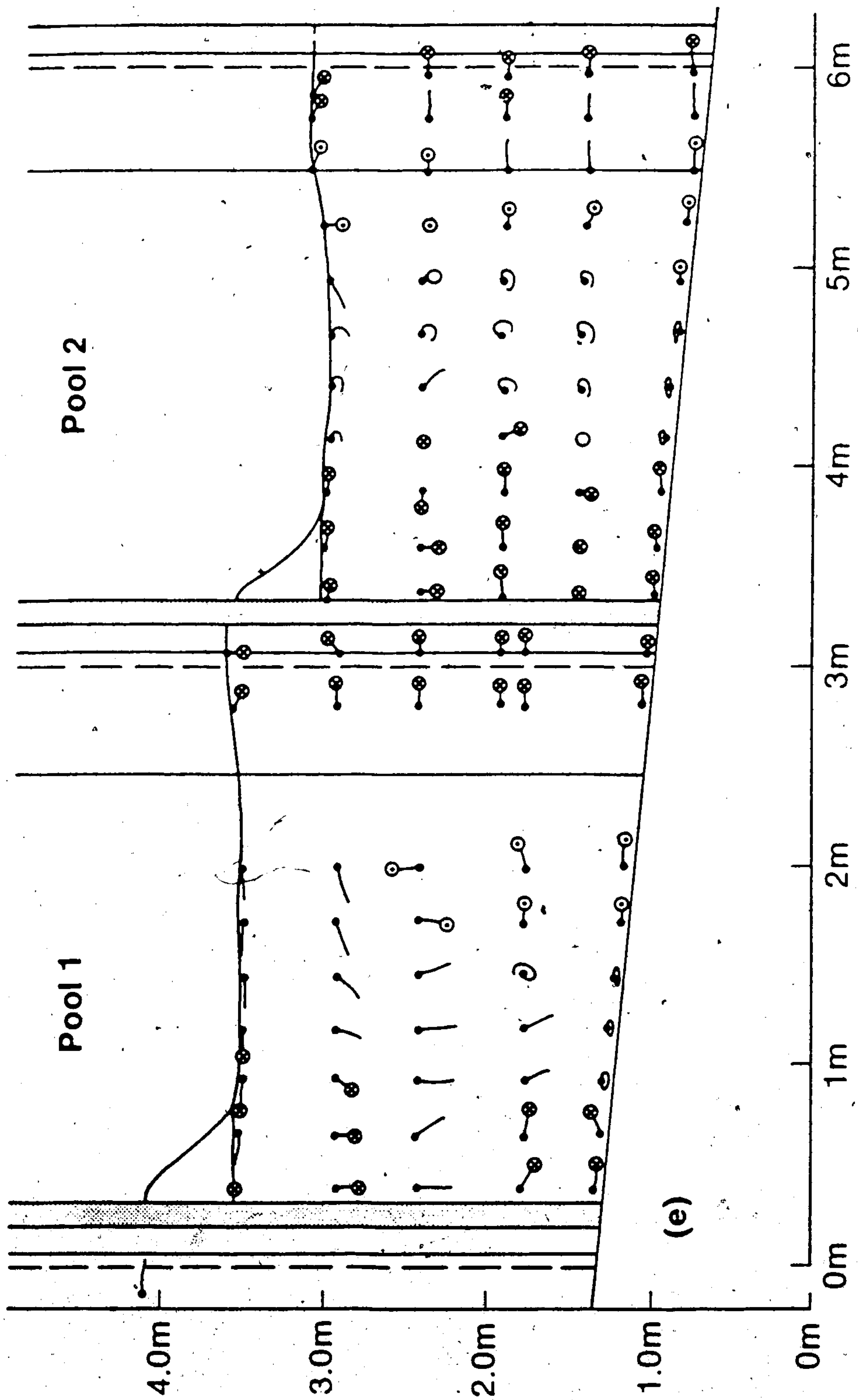
z'=1.71 m   Q ≐ 1.67 m^3/s (No Tailwater Control)



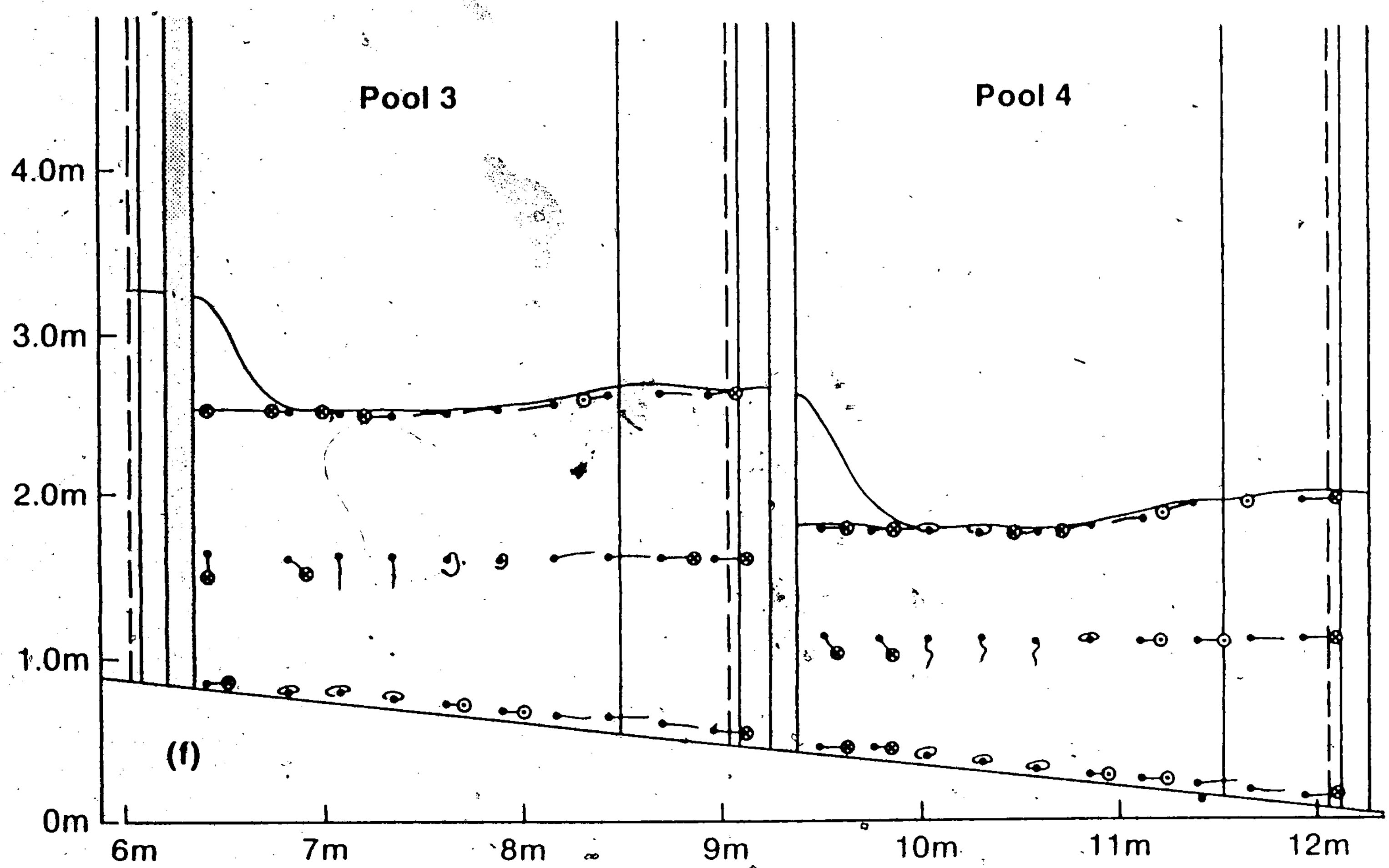
z'=0.73 m   Q = 1.67 m^3/s (No Tailwater Control)



z'=0.73 m   Q = 1.67 m^3/s (No Tailwater Control)



z'=0.24 m Q = 1.67 m^3/s (No Tailwater Control)



z′=0.24 m Q = 1.67 m^3/s (No Tailwater Control)

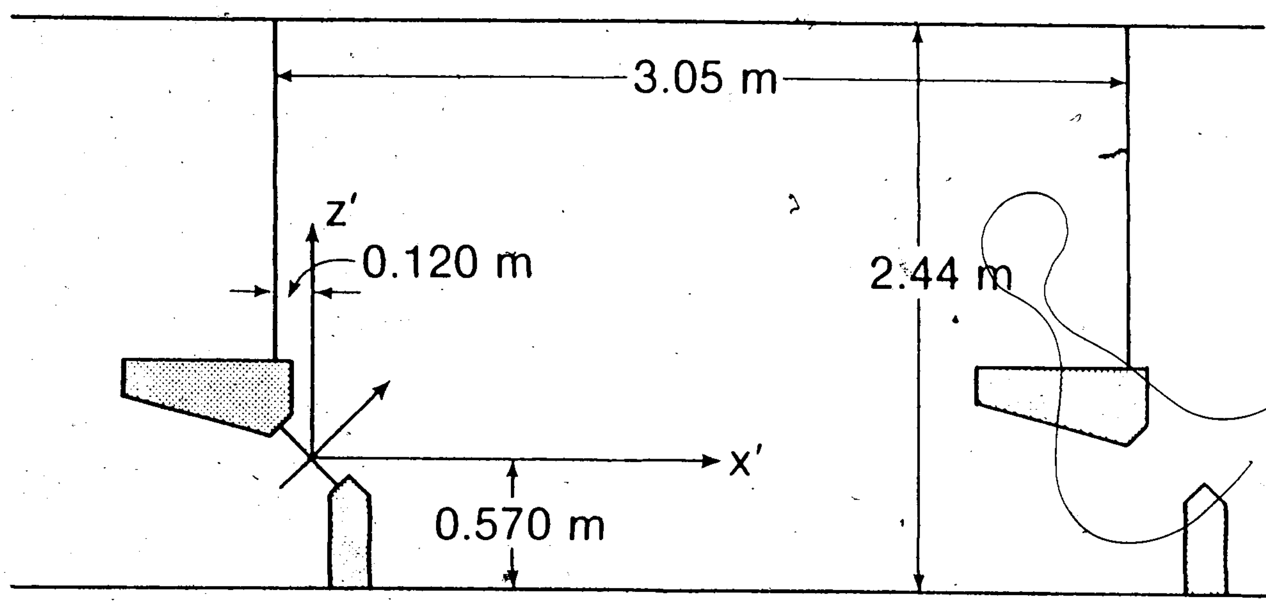


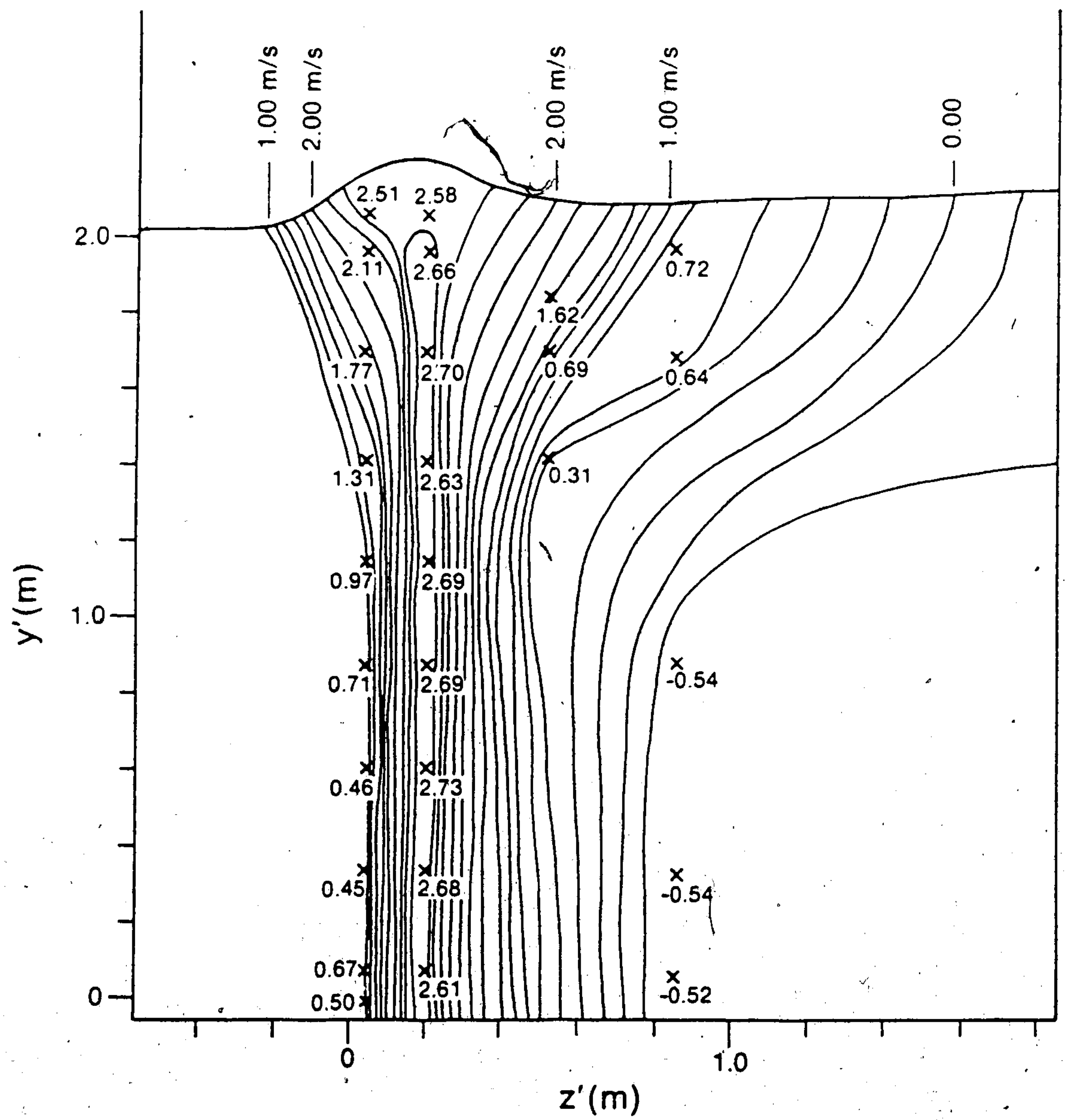
Fig. 18 Coordinate system in pools.

Fig. 19 Velocity contours in pool 2.

(Looking Upstream)

Pool #2 Q = 1.67 m^3/m (Free Flowing Tail Water)

(a) Prototype Velocities

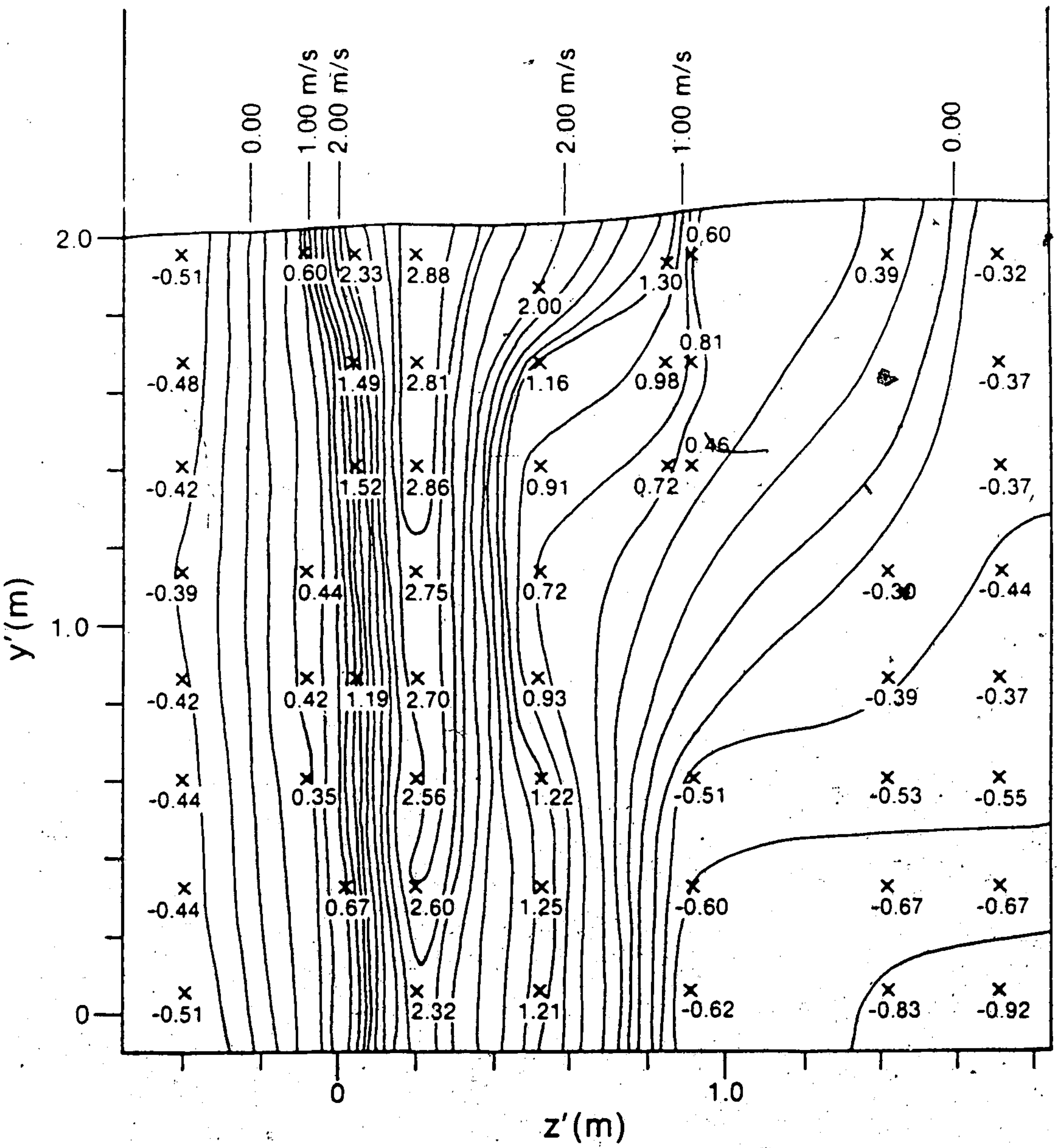


Velocity Contours (m/s)
x'=0.49 m

(Looking Upstream)

Pool #2 Q = 1.67 m^3/m (Free Flowing Tail Water)

(b) Prototype Velocities

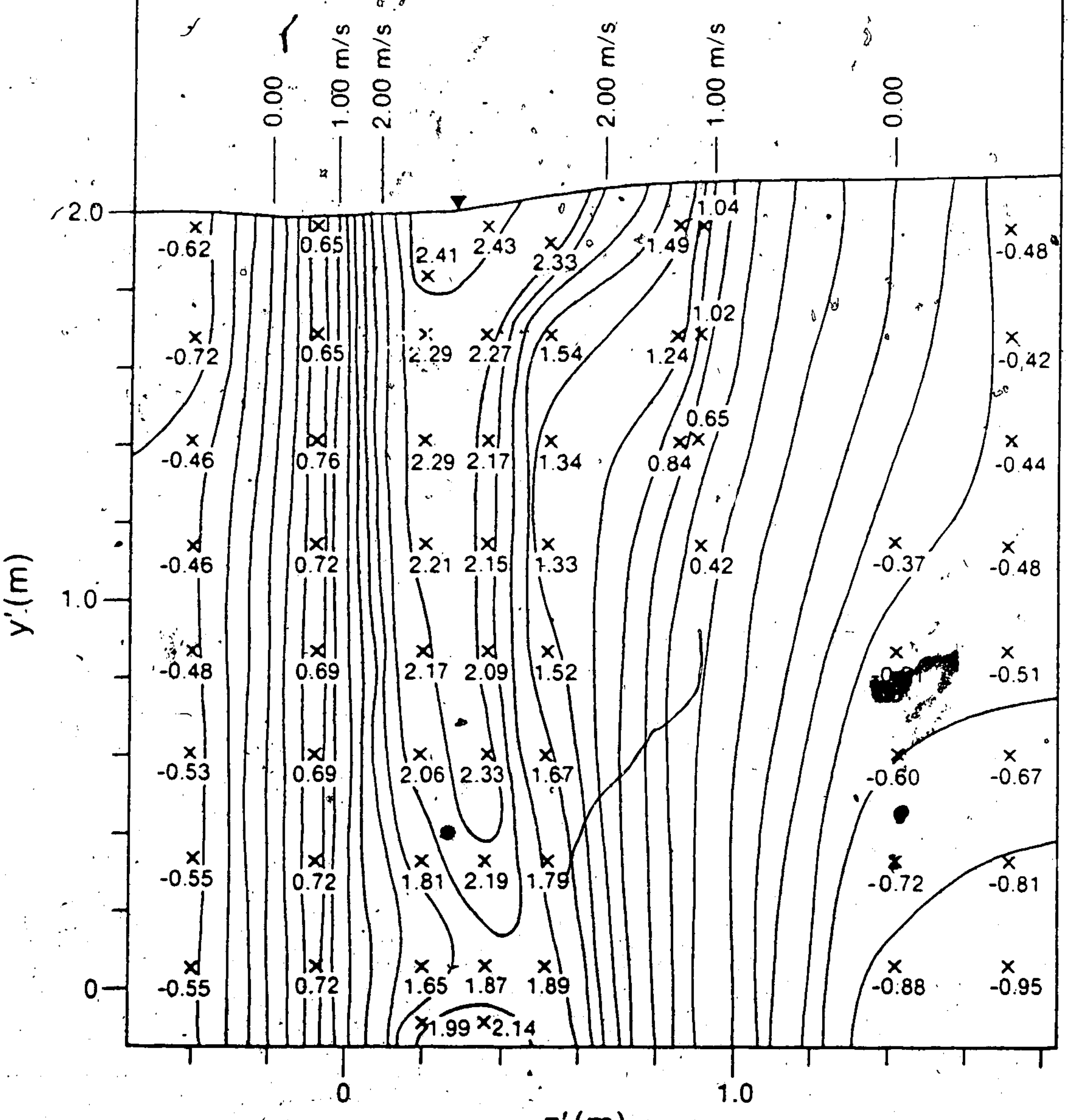


Velocity Contours (m/s)
x′=0.76 m

(Looking Upstream)

Pool #2 Q = 1.67 m³/m (Free Flowing Tail Water)

(c) Prototype Velocities

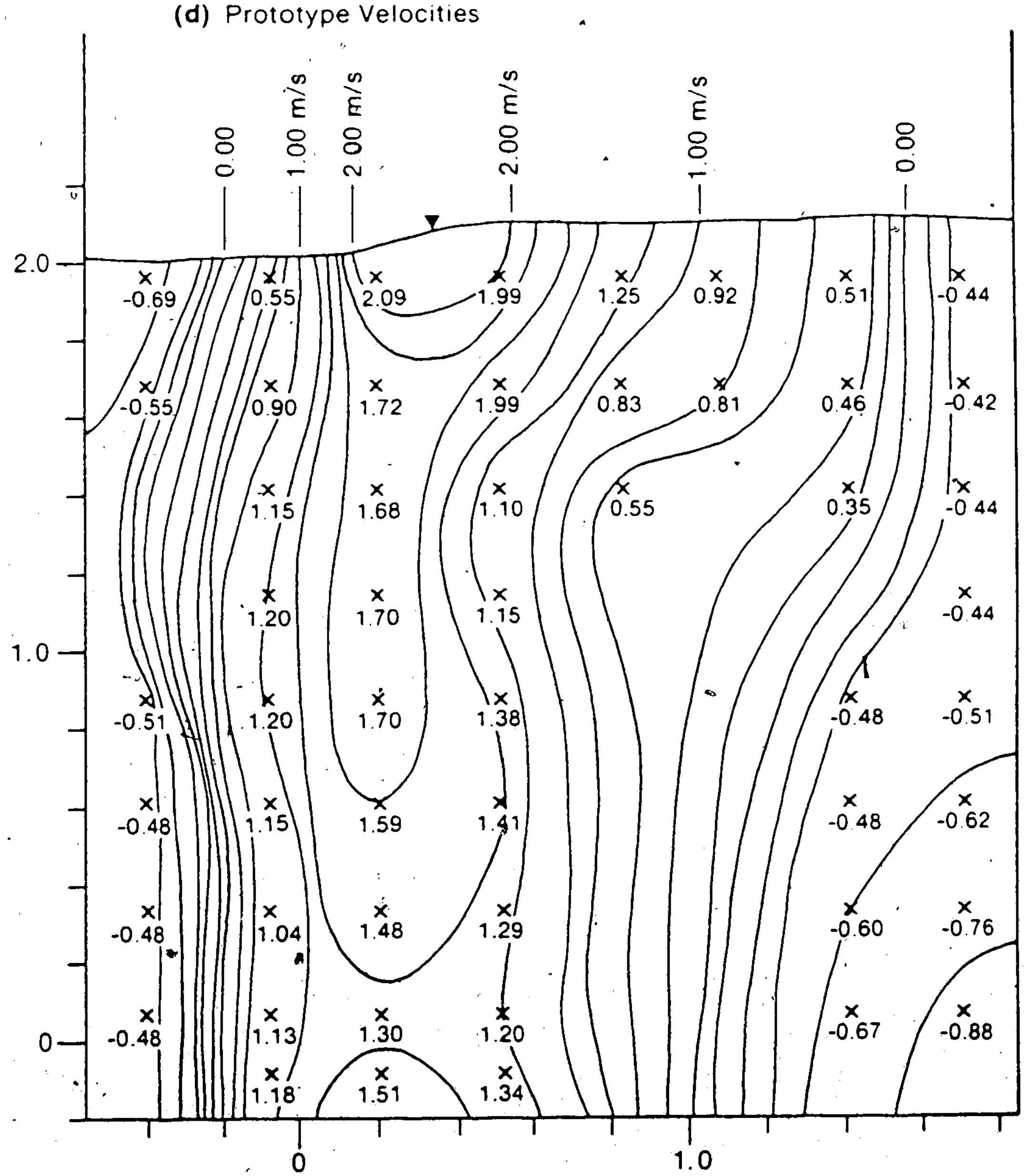


Velocity Contours (m/s)
x'=1.30 m

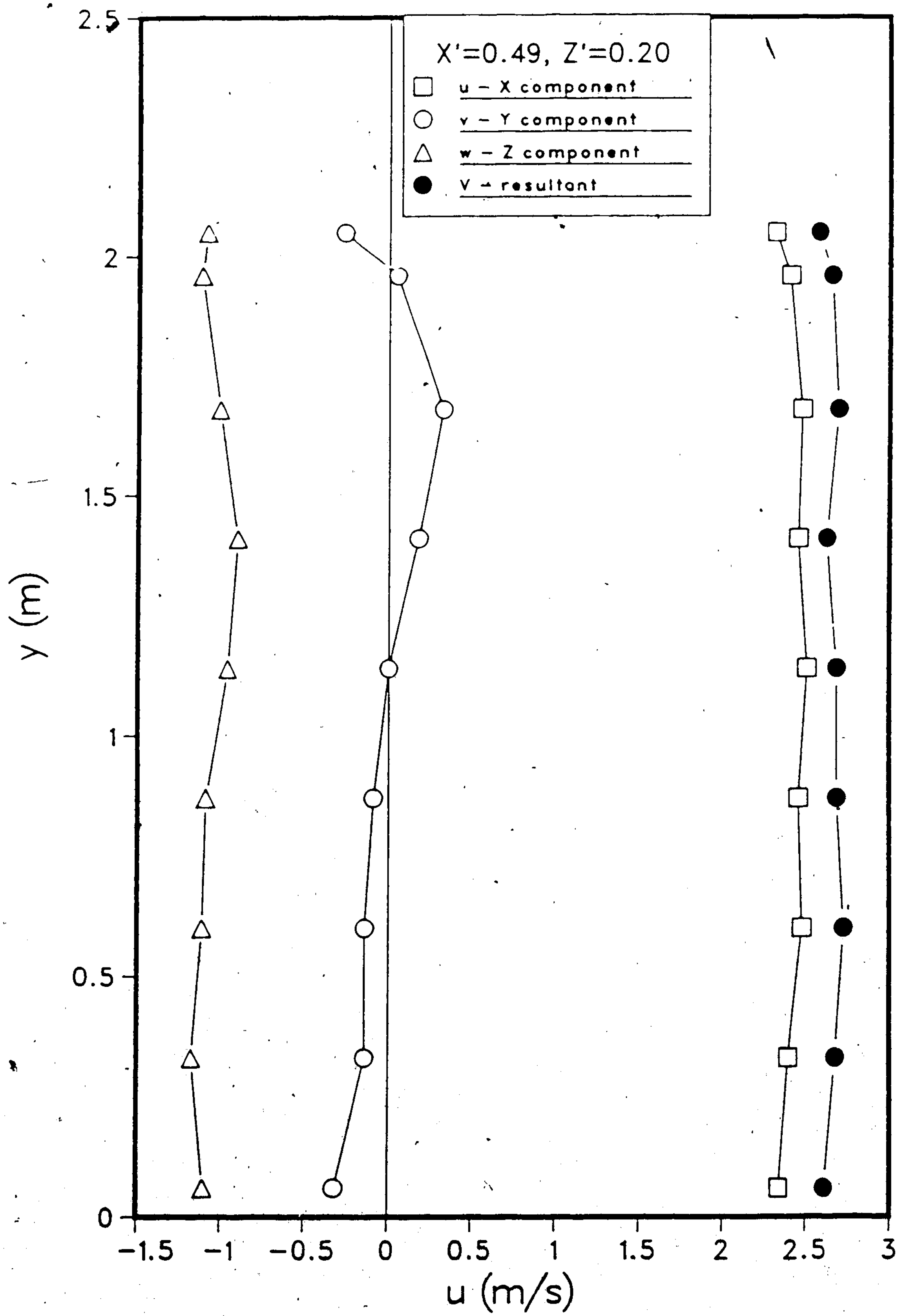
(Looking Upstream)

Pool #2 Q = 1.67 m^3/m (Free Flowing Tail Water)

(d) Prototype Velocities



Velocity Contours (m/s)
x'=1.84 m


X'=0.49, Z'=0.20
u – X component
v – Y component
w – Z component
V – resultant
y (m)
u (m/s)
0
0.5
1
1.5
2
2.5
−1.5
−1
−0.5
0
0.5
1
1.5
2
2.5
3

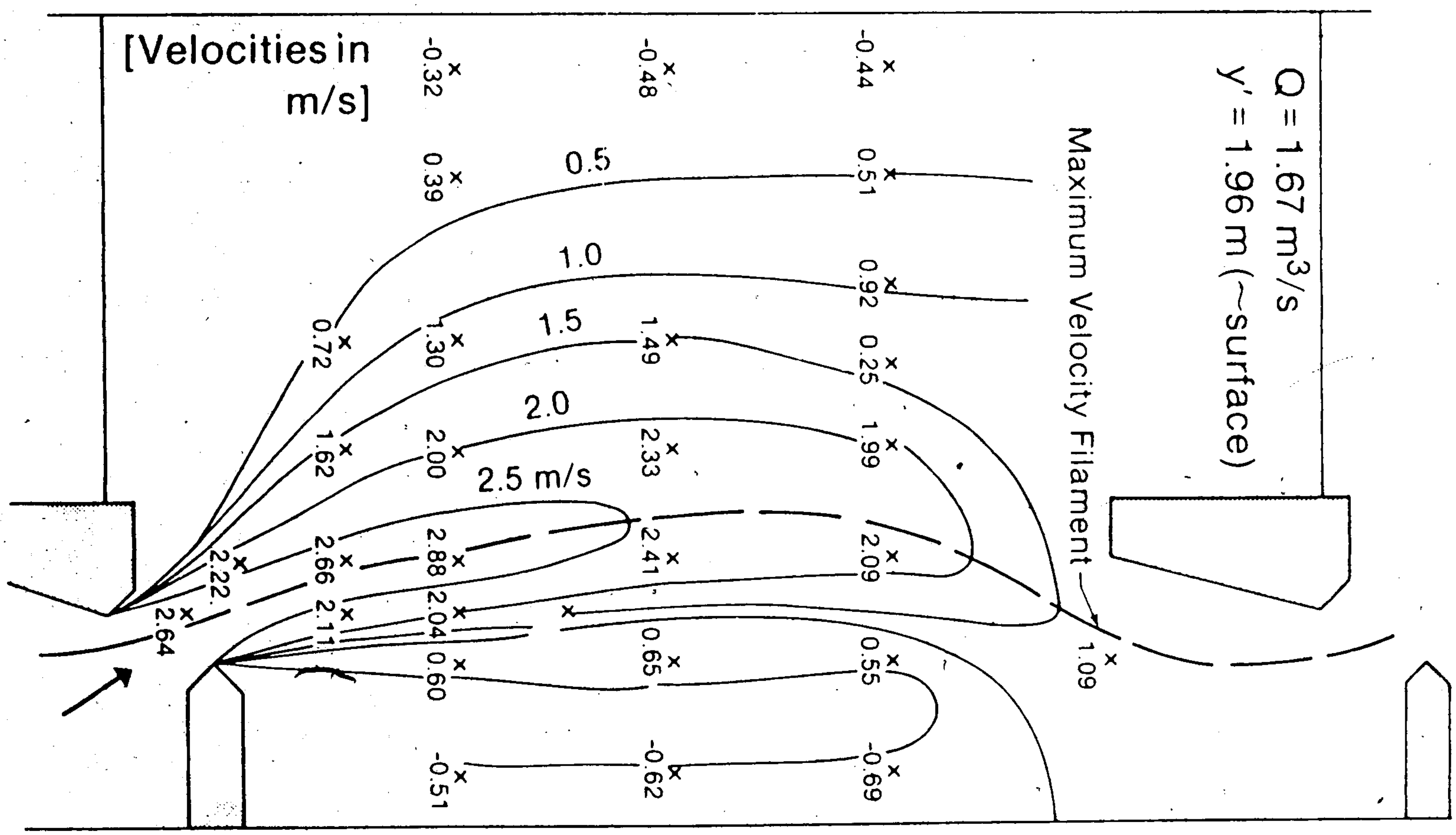


Fig. 21 Locus of maximum velocity.

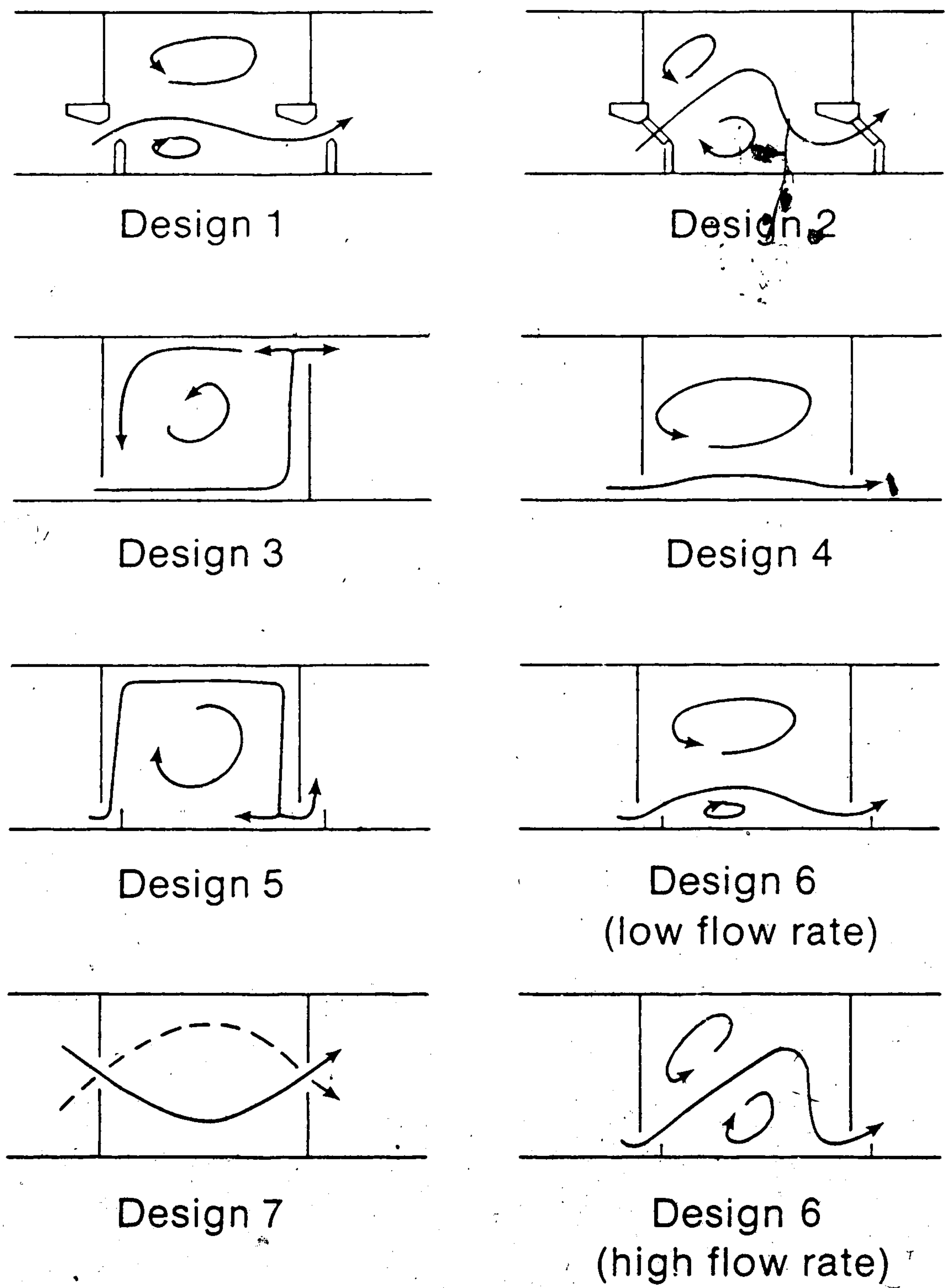
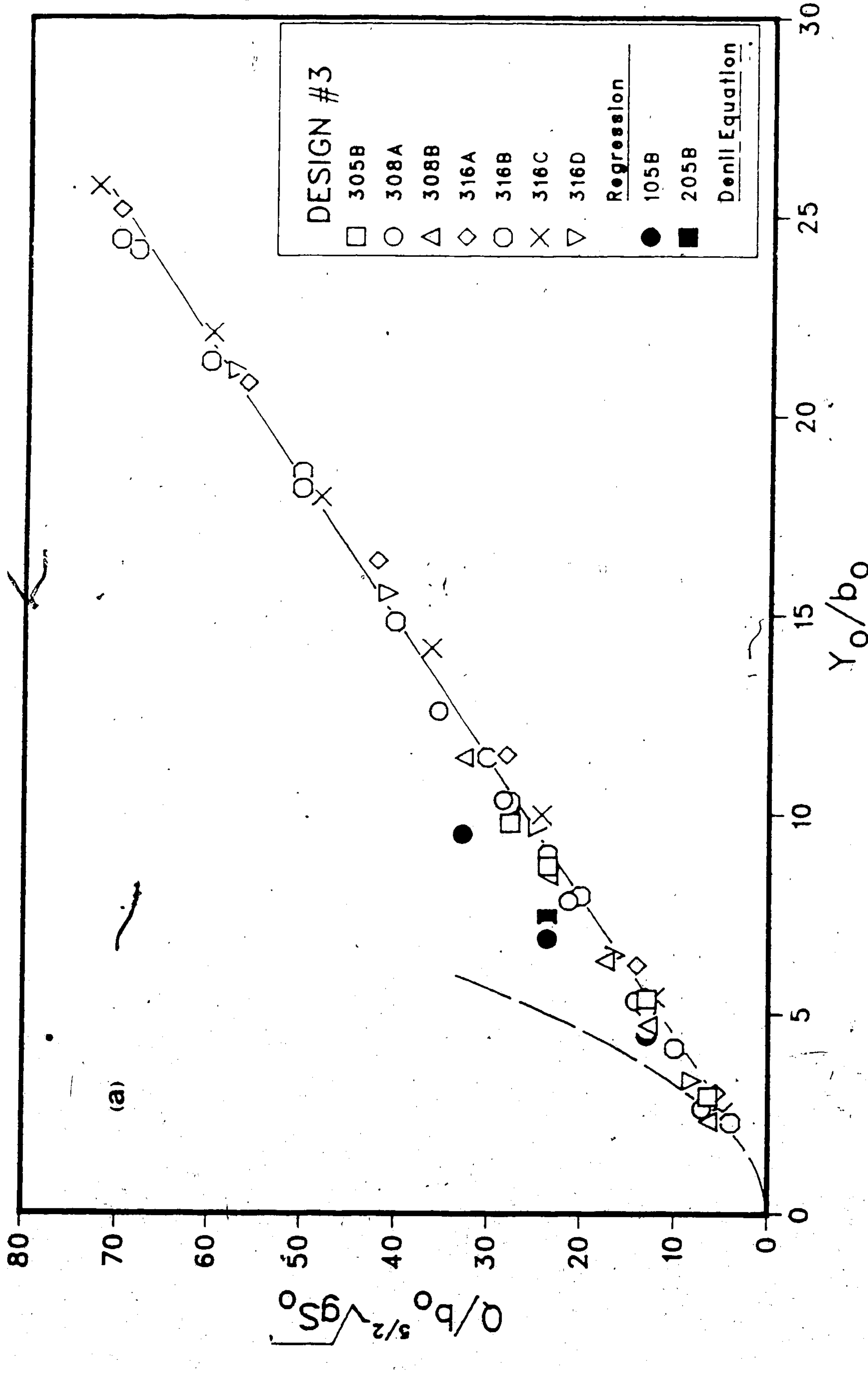
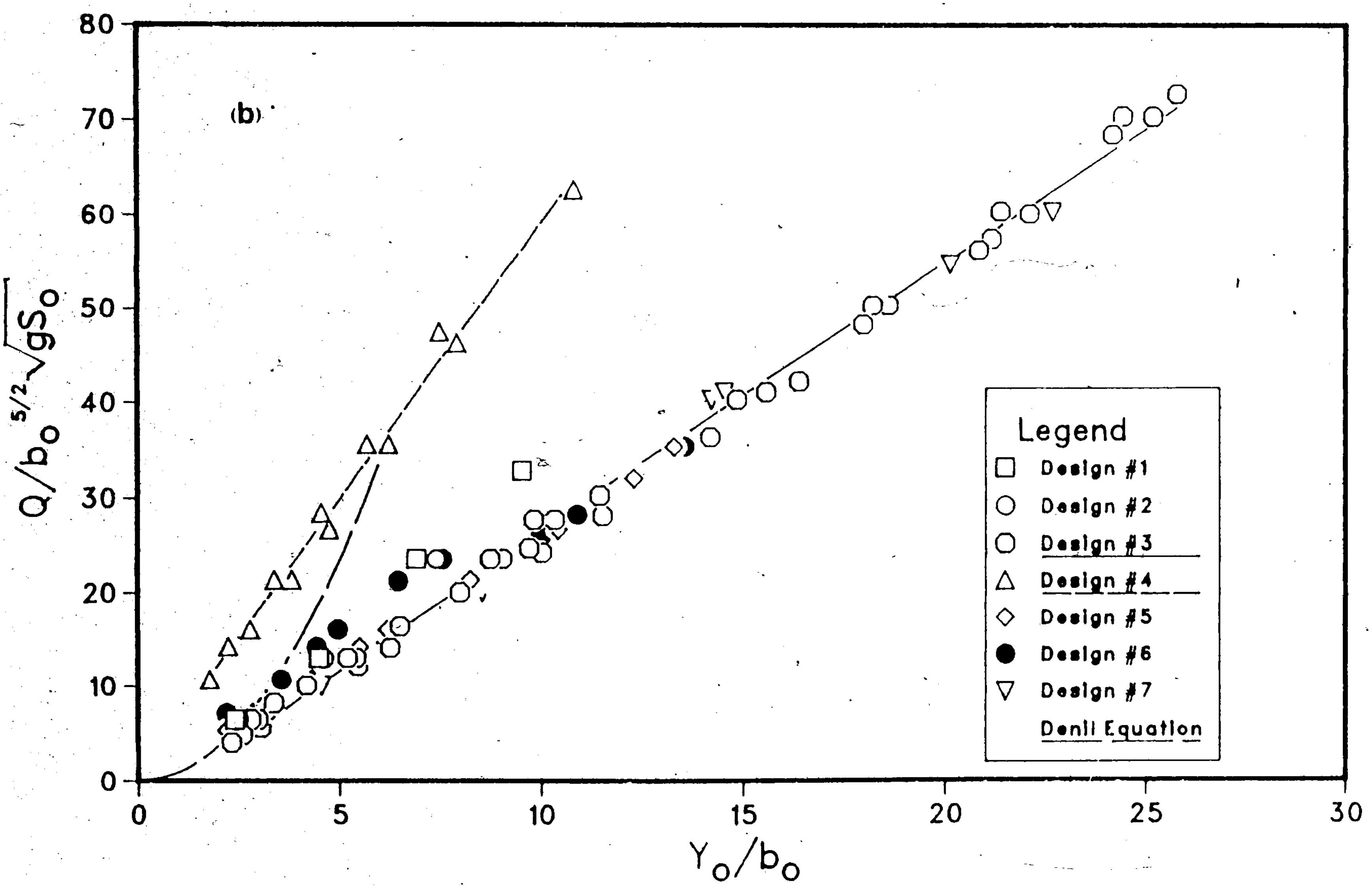


Fig. 22 Circulation patterns - all designs.

Fig. 23 Dimensionless rating curves.



(a)
DESIGN #3
305B
308A
308B
316A
316B
316C
316D
Regression
105B
205B
Denil Equation
$Q/b_o^{5/2}\sqrt{gS_o}$
Y_o/b_o
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80


(b)
Legend
Design #1
Design #2
Design #3
Design #4
Design #5
Design #6
Design #7
Denil Equation
$Q/b_o^{5/2}\sqrt{gS_o}$
Y_o/b_o
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30

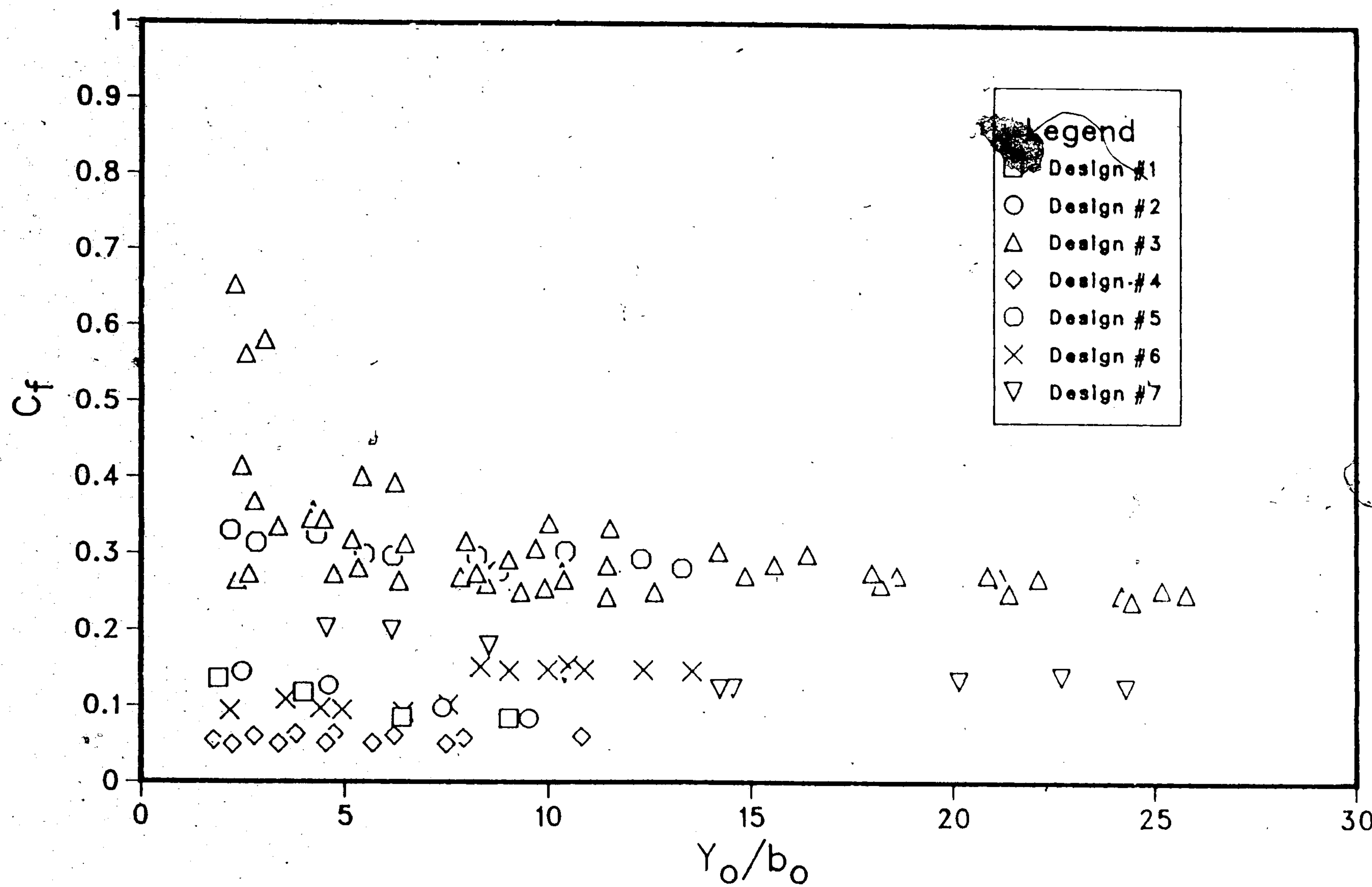


Fig. 24 Variation of the fluid friction coefficient with y_o/b_o.

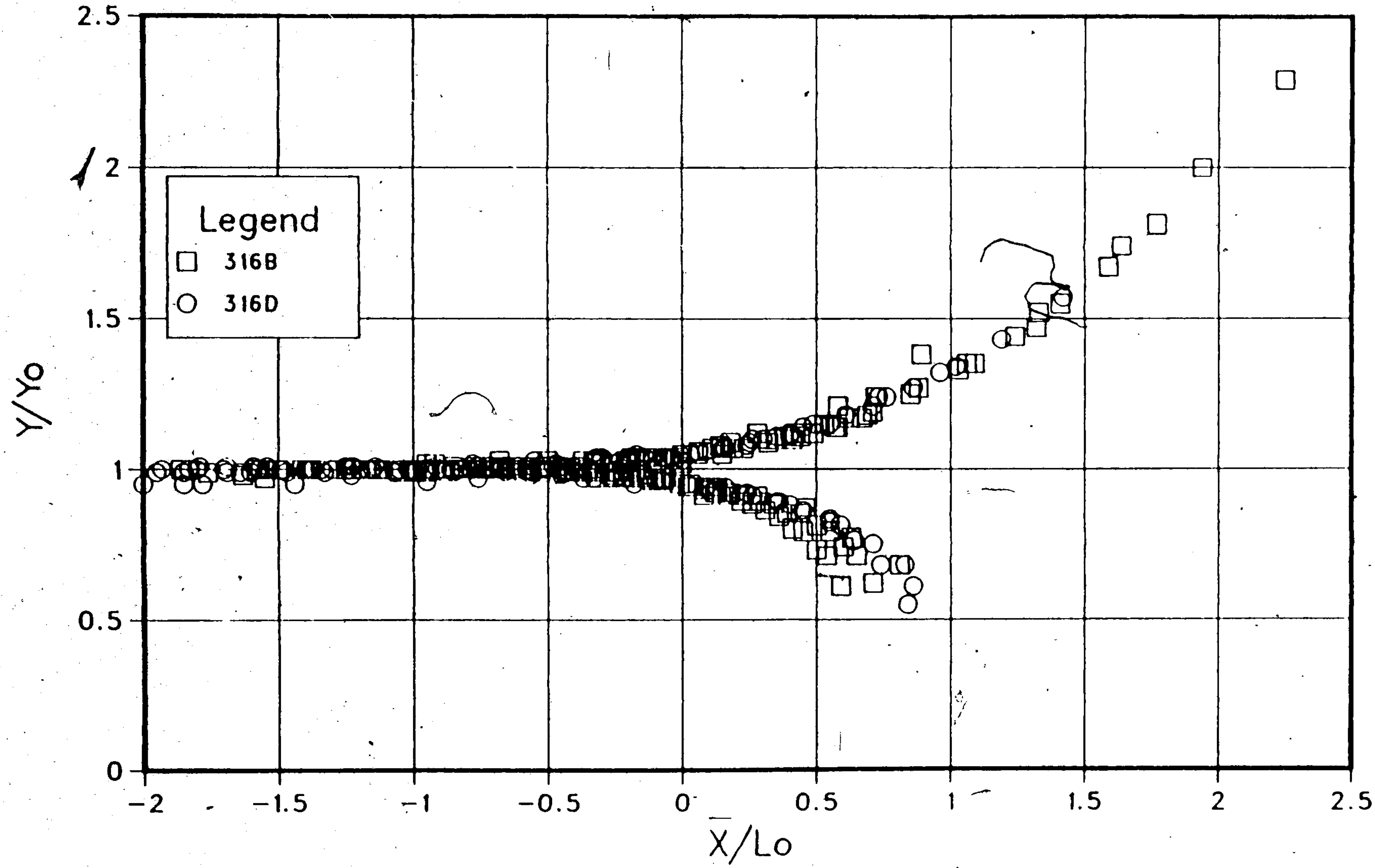
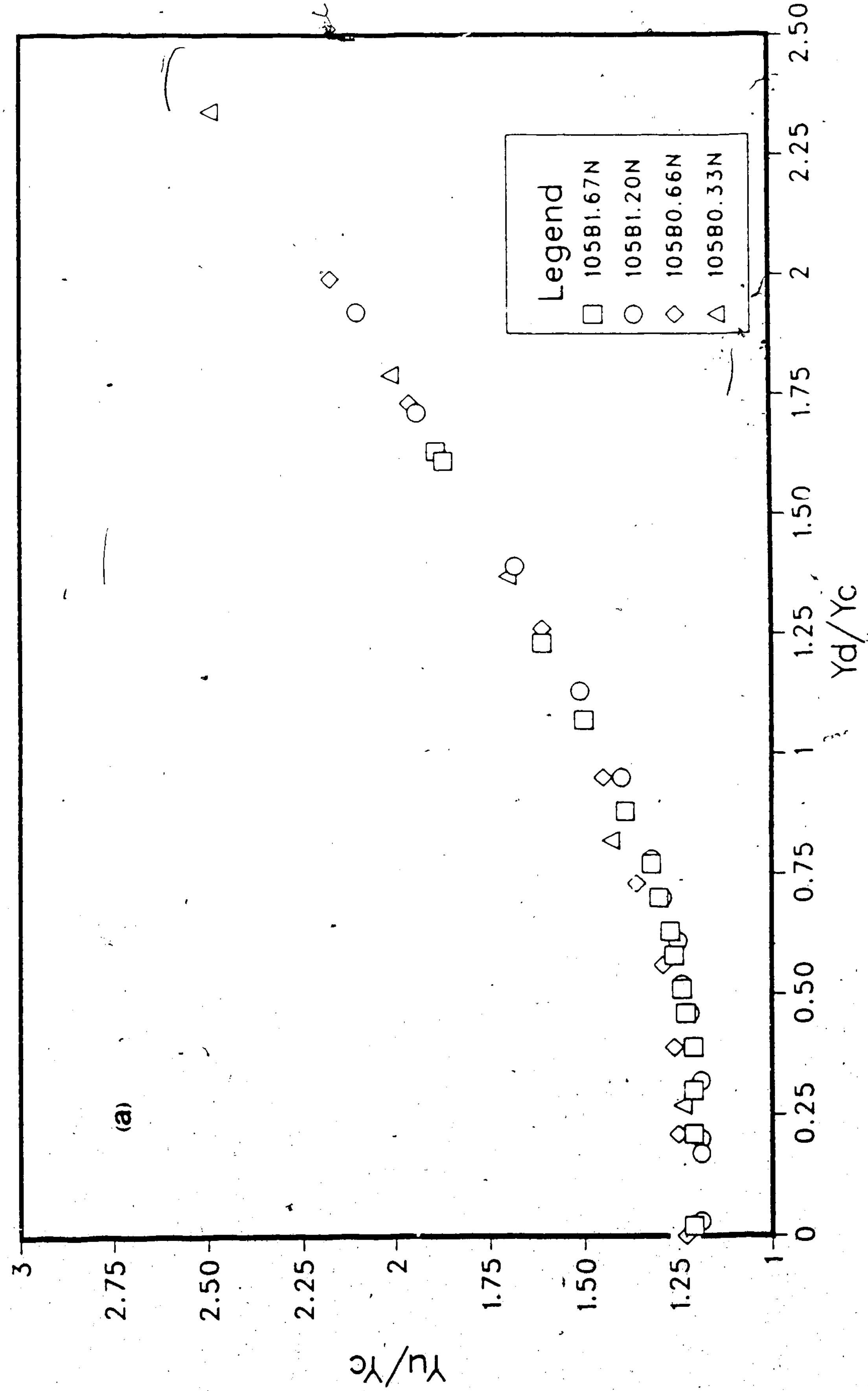
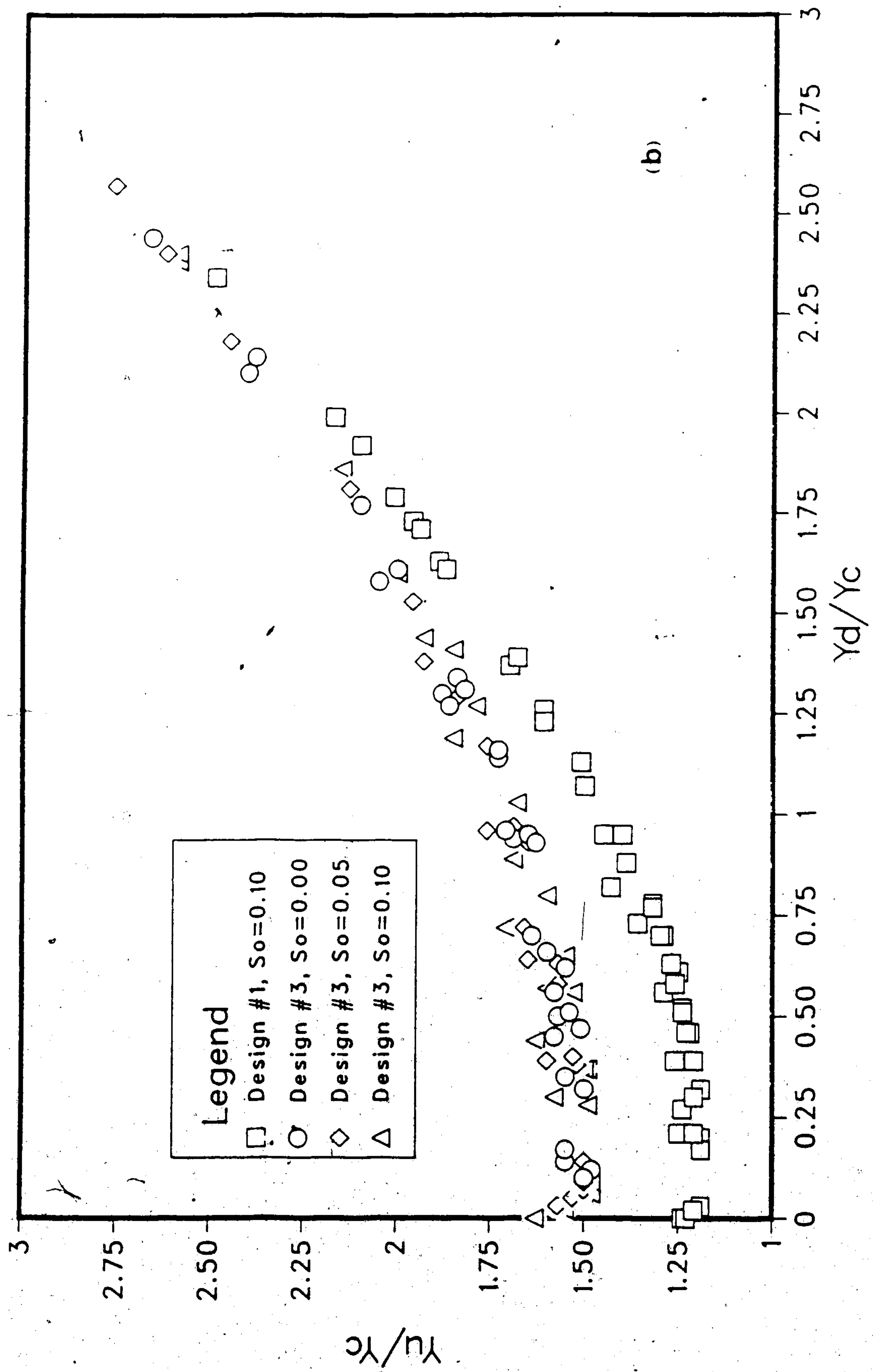


Fig. 25 Dimensionless non-uniform flow profiles.

Fig. 26 Variation of y_u/y_c against y_u/y_c.



Legend
105B1.67N
105B1.20N
105B0.66N
105B0.33N
(a)
Yd/Yc
Yu/Yc
0
0.25
0.50
0.75
1
1.25
1.50
1.75
2
2.25
2.50
2.75
3



Legend
Design #1, So=0.10
Design #3, So=0.00
Design #3, So=0.05
Design #3, So=0.10
(b)
Yd/Yc
Yu/Yc
0
0.25
0.50
0.75
1
1.25
1.50
1.75
2
2.25
2.50
2.75
3

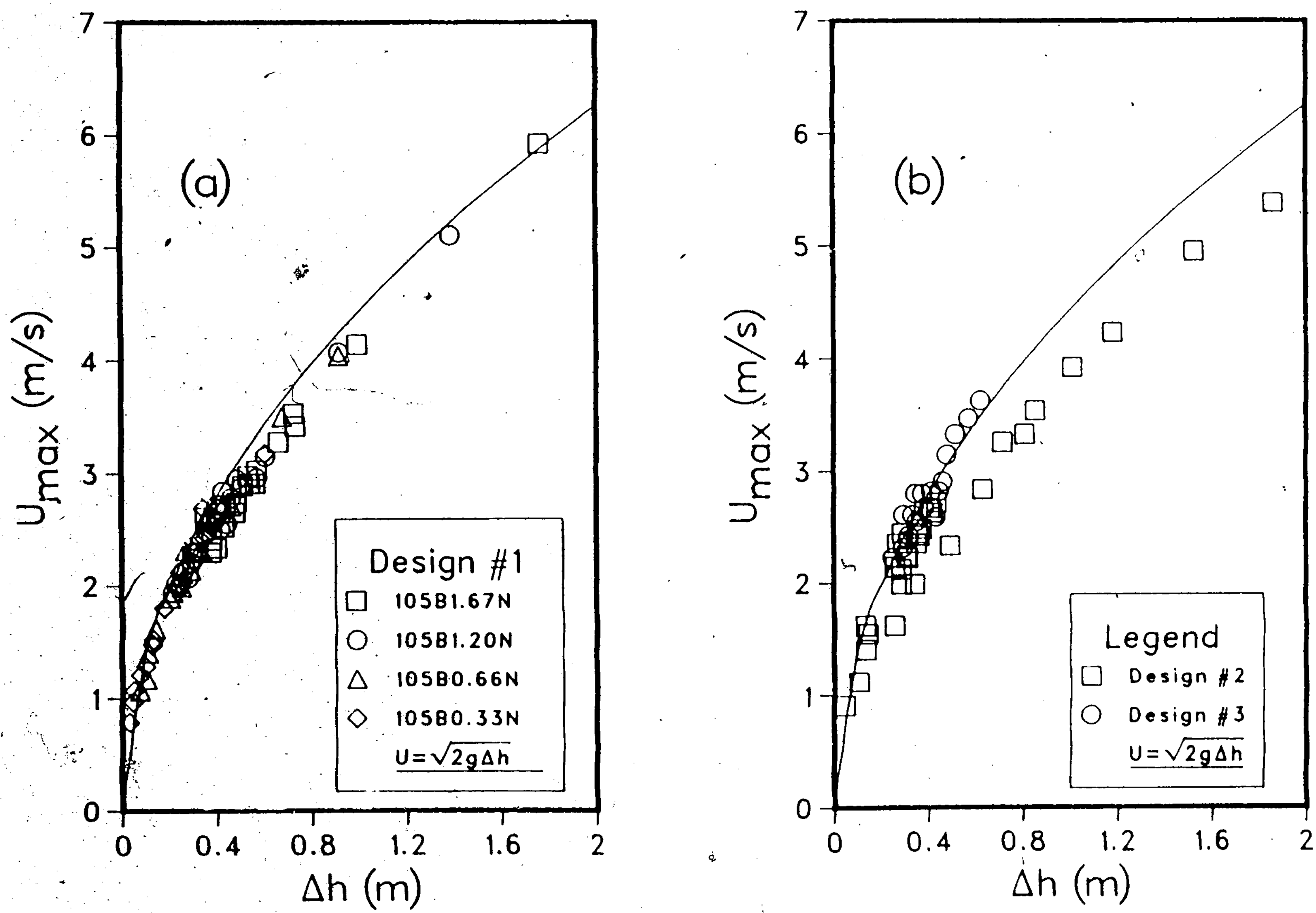


Fig. 27 Variation of u_m with Δh.

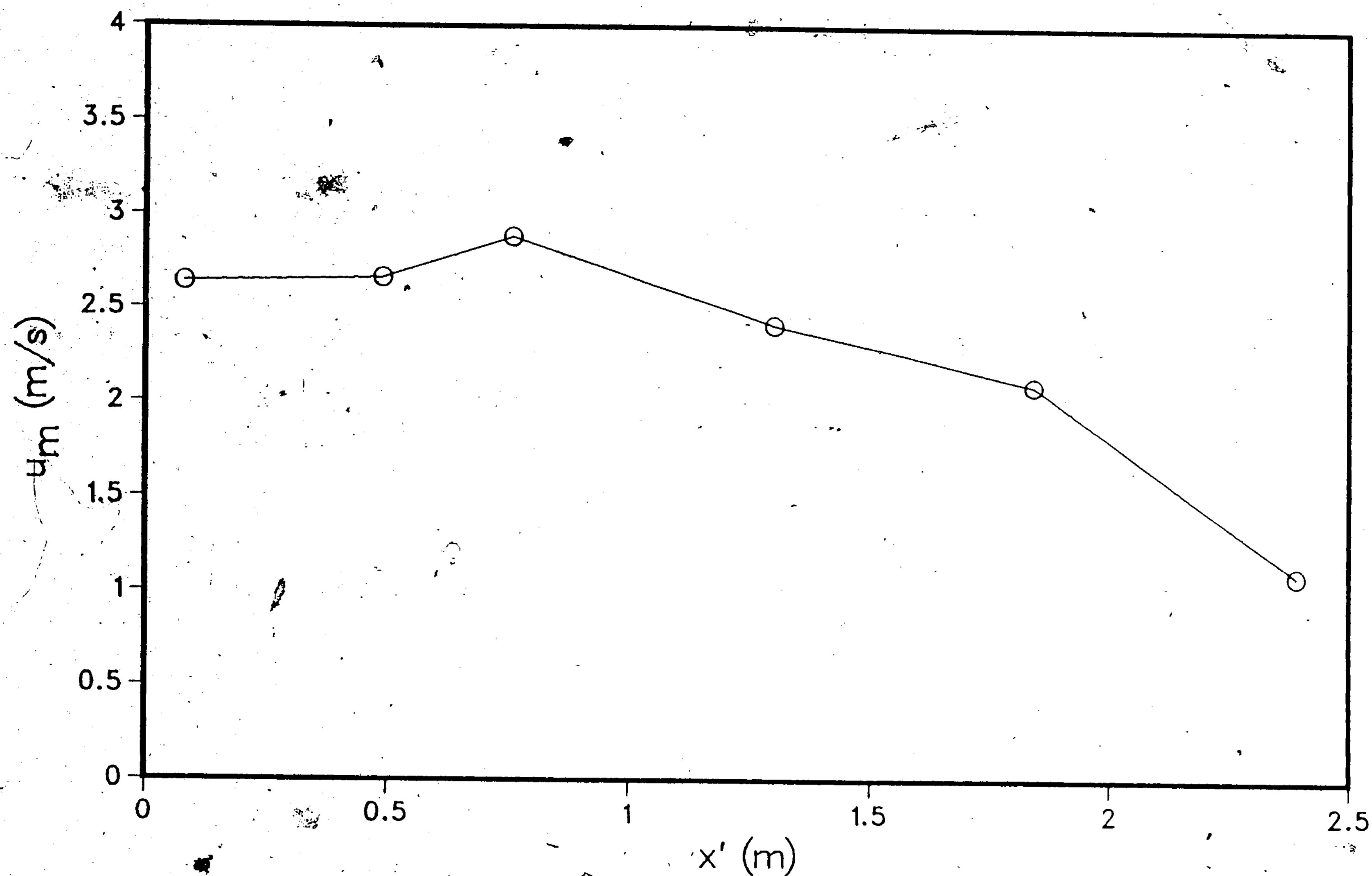
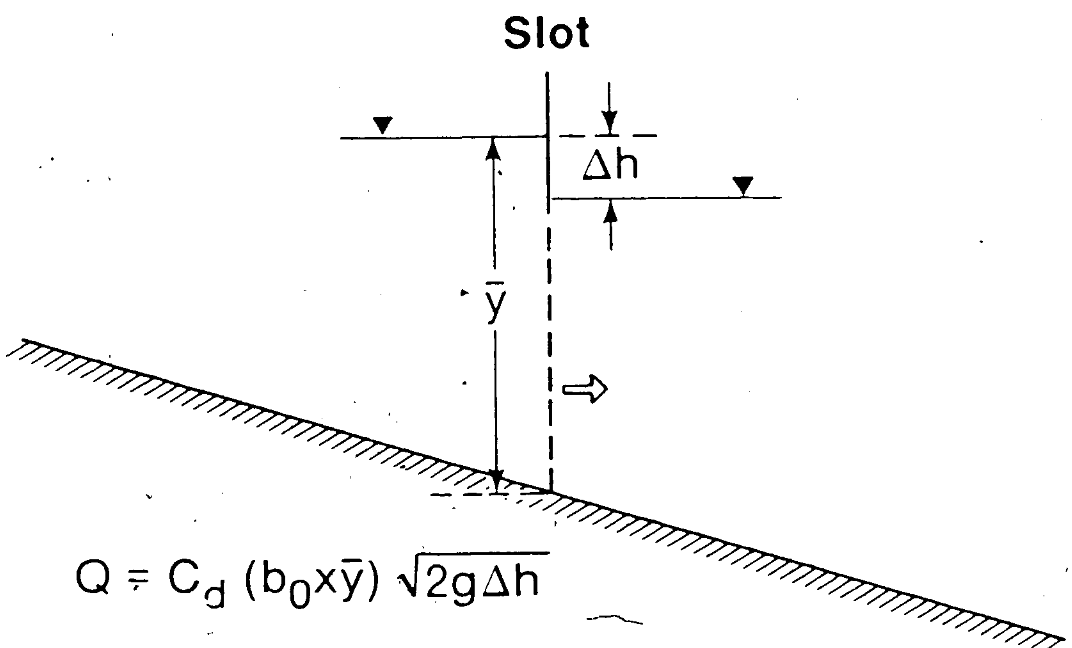


Fig. 28 Variation of u_m against x'.



$$Q = C_d\,(b_0 \times \bar{y})\,\sqrt{2g\Delta h}$$

b_0 = slot width; Δh = differential head between adjacent pools

$\bar{y}$ = depth of flow at slot (on upstream side)

Fig. 29 Definition sketch for the discharge coefficient, C_d.

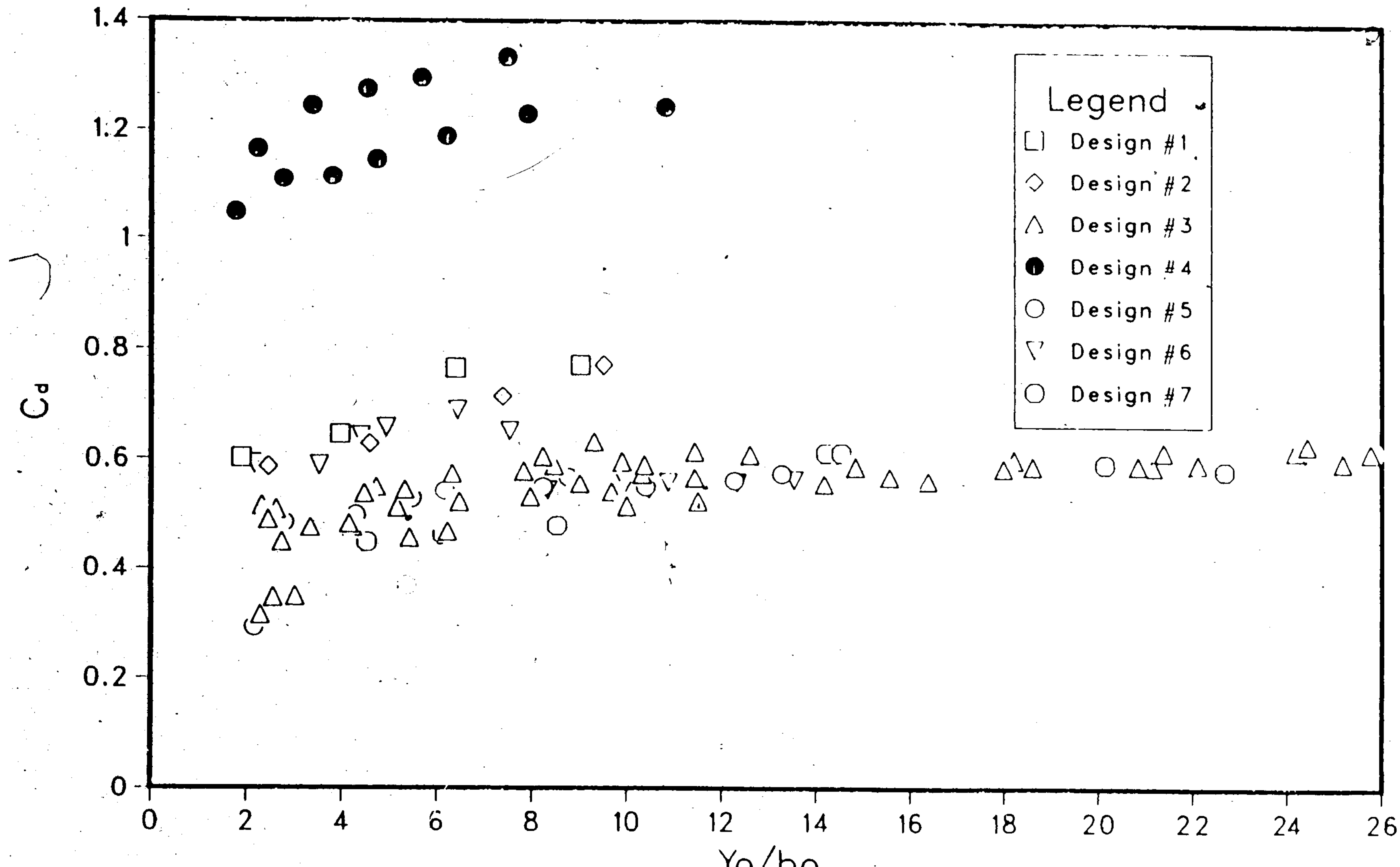


Fig. 30 Variation of C_d with y_o/b_o.

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