EXPERIMENTAL AND THEORETICAL STUDY OF HYDRAULIC JUMP IN HORIZONTAL CHANNEL

THESIS SUBMITTED FOR PARTIAL FULFILMENT OF THE REQUIREMENTS FOR AWARDING THE DEGREE OF MASTER OF MECHANICAL ENGINEERING IN FACULTY OF ENGINEERING AND TECHNOLOGY

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We hereby recommend that this thesis under our supervision by ***Avanish Rai****, entitled,* ***"EXPERIMENTAL AND THEORETICAL STUDY OF HYDRAULIC JUMP IN A HORIZONTAL CHANNEL"*** *be accepted in partial fulfillment of the requirements for awarding the degree of Master of Mechanical Engineering under Department of Mechanical Engineering of Jadavpur University.*

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*The foregoing thesis entitled "**EXPERIMENTAL AND THEORETICAL STUDY OF HYDRAULIC JUMP IN A HORIZONTAL CHANNEL** " is hereby approved as credible study of Fluid Mechanics and Hydraulics Engineering and presented in a manner satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval, the undersigned, do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose for which it is submitted.*

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CONTENTS

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 HYDRAULIC JUMP AND GRADUALLY VARIED FLOW

CHAPTER 4 EXPERIMENTAL SET UP AND EXPERIMENTATION

CHAPTER 5 RESULTS AND DISCUSSIONS

CHAPTER 6 CONCLUSION AND FUTURE SCOPE OF WORK

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ABSTRACT

In the present work, the study of Hydraulic Jump in a horizontal channel is done. The study involves both experimental and theoretical results and comparison of both the results is presented here. The experiments were performed in a horizontal rectangular channel in Hydraulics Laboratory of Jadavpur University. All the useful parameters are calculated and compared with the theoretical results like location of jump, length of jump, height of jump, Froude number and depth ratio. The study is carries for a fixed volume flow rate. There are some discrepancies and that is due to the roughness in the channel bed, unsteadiness in the jump, and assumption in the derivation of theoretical results. The study can be much more accurate with some improvement in the channel setup like constant head tank, improved instrumentation and measuring devices, smooth channel bed etc. For further advance study, it can be performed for the slopping channel bed. Calibrated frictional plates can be used on the channel bed to observe the effect of friction on the various parameters of jump.

LIST OF NOTATIONS

hc	Critical depth
h_{vc}	Depth of flow at Vena Contracta
hi	Depth of Opening in Inlet Sluice gate
ho	Depth of Opening in Outlet Sluice gate
h_1	Depth of supercritical flow of Hydraulic Jump
h_2	Depth of subcritical flow of Hydraulic Jump
h_{tw}	Depth of Tail water
Fr_1	Froude Number of Supercritical flow
Fr_2	Froude Number of Subcritical flow
g	Acceleration due to gravity
H	Depth of water level in the Supply Tank
B	Width of the channel
Q	Volumetric discharge
L	Length of the channel
L_j	Length of Hydraulic Jump
L_x	Location of Hydraulic Jump from inlet gate
i	Energy gradient slope
E	Specific Energy
E1	Specific Energy of Supercritical flow

E2	Specific Energy of Subcritical flow
u_1	Velocity of Supercritical flow
u_2	Velocity of Subcritical flow
m	Hydraulic mean depth
P	Wetted perimeter
D	Depth

LIST OF FIGURE

LIST OF FIGURE

LIST OF FIGURE

LIST OF TABLE

CHAPTER-I

INTRODUCTION

1.1 GENERAL DESCRIPTION

In the phenomenon of Hydraulic Jump, the supercritical flow is converted to subcritical flow by using an obstruction. This abrupt change in flow condition of hydraulic jump takes place through considerable turbulence and energy loss. Because of its importance in the design of stilling basins and also other hydraulic engineering works, hydraulic jump has attracted attention for years. After the research of many years, most of the features of hydraulic jump are now well understood. For having a jump, there must be a flow obstruction in the downstream. The downstream could be anything like a weir or a dam, a bridge abutment or anything like that. During hydraulic jump, the depth of water increases and mixing takes place, eddies are formed and energy dissipation takes place. For making a condition for jump to occur, it is advisable to install impediments in the channel. One of the very advantageous application of hydraulic jump is mixing of the chemicals in the water treatment plant, as there are eddies are formed, energy dissipation takes place and and mixing is done. So it is very useful in mixing of chemicals. Any hard substance like Concrete block can be installed in the channel to force the jump, as it would reduce the velocity and thus an abrupt rise in the level of water surface will be there and jump takes place. Thus the flow will change its nature. It will be converted from supercritical (F>1) to subcritical (F<1). Large turbulent eddies are formed in the beginning of the jump. As the jump proceeds, the large eddies are now broken into a smaller one and the energy transfer takes place from the large eddies to the smaller eddies. These smaller eddies do the work of dissipation of heat and energy[1].

For a horizontal rectangular channel of constant width, and neglecting the wall friction, the sequent depth ratio of the hydraulic jump is calculated by the well-known Belanger equation

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1 + 8F^2{}_1} - 1\right) \qquad \ldots\ldots (1.1)$$

where the subscripts 1 and 2 stand for upstream and downstream flow conditions of the hydraulic jump (Fig.1.1), respectively; and Fr_1 is the inflow Froude number. In this derivation, velocity distribution is assumed to be uniform over the section and the pressure distribution is hydrostatic both at the beginning and the end of the jump.

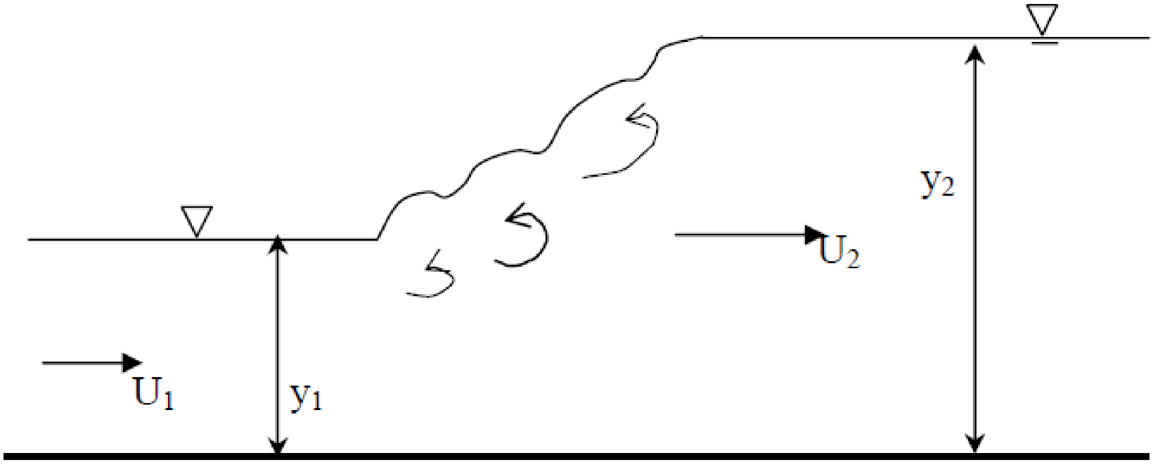


Figure 1.1: Definition sketch of a hydraulic jump

Hydraulic jump can be controlled by using the different conditions by using blocks of various shapes like crested weir, broad crested weir and abrupt rise and abrupt drop in channel bed.

The formation of hydraulic jump and control of its position for all probable operating conditions are insured by these obstructions. The supercritical flow will continue to travel downstream, when the normal tail water depth is less than the sequent depth of a stable jump. In such situations the jump characteristics like formation and position of the jump will be affected by designed sills placed in the channel bottom. If the stable jump is not formed, it will affect the results and the desired result will not be obtained. On the other hand if the normal tail water depth is greater than the sequent depth of a stable jump, the submerged jump will be obtained.

Hydraulic jumps in rectangular channel may be described by the approaching conditions, that are the inflow Froude number $Fr_{1,}$ the inflow depth $y_{1,}$ length of jump and the location of jump. In this study, a hydraulic jump in the rectangular horizontal section of zero slope channels is considered.

1.2 SCOPE AND IMPORTANCE OF THE STUDY

A situation when the tail water depth is not equal to the required conjugate depth at all discharges should be anticipated in practice. Then the jump will be formed closer to the structure, be repelled downstream at different discharges. The jump should form close to the structure ideally and certain artifices are used to control the location of the jump, i.e. to force the jump to occur at a desired location. When the jump is forced to occur at a certain place, then the jump is known as a forced jump. Some devices can be used for the purpose of generating forced jump may be baffle blocks and sills or a depression or rise in the floor level. Some examples of this case are jump at an abrupt drop, jump at an abrupt rise, and jump under influence of cross jets. Further in rectangular horizontal channel, the jump characteristics can be controlled be controlling the volume flow rate, inlet sluice gate opening and outlet sluice gate opening. Also by using a baffle in the downstream, hydraulic jump can be created. It also depends on the size of baffle and place at which the baffle is placed in the channel. Usually for better experimental results, it is advisable to use a constant head tank, smooth channel in which the friction is minimize because the jump is very much affected by the roughness of the channel. Length of jump and location of jump will be affected and the desirable results may not be obtained [2-3].

A Belanger's model to determine the sequent depth for channel is developed using one-dimensional momentum and continuity equation. It will be possible to develop a mathematical relationship in terms of some known variables such as height of drop, upstream Froude number etc, length and location of jump from experimental data.

Therefore, the present study is directed towards the evaluation of related parameters using the experimental data in the laboratory flume.

1.3 OBJECTIVES OF THE STUDY

This study contains the experimental work related to the hydraulic jump in an open channel and parameters like length of jump, height of jump, location of jump, Froude No etc. for a certain outlet and certain inlet gate opening for a fixed discharge. The study involves four different outlet gate openings and for each outlet gate opening, there are six different inlet gate openings which are increasing in manner. At upstream i.e. near inlet gate the flow will be supercritical and this supercritical flow will be converted into subcritical flow in the downstream. This work is also done to investigate the characteristics of hydraulic jump. These parameters are compared with theoretical predicted parameters. The flow profile for experimental results and theoretical computed results are studied, and compared

. So in brief, the objectives of the study are

- To find out the readings of the parameters length, height, location of the jump, Froude number, depth ratio and flow profile experimentally.
- To find out all these parameters theoretically be theoretical computation.
- To present a comparison between experimental results and theoretical computation.

CHAPTER-II

LITERATURE REVIEW

2.1 INTRODUCTION

Hydraulic jump is a phenomenon on which many researchers have done the research work and many researchers are working. The first description of hydraulic jump was presented by Leonardo da Vinci. In 1818 an Italian engineer Bidone[1] was the first person to do some experimental investigation of hydraulic jump (Chow, 1959). After then, it took attention of many researchers and considerable amount of research started on this subject. Belanger in 1828 gave some analytical results (Equation 1.1) which are truly valid. One of the main reasons for the interest of this topic is its practical applications in various fields.

Investigation of the effect of prismatic roughness elements on hydraulic jump properties have been done by Celik et al[4]. He found that both length and sequent depth of a hydraulic jump in a smooth channel are more than the length and sequent depth of a jump on a rough channel.

The effect of corrugated beds on the properties of hydraulic jump were analysed by Ayanlar[5]. Corrugated aluminium sheets of different wave length were used by him and kept the incoming Froude number in the experiment with a range of $4 \leq Fr1 \leq 12$. He concluded that compared with the results of the Hydraulic Jumps on smooth channel beds, corrugations reduce the required tail water depth for the upstream conditions, y_1 and Froude number.

The effect of wall friction on the sequent depth ratio was analysed by Hager and Bremen[6], both theoretically and experimentally. They stated that Belanger equation slightly disagree the sequent depths of Hydraulic Jumps in laboratory studies. They suggested that the existence of a significant scale effect in model studies are indicated with flow with small incoming depth and there must be a limit for this scale.

2.2 MAIN CHARACTERISTICS

In the Hydraulic Jump, the water surface start rising abruptly at the beginning, or end, of the jump, and it oscillates about a mean position, and the jump continues to rise up and a section denotes the end of the jump at which it is essentially level. The supercritical depth at the beginning is represented as y_1 and it is called as initial depth and the subcritical depth which is termed as sequent depth at the end is represented as y_2.

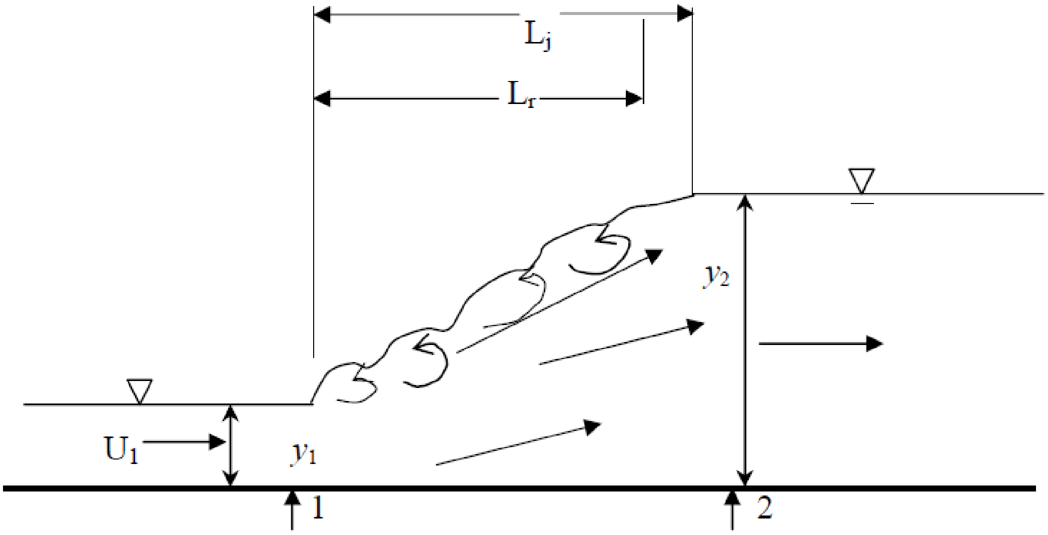


Fig 2.1: Length characteristics of a classical jump

At the start of jump (section 1 in the figure 2.1) the flow depth is y_1, and the average velocity,

$$u_1 = \frac{Q}{by_1}$$

Where,

Q = discharge

b = channel width.

At the end of the jump (section 2 in the figure 2.1) the depth is y_2 and the velocity, $u_2 = Q/(by_2)$. The supercritical Froude number is given by:

$$Fr_1 = \frac{v_1}{\sqrt{gh_1}} \qquad \text{..... (2.1)}$$

The upstream condition in the hydraulic jump is called supercritical where Froude number is larger than one and the depth is lower than the critical depth. Critical depth is a depth in an open channel which is associated with minimum specific energy condition.

$$hc = \left(\frac{Q^2}{g}\right)^{\frac{1}{3}} \qquad \text{..... (2.2)}$$

Where,

hc= critical depth

Q=volume flow rate

The downstream condition is called subcritical where Froude number is smaller than one and the depth is more than the critical depth. At the upstream of jump, specific energy is higher than that at the downstream; this difference in specific loss is known as the energy loss in hydraulic jump.

The boundary shear stress on the bed and the turbulent velocity fluctuations at the beginning and at the end are neglected if the velocity distribution is assumed to be uniform and the pressure distribution is hydrostatic both at the beginning and at the end of the jump. It can be shown that the ratio of the sequent depth to initial depth is given by the well-known Belanger equation:

$$\frac{y_2}{y_1} = \frac{1}{2}(\sqrt{1 + 8F^2{}_1}) - 1$$

The length of the jump has been a controversial issue because it is fluctuating in nature. It is generally agreed that the section at which the water surface becomes essentially level and the mean surface elevation is maximum is at end of jump. The length of jump is the distance of a point where the water level starts rising up and eddies formation starts to the point where the water level is maximum and it is now settled down. So the length of the jump is the horizontal distance from section 1 to section 2 and is denoted by Lj. It is found that, if Lr is the length of the surface roller, it means the length up to which the rollers are formed. Generally the length of surface roller is less than length of jump. Air is entrained in the jump due to breaking of the surface. Errors are introduced in the determination of the length of jump Lj because of air trapping. By experiment it was observed that Lj/y_2 is a function of Froude Number. The variation of Lj/y_2 with Froude Number obtained by Bradely and Peterika[7] is shown in Figure (fig 2.2). This curve is usually recommended for general purpose. It is seen from Figure 2.2 that while Lj/y_2 depends on Froude Number for small values of inflow Froude number, the relative jump length Lj/y_2 is nearly constant at a value of 6.1 for higher values of Froude Number (i.e., F_1>6.0).

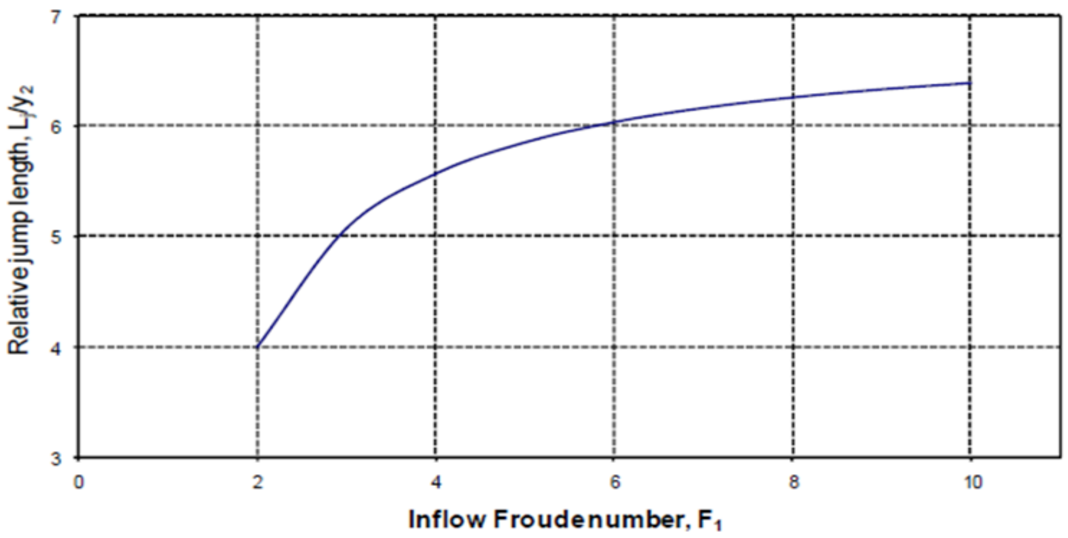


Fig 2.2: Length of hydraulic jump on horizontal floor[7]

In hydraulic jump, there is a large amount of energy. If E_1 and E_2 are the specific energies at the beginning and at the end of the jump respectively, and if E_L is the loss of specific energy in the jump, it can be shown that

$$\frac{E_L}{E_1} = \frac{8F_1^4 + 20F_1^2 - \left(8F_1^2 + 1\right)^{3/2} - 1}{8F_1^2\left(2 + F_1^2\right)} \qquad \text{...... (2.3)}$$

It can be found from the above equation that for an inflow Froude number F_1 equals to 20 the energy loss is equal to 86% of the initial specific energy is dissipated during the jump[8].

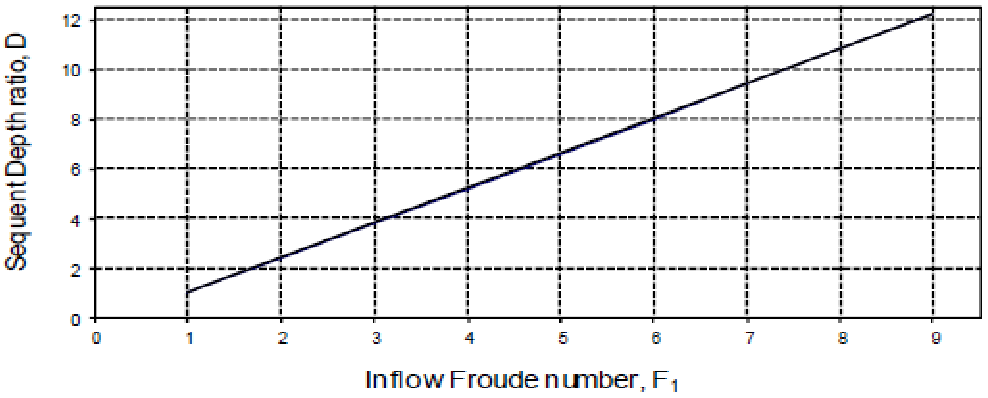


Fig 2.3: Relation between (y2/y1) and Froude Number

The graph of the Figure 2.3 can be mathematically expressed as:

$$Lj = 6.9(y_2 - y_1) \qquad \text{..... (2.4)}$$

Equation (1.1) is shown in graphical form in Fig. 2.3. This curve has been verified satisfactorily with many experimental data and is very useful in the analysis and design for hydraulic jump. From the above graph, it can be easily justified that for higher Froude number values, the sequent depth ratio is higher. It means the y_2 value will be higher. So we can say that the jump will be a much stronger jump.

2.3 APPLICATIONS OF HYDRAULIC JUMP

Though hydraulic jump is very useful at many places, the most important application of hydraulic jump is below sluiceways, gates and weirs etc. There is very high energy loss in the hydraulic jump. In the downstream portion of hydraulic structure, the energy dissipation is allowed so that the outgoing stream can safely be conducted to the channel below. The channel may be used with baffles and sills for improving the performance.

The most important application of the hydraulic jump is in the dissipation of energy below sluiceways, weirs, gates, etc. so that objectionable scour in the downstream channel is prevented. The high energy loss that occurs in hydraulic jump has led to its adoption as a part of the energy dissipater system below a hydraulic structure. Downstream portion of a hydraulic structure where the energy dissipation is deliberately allowed to occur so that the outgoing stream can safely be conducted to the channel below is known as a stilling basin. It is a fully paved channel and may have additional appurtenances, such as baffle blocks and sills to aid in the efficient performance over a wide range of operating conditions. It has also been used to raise the water level downstream to provide the requisite head for diversion into canals and also to increase the water load on aprons, thereby counteracting the uplift pressure and thus lessening the thickness of the concrete apron required in structures on permeable foundations. Some of the other important uses of hydraulic jump are: a) efficient operation of flow measurement flumes, b) mixing of chemicals, c) to aid intense mixing and gas transfer in chemical processes, d) in the desalination of sea water and e) in the aeration of streams which are polluted by bio-degradable wastes[9].

2.4 FORMATION OF HYDRAULIC JUMP

Hydraulic jump is a phenomenon where the flow is converted from supercritical to subcritical. The supercritical flow is inertia dominated and Froude Number will be more than one while in subcritical flow, it is gravity dominated and Froude No is lesser then one. In short we are getting supercritical flow at upstream and subcritical flow at downstream.

Hydraulic jump is a flow phenomenon associated with the abrupt transition of a supercritical (inertia-dominated) flow to a subcritical (gravity-dominated) flow.

Subcritical flow is produced by downstream control and supercritical flow is produced by upstream control. Depth-Discharge relationship in its own vicinity is fixed by a certain control. The control can also change the nature of the flow, velocity of flow, discharge and also the Froude No. So, it will produce subcritical flow upstream and supercritical flow downstream. If the upstream control causes supercritical flow while the downstream control dictates subcritical flow, there is a conflict which can be resolved only if there is some means for the flow to pass from one flow condition to the other – thus hydraulic jump forms[9].

2.5 ANALYSIS OF HYDRAULIC JUMP ON LIQUID SURFACE

In spite of the very much complexity of the flow transition, application of simple analytic tools to a two dimensional analysis is effective in providing analytic results which closely parallel both field and laboratory results. Analysis shows:

- Height of jump- upstream height and downstream height depends on the flow rate.
- Loss of Energy in the jump
- Location of the jump
- Jump characteristics

2.6 HYDRAULIC JUMP FEATURES

Highly turbulent flow with significantly dynamic velocity and pressure components

- Pulsations of both pressure and velocity, and wave development downstream of the jump.
- Two-phase flow due to air entrainment.
- Erosive pattern due to increased macro-scale vortex development.
- Sound generation and energy dissipation as a result of turbulence production.

CHAPTER-III

HYDRAULIC JUMP AND GRADUALLY VARIED FLOW

3.1 FLOW CONDITIONS

In an open channel, flow of water can be classified into three different types such as Supercritical flow, critical flow and subcritical flow as given in Figure (3.1). For making it a hydraulic jump, the flow must be in supercritical flow at the upstream side and end subcritical flow at the downstream side.

A subcritical flow is defined as having a Froude number less than one. In this case, the velocity of the flow u_2 in the subcritical region is lower than the gravity wave velocity. On the other hand, Supercritical flow is defined as having a Froude number greater than one. The supercritical flow has high velocity u1 greater than gravity wave velocity at given flow depth. The critical flow is the condition in which the Froude number is equal to one.

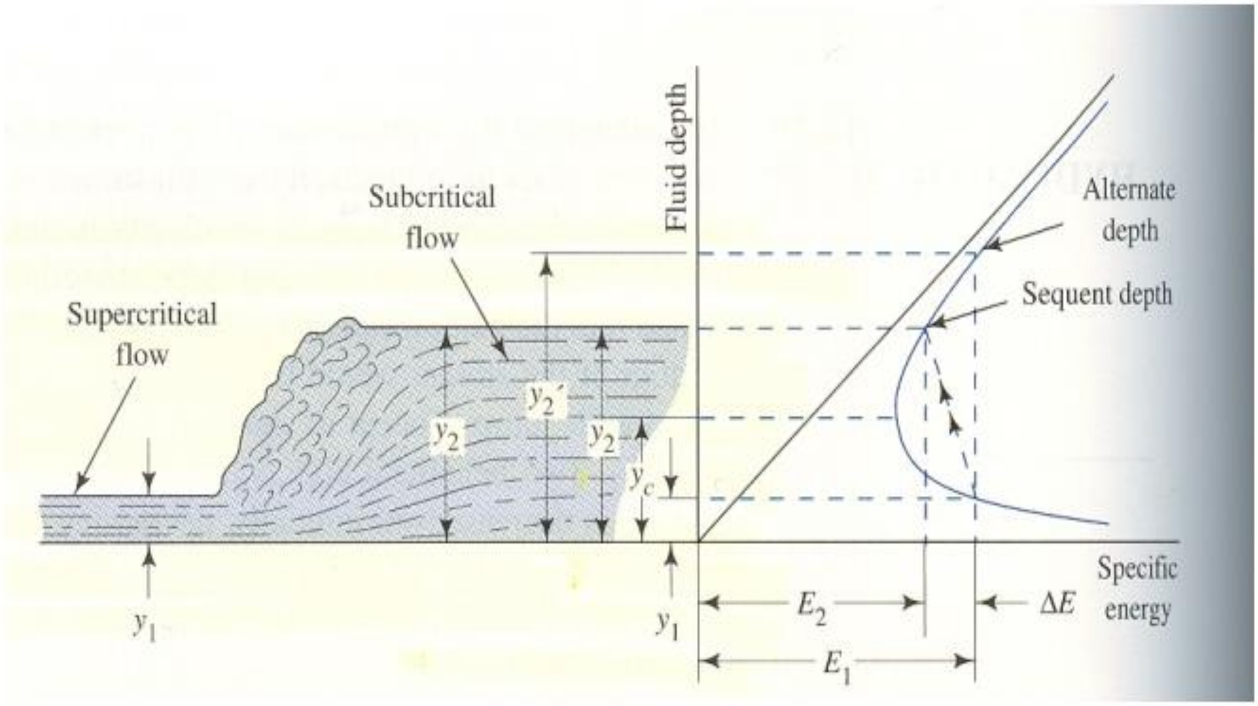


Fig 3.1: Specific Energy condition of hydraulic jump

3.2 BASIC CHARACTERISTICS OF HYDRAULIC JUMP

The basic characteristic of a Hydraulic Jump are

i) The initial depth and sequent depths.
ii) The energy loss in the jump.
iii) Height of the jump.
iv) Length of the jump.
v) Location of jump

3.2.1 THE INITIAL DEPTH AND THE SEQUENT DEPTH

Before the jump, the velocity is higher and the flow is supercritical and the depth is lesser and after the jump, velocity is lesser and depth is more. It is so because fluid has to maintain the continuity. The depth before the jump is called the initial depth h_1 and that after the jump is called the sequent depth h_2. The initial and sequent depths h_1 and h_2 are shown on the specific-energy head curve (Fig. 2.1). Initial depth and sequence depth should be distinguished from the alternative depths h1 and $h_{2í}$, which are the two possible depths for the same specific energy. The initial and sequent depths are the actual depths before and after a jump. The specific- energy head E_1 at the initial depth h_1 is greater than the specific-energy head E_2 at the E. because there is some loss in the jump. If there were no energy losses, the initial and sequent depths would become identical with the alternative depths. We can determine a relationship between the initial depth and the sequent depth of a hydraulic jump on a horizontal floor in a rectangular channel. The external forces of friction and the weight effect of the water in a hydraulic jump on a horizontal floor are negligible, because the jump takes place along a relatively short distance and the slope angle of the floor is zero. The momentum transfers through section 1 and 2 in Fig. 2.1, respectively, i.e. before and after the jump, can therefore be considered equal; that is,

$$\rho \frac{Q^2}{gA_1} + \rho z_1 A_1 = \rho \frac{Q^2}{gA_2} + \rho z_2 A_2 \qquad \text{……. (3.1)}$$

For a rectangular channel of width b,

$Q = V_1A_2 = V_2A_2$;

$A_1 = bh_1$ and $A_2 = bh_2$;

$z_1 = \frac{h1}{2}$ and $z_1 = \frac{h2}{2}$

Substituting these relations and $Fr_1 = \frac{V_1}{\sqrt{gh_1}}$ in the above equation and simplifying, it can be derived[8,11]:

$$\left(\frac{h_2}{h_1}\right)^3 - \left(2Fr_1^2 + 1\right)\left(\frac{h_2}{h_1}\right) + 2Fr_1^2 = 0$$

Factoring:

$$\left[\left(\frac{h_2}{h_1}\right)^2 + \frac{h_2}{h_1} - 2Fr_1^2\right]\left(\frac{h_2}{h_1} - 1\right) = 0$$

From which it follows:

$$\left[\left(\frac{h_2}{h_1}\right)^2 + \frac{h_2}{h_1} - 2Fr_1^2\right] = 0$$

The solution of this quadratic equation is

$$\frac{h_2}{h_1} = \frac{1}{2}\left(-1 \pm \sqrt{1 + 8Fr^2{}_1}\right)$$

Obviously the solution with the minus sign is not possible (it would give a negative $\frac{h_2}{h_1}$).

Thus, $$\frac{h_2}{h_1} = \frac{1}{2}\left(\sqrt{1 + 8Fr_1^2} - 1\right)$$

With $Fr_2 = \frac{v_2}{\sqrt{gh_2}}$

3.2.2 ENERGY LOSS IN THE JUMP

The loss of energy in the jump is equal to the difference in specific energies before and after the jump as figure (3.1). It can be shown that the loss is

$$\Delta E = E_1 - E_2 = \frac{(E_1 - E_2)^2}{4E_1E_2}$$

Where

E_1 is Specific Energy of Supercritical flow

E_2 is Specific Energy of Subcritical flow

h_1 is depth of Supercritical flow

h_2 is depth of Subcritical flow

3.2.3 HEIGHT OF THE JUMP (hj)

The Height of the jump is equal to the difference between the depths before and after the jump as figure (3.1 and 3.2). It can be shown that the height of the jump is

$$h_j = h_2 - h_1$$

3.2.4 LENGTH OF THE JUMP (L_j)

Length of hydraulic jump may be defined as the distance measured from the front face of the jump to a point on the surface immediately downstream from the roller. It can be seen in figure (3.2).

3.2.5 LOCATION OF JUMP (L_x)

The hydraulic jump is formed whenever the momentum equation is satisfied between the supercritical and subcritical parts of the stream. In other words, if the initial depth h_1, the sequent depth h_2 and the approaching Froude number Fr_1 satisfies equation (1.1) in a smooth rectangular channel, the hydraulic jump will occur. Location of Hydraulic jump is measured from the inlet sluice gate to the point where the flow fluctuates or roller starts. It can be seen in figure.

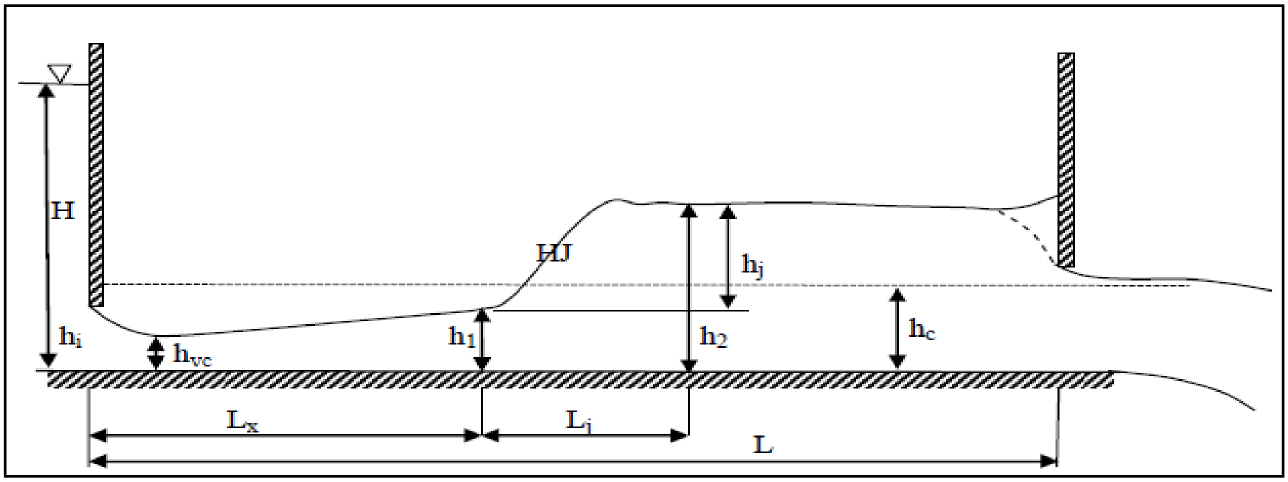


Fig 3.2: Related parameter of hydraulic jump

Where H= Height of water level in tank

hi= Inlet gate opening

h_{vc}= Depth of flow at Vena Contracta

h_1= Depth of supercritical flow Hydraulic Jump

h_2= Depth of subcritical flow of Hydraulic Jump

Lx= Location of hydraulic Jump

Lj= Length of Hydraulic Jump

hc = Critical depth

hj= Height of Hydraulic Jump

3.3 CLASSIFICATIONS OF HYDRAULIC JUMP

Hydraulic jump can be classified based on incoming Froude number and the position of hydraulic jump.

$$Fr = \frac{v}{\sqrt{gh_1}}$$

(a)Undular jump (1 < Fn1<1.7)

- Slight undulation
- Two conjugate depths are close
- Transition is not abrupt – slightly ruffled water surface

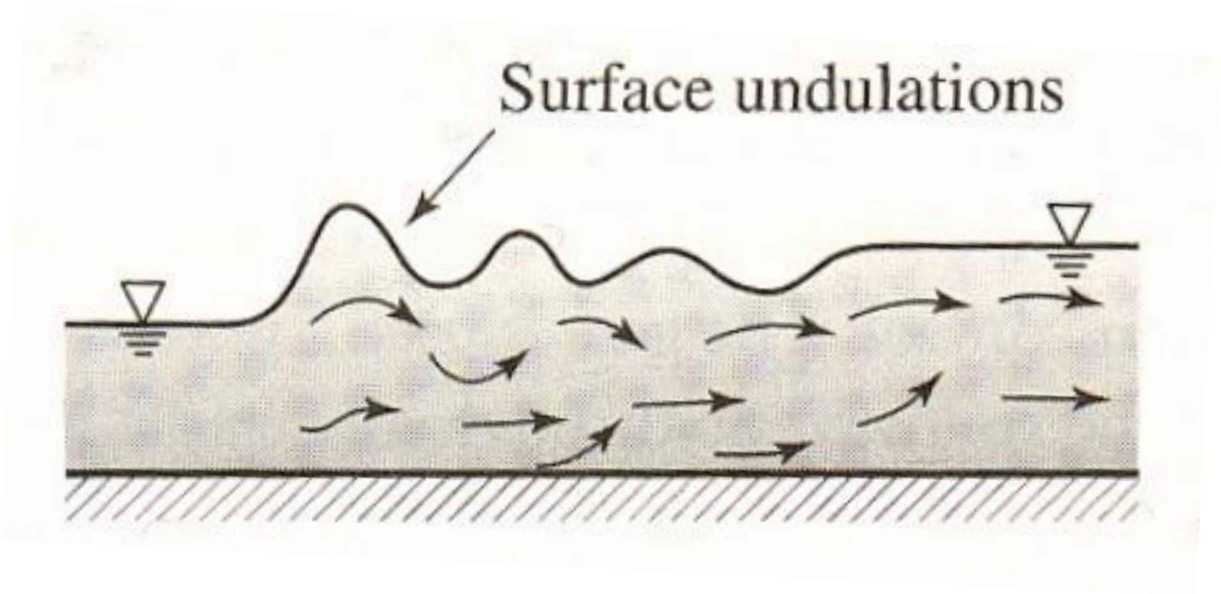


Fig 3.3: Undular Jump

(b) Weak jump (1.7<Fn1<2.5)

- Eddies and rollers are formed on the surface
- Energy loss is small
- The ratio of final depth to initial depth ~ between 2.0 and 3.1.

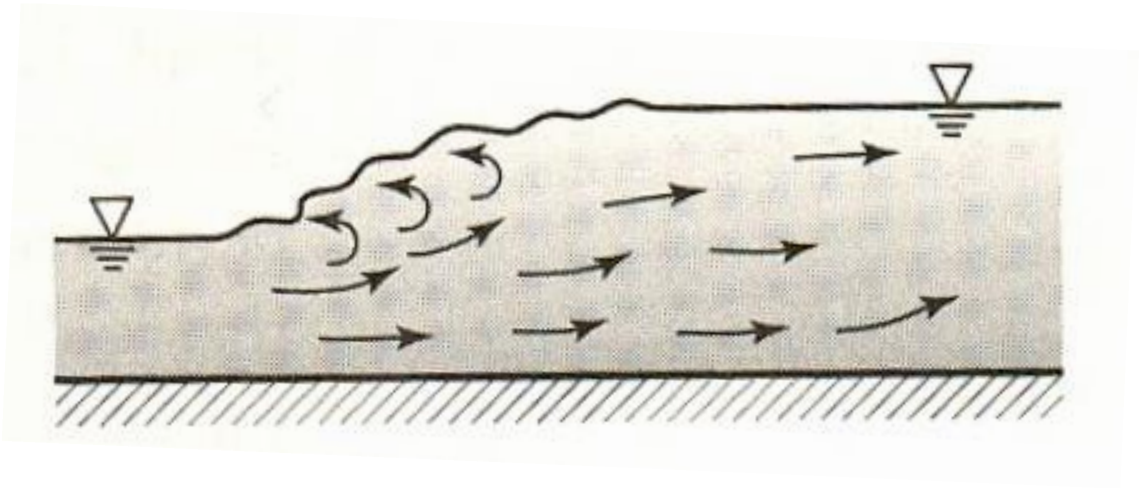


Fig 3.4: Weak Jump

(c) Oscillating jump (2.5 <Fn1<4.5)

- Jet oscillates from top to bottom – generates surface waves that persist beyond the end of the jump.
- Ratio final depth to initial depth ~ between 3.1 to 5.0
- To prevent destructive effects this type of jump should be avoided.

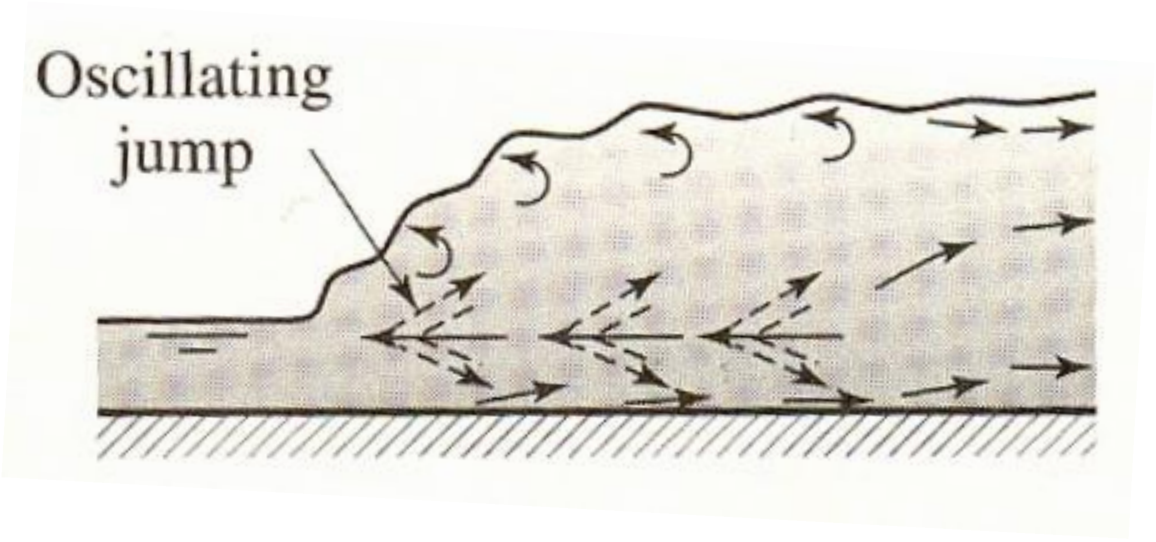


Fig 3.5: Oscillating Jump

(d) Stable jump (4.5<Fn1<9)

- Position of jump fixed regardless of downstream conditions
- Good dissipation of energy

- Considerable rise in downstream water level
- Ratio of final to initial depth ~ between 5.9 and 12.0

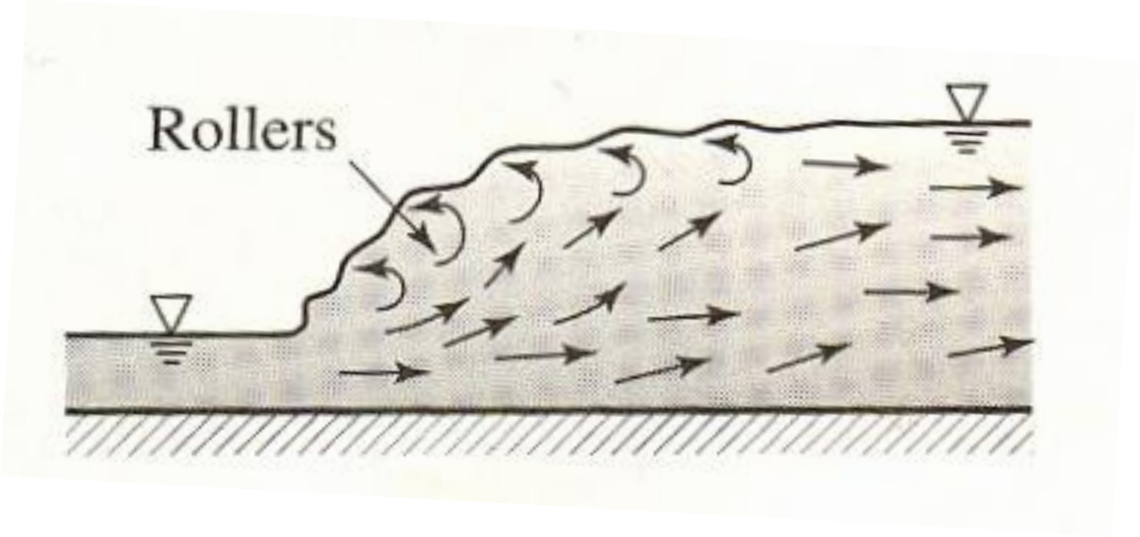


Fig 3.6: Stable Jump

(e) Strong or rough jump (Fn1 > 9)

- Froude Number should not be allowed to exceed 12 – otherwise required stilling basins will be large and massive.
- Ability of jump to dissipate energy is massive
- Ratio of final to initial depth ~ over 12 and may exceed 20

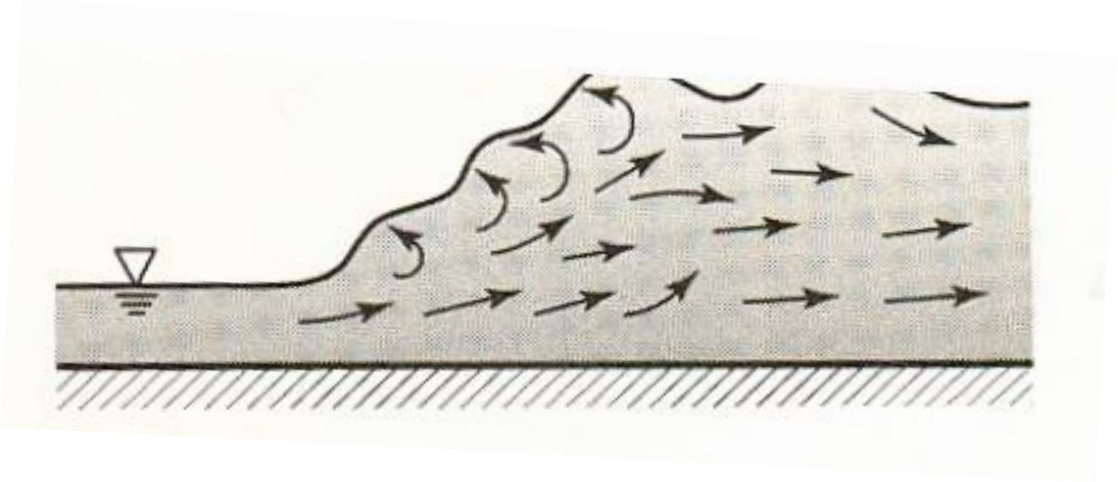


Fig 3.7 Strong Jump

3.4 GRADUALLY VARIED FLOW

Uniform flow requires a cross section constant in shape and area so it is generally to be found only in artificial channels. It demands that the slope of the bed to be constant and the liquid surface must be parallel to the bed of the channel. With a natural stream, true uniform flow is extremely rare because of the shape and size of cross-section and also the slope of the bed usually vary appreciably. Indeed, even for artificial channels uniform flow is never attained at all. The equations for uniform flow therefore give results that are only approximations to the truth when applied to flow in natural channels and, even so, care should be taken that they are not applied to long lengths of the channels over because conditions are not even approximately constant. There is only one depth at which uniform flow can take place for a particular shape of channel and for a given discharge and bed slope. It is known as the normal depth. There are, however, innumerable ways in which the same steady rate of flow can pass along the same channel in non-uniform flow. The liquid surface takes the form of a curve as it is not parallel to the bed. There are two kinds of steady, non-uniform flow. In one the variations of depth and velocity take place over a long distance. Such flow is termed gradually varied flow. In the other type of non-uniform flow the changes of depth and velocity take place in only a short distance and it is very rapid. This type of non-uniform flow is termed rapidly varied flow. There is in practice no rigid dividing line between these two types, but for the purposes of analysis gradually varied flow, effects of the acceleration of the liquid to be negligible as it changes slowly. Limitation of analysis is important because formula based on the assumption of gradually varied flow is not applicable to flow in which the changes take place more rapidly. Gradually varied flow may result from a change in the geometry of the channel – for example, a change in the shape of the cross-section, a change of slope, or an obstruction – or from a change in the frictional forces at the boundaries. Gradually varied flow can take place when the flow is either tranquil or rapid but as we have already seen a change from tranquil to rapid flow or vice versa usually occurs abruptly. Curve of the liquid surface is usually known as a backwater curve When, in tranquil flow, the depth is increased upstream of an obstruction. The converse effect–of all in the surface as the liquid approaches a free outfall from the end of the channel, for example – is termed a down drop or drawdown curve. Both curves are asymptotic to the surface of uniform[2].

3.4.1 THE EQUATIONS OF GRADUALLY VARIED FLOW

It is frequently important in practice to be able to estimate the depth of a stream at a particular point or to determine the distance over which the effects of an obstruction such as a weir are transmitted upstream. Such information is given by the equation representing the surface profile. The area of the cross-section is determined by depth at a particular section and hence the mean velocity and the surface profile defines the flow. How the depth changes with distance along the channel is needed to be investigated. The effects of boundary friction are important since the changes in gradually varied flow occupy a considerable distance. Slope i of the energy line and the slope s of the channel bed are two major parameters to determine the equations. Where as in uniform flow both the slope lines are same but in non-uniform flow they are not same. Over a short length channel for which the bed falls by an amount sδl, the depth of flow increases from h to h+δh and the mean velocity increases from u to u+δu, we assume that the increase in level δh is constant across the width of the channel. An assumption is there that the streamlines in the flow are sensibly straight and parallel and that the slope of the bed is small so that the variation of pressure with depth is hydrostatic, then the total head above the datum level is $h+ s\delta l+\alpha u^2/2g$ at the first section. α is the kinetic energy correction factor accounting for non-uniformity of velocity over the cross section. For simplicity we assume that α differs only slightly from unity so that, without appreciable error as its value is not generally known it may be omitted as a factor. Similarly, h+δh+ (u+δu) 2/2g is the total head above datum at the second section. If the head loss gradient is i, then

$$h + s\delta l + \frac{u^2}{2g} - i\delta l = h + \delta h + \frac{(u + \delta u)^2}{2g} \qquad \text{..........3.2}$$

Rearrangement gives $\delta h= (s-i)\delta l-u\delta u/g$, the term in $(\delta u)^2$ being neglected. Therefore in the limit as δl →0

$$\frac{dh}{dl} = (s - i) - \frac{u}{g} * \frac{du}{dl}$$

.........3.3

To eliminate du/dl we make use of the one-dimensional continuity equation Au=constant which, when differentiated with respect to l, yields $A * \frac{du}{dl} + u * \frac{dA}{dl} = 0$

$$\frac{du}{dl} = -\frac{u}{A} * \frac{dA}{dl}$$

.........3.4

To evaluate dA/dl we assume that, although the cross-section may be of any shape whatever, the channel is prismatic, that is, there is no dependency of shape and alignment. δA then equals Bδh where B denotes the surface width of the cross-section. So putting dA/dl =Bdh/dl in equation 3.4 and then substituting

into equation 3.2 we obtain

$$\frac{dh}{dl} = (s - i) + \frac{u^2 B}{gA} * \frac{dh}{dl}$$

So

$$\frac{dh}{dl} = \frac{(s - i)}{1 - (u^2 B / gA)} = \frac{dh}{dl} = \frac{s - i}{1 - \frac{u^2}{g\bar{h}}}$$

CHAPTER-IV

EXPERIMENTAL SET UP AND EXPERIMENTATION

4.1 DESCRIPTION OF THE EXPERIMENTAL SETUP

The setup of hydraulic jump experiment, on which the hydraulic jump experiment is performed, is in the hydraulics laboratory of Jadavpur University. The setup contains a big rectangular channel in which the water is supplied by a pump. The channel setup is 8.00 m long, 0.45 m in width and 0.53 m in height. The channel is metallic and side wall of mid channel is made of glass, which is 2.3 m in length. The advantage of this glass channel is that jump can easily be observed in a better way because of transparent glass side walls.

Fig 4.1 Rectangular Channel Setup

The channel is provided with two gates, one at the start of the channel and the other one at the end of the channel. By controlling these gates, the location of hydraulic jump and other phenomenon can be adjusted. Like if we close the inlet gate, the velocity at inlet will be more and jump goes away from the inlet gate and if we open the inlet gate, the jump will come towards the inlet gate. Same condition is with outlet gate, if we decrease the outlet gate opening, the jump will go away from outlet gate. It means the jump will shift towards the inlet gate and if we open the outlet gate opening, the jump will come towards the outlet gate. After this channel, there is a return channel which is made of brick. It returns the water which comes out of the setup channel. At the end of the return channel, a rectangular notch is there. By using this notch, we can calculate velocity. This whole setup is on the first floor of hydraulics laboratory. After the notch, there is a pipe which takes the water to the reservoir which is on the ground floor. Water is supplied to the setup by a pump which is on the ground floor and it takes water from the reservoir. The water recalculates again and again. There are two valves after pump which controls the discharge in the setup, one is bypass valve which bypasses the flow directly, means if the opening of the bypass valve is more, more water will be bypassed and less water is available for the setup. There is one more valve which is main valve. It directly connects the pipe carrying flow to the setup thus it also controls the discharge in the setup. On rectangular channel, one moving trolley is mounted which moves on the channel by help of rollers. A point gauge is mounted on this trolley which can move vertically. A scale is attached by it which will tell the vertical movement of the point gauge. By using this point gauge, the water height of upstream and downstream can be measured easily.

4.2 PROCEDURE OF EXPERIMENT

In the present Experiment the water supplied from the sump of Hydraulics Laboratory. This water comes through a pipeline in a small storage tank. One side of this tank is inlet gate of the channel. At the end of the channel, there is an outlet gate. We keep the outlet gate opening fixed and then varied the inlet gate opening for a fixed discharge. For any particular outlet gate opening, the length of jump, height of jump, location of jump, upstream height, downstream height, tail water depth, water level over the rectangular notch reading are taken.

A travelling point gauge assembly with option for moving both across the flume and along the flume has been designed, fabricated and installed in the course of the present work. The pointer is fitted with a measuring scale for indicating the depth of flow. In every set of experiments, H, Head of water in a supply tank, h_1, the water depth of incoming flow just before jump, h2 the water depth just after the jump; Lx, starting point of the jump; Lj Length of the jump and h_{tw}, depth of water just before the outlet sluice gate, were measured. The water depths, h_1, h_2, and h_{tw} were measured by the point gage. At any particular axial location, the centre line depth measurements were taken. The location of the jump Lx was measured by tape. The distance from the inlet sluice gate to the point where the water surface was started to suddenly rise up or fluctuate, was defined as starting point of the jump.

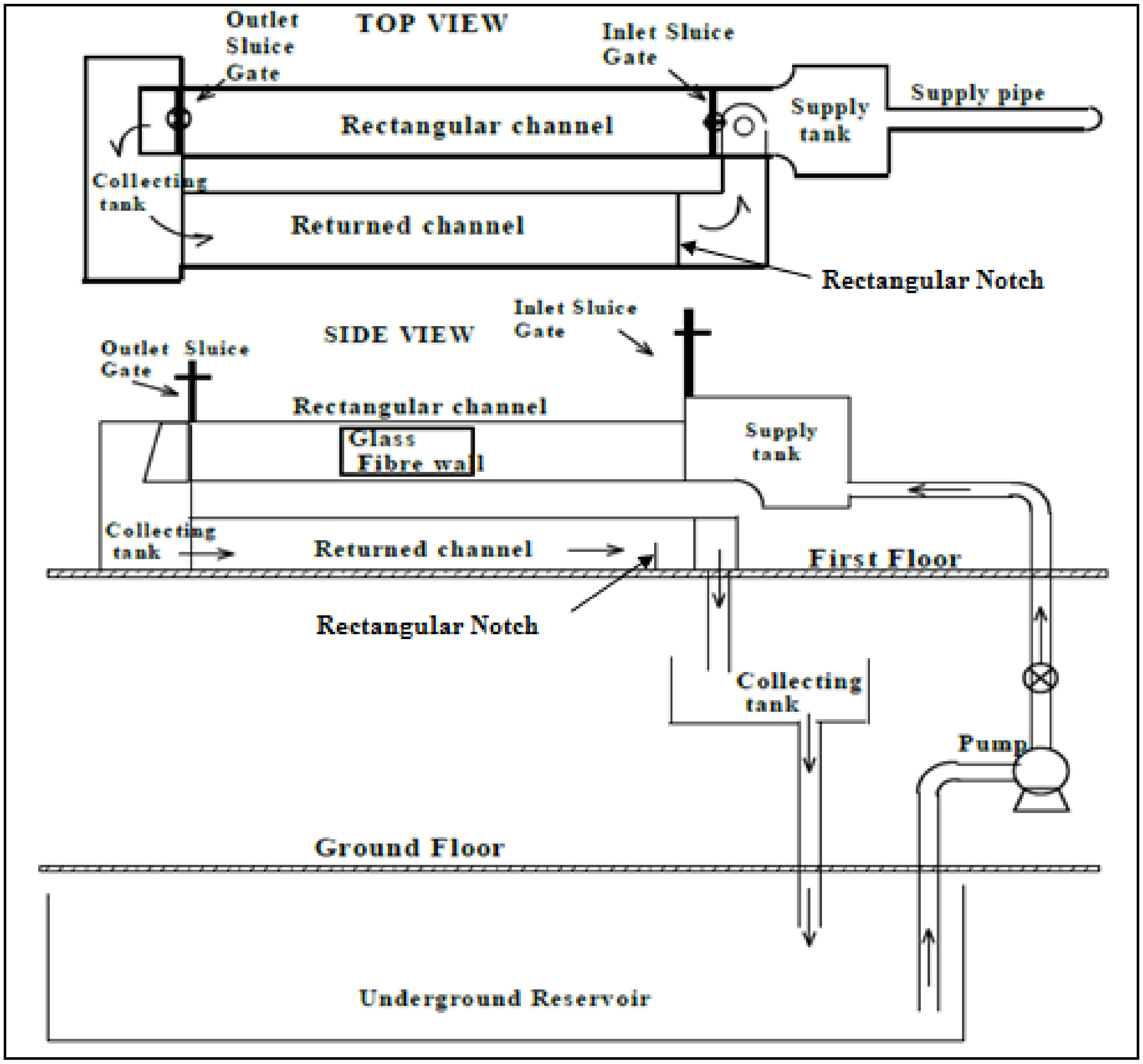


Fig. 4.2: Schematic Diagram of the Rectangular Channel set up

The length of hydraulic jump was obtained by taking difference between the starting point of the jump and end of the jump, which were measured by tape.
The Froude number range of the experiments had been kept between 2 to 4 that was achievable for the given fixed discharge with different openings of the inlet sluice. Higher Fr i.e. higher flow rate was not feasible because of overflow problem in the inlet tank as described earlier.

4.3 MEASUREMENT OF DIFFERENT EXPERIMENTAL QUANTITIES

The discharge through the flume had been constant during the experiment with a fixed setting of the pump delivery valve. The setting has been fixed based on occurrence of hydraulic jump formation with different openings of the inlet sluice valve. During the course of the experimentation the quantities that were measured had been velocity of flow, depths of flow at various locations, sluice openings and location of jump for subsequent calculations.

In the experiment, we have to calculate different experimental quantities like location of jump, length of jump, height of jump etc. These quantities are measured by using meter scale and also a point gauge which is mounted on a moving trolley, which moves on the rectangular channel. Procedures of measurement technique are described below.

4.3.1 MEASUREMENT OF LENGTH OF JUMP (L_j)

Length of hydraulic jump may be defined as the distance measured from the front face of the jump to a point on the surface immediately downstream from the roller. It can be seen in figure. It is measured by a meter scale. Proper care is done in measuring the length of jump.

Fig 4.3: Point gauge mounted on moving trolley

4.3.2 MEASUREMENT OF HEIGHT OF JUMP (h_j)

It is actually the difference between the height of the upstream and height of downstream. On the channel, a point gauge is there, which is mounted on a moving trolley. It can go up and down and a centimeter scale is attached to it, initially when we have to take readings, it is made to touch the bottom of the channel and reading on the scale attached to it is taken. After that it is made to move upward and touch the top surface of the water stream and again the reading on the centimeter scale is taken. The difference in the both reading will tell the upstream water height if it is performed in upstream and will give the downstream water height if it is performed in the downstream. This point gauge can also move perpendicular to the length of the channel. Thus the readings can be taken at different places for a definite cross section of water. And the average of all the reading will give comparatively more accurate value.

4.3.3 MEASUREMENT OF LOCATION OF JUMP (Lx)

Location of jump is that quantity, which tells about the distance from the inlet gate to where the jump starts. It is measured from inlet gate by using a meter scale. It is controlled by controlling the inlet and outlet gate as well. If the inlet gate opening is less, the jump will occur at more distance from the inlet gate and if the inlet gate opening is more, the jump will occur closer to the inlet gate. And also if the outlet gate opening is more, the jump will occur near to outlet gate and if it is less, the jump will occur near to inlet gate.

Fig 4.4: Hydraulic jump in channel

4.3.4 MEASUREMENT OF VELOCITY AND FLOW RATE THROUGH THE CHANNEL

Beside the rectangular channel, there is a returning channel made of brick which takes the water coming out of the channel and returns it to the reservoir. There is a rectangular notch fixed in the returning channel whose width is 53.5 centimeter and height is 35.5 centimeter. Flow passes over the notch and the height of water above the notch is measured and by using Rechbok Formula, discharge through channel is calculated.

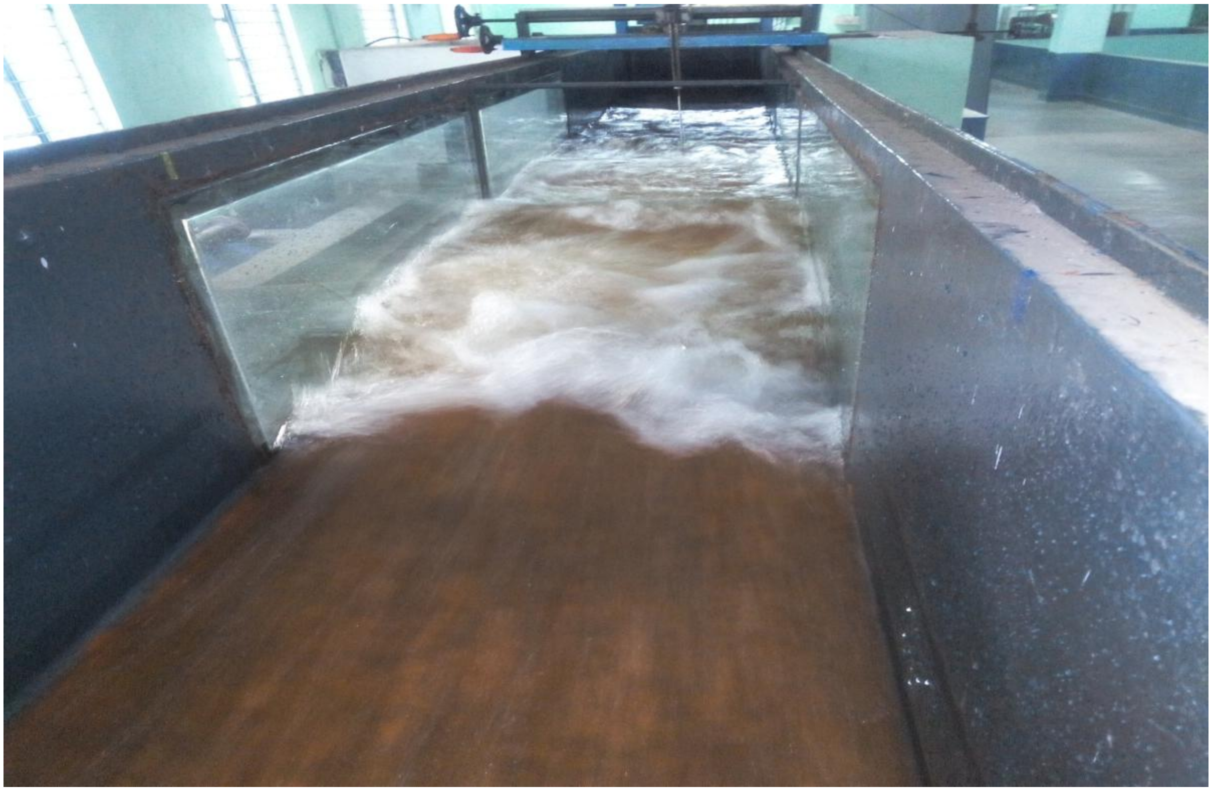


Fig 4.5: Top view of hydraulic jump

Rechbok Formula

$$Q = \frac{2}{3}\sqrt{2}\left(0.602 + 0.0832\frac{h}{z}\right)B\sqrt{g}\left(h + 0.00125\right)^{1.5}\ m^3/s \qquad \text{………. (3.1)}$$

By using this formula, discharge can be calculated and it will also be the discharge of the channel setup. Thus by applying the continuity equation, the velocity can be calculated for both upstream and downstream.

Here

Q = Discharge,

h = height of water above notch,

z = width of notch,

g = acceleration due to gravity

Fig 4.6: Rectangular notch

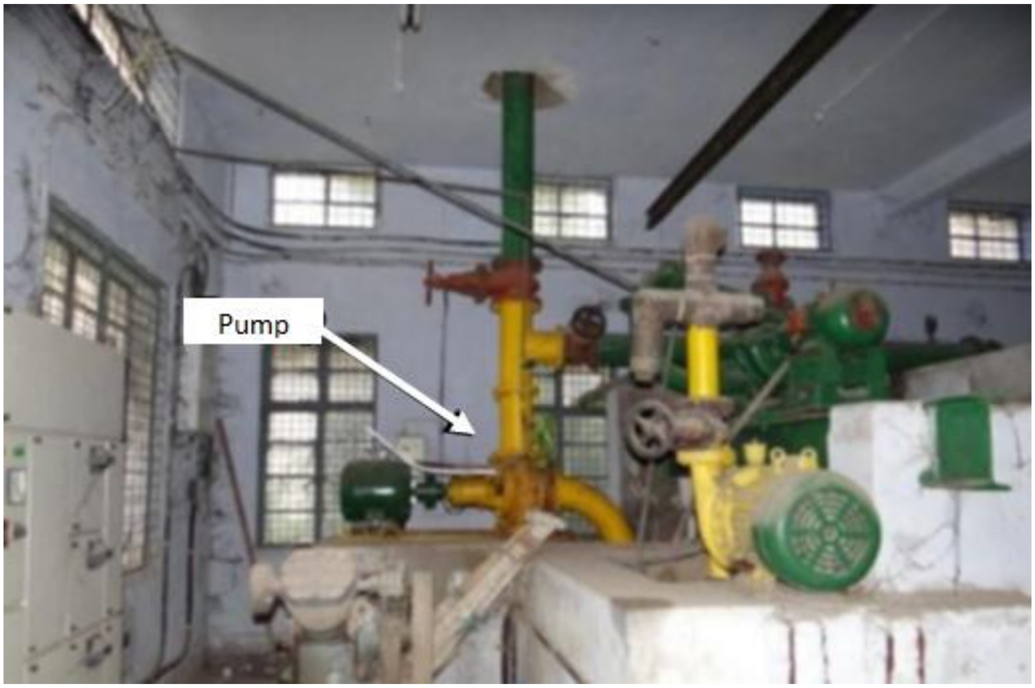


Fig. 4.7: Water Pump for the flow through channel

(a) Near the Inlet Sluice Gate **(b) Near the Outlet Gate**

Fig. 4.8: Top view of Rectangular Channel bed (on which the experiments were done) at Fluid Mechanics & Hydraulic Lab, Jadavpur University, Kolkata.

4.4 THEORETICALLY PREDICTED PROFILE

Prediction of the location of hydraulic jump and formulated different formula and computation methods was done by many researchers. If the initial depth, sequent depth and the approaching Froude number satisfy the equation (1.1), then only the jump will occur in the channel.

Here, the hydraulic jump is to predict the location of jump by the equation of gradually varied flow for the horizontal rectangular channel. This rectangular channel is assumed as prismatic channel. It will be computed that the calculation based on the equation of gradually varied flow.

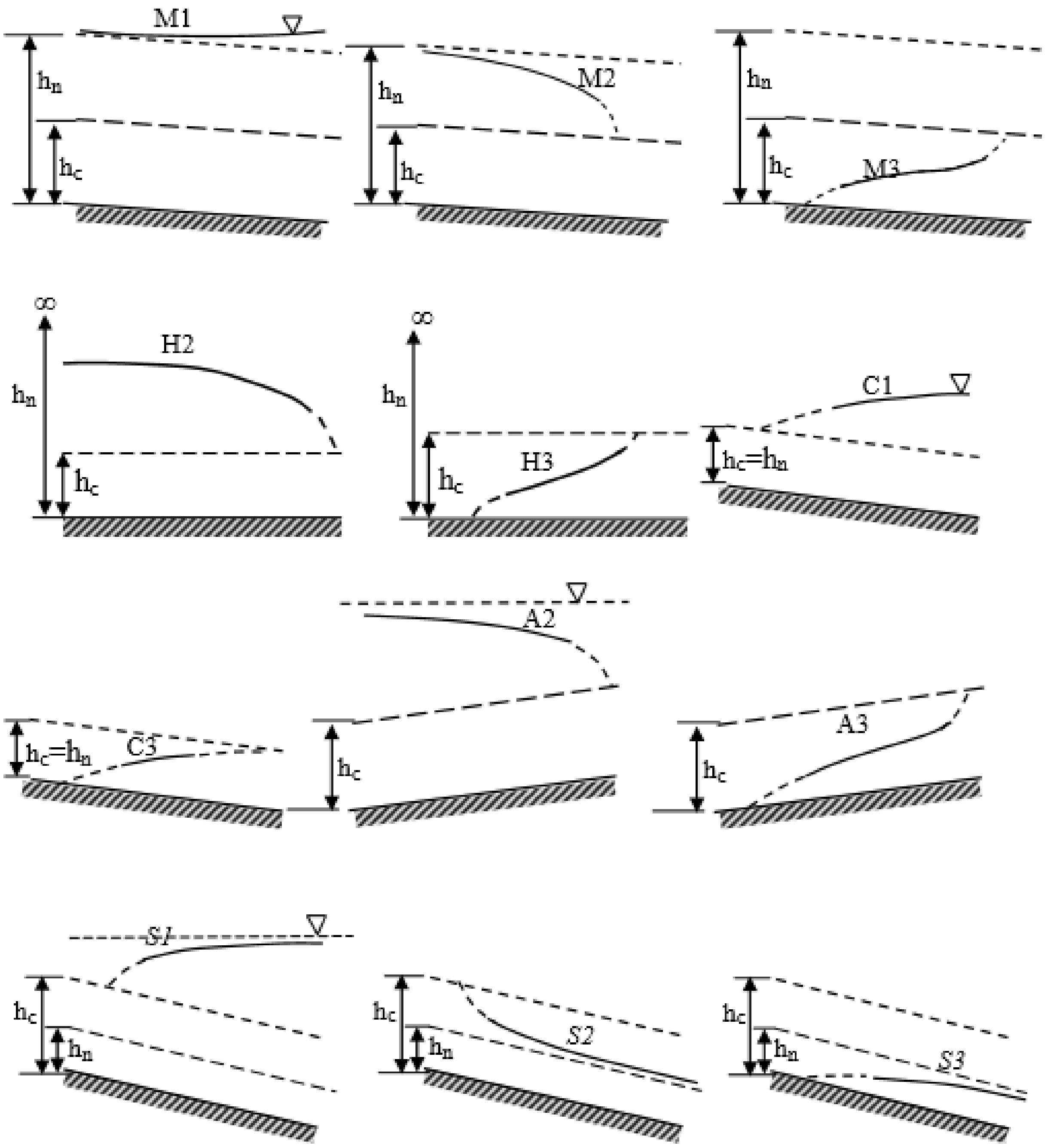


Fig. 4.9: Different types of water surface profile[13]

The primary classification of gradually varied flow refers to the slope of the bed. Such as A (adverse) slope i.e. uphill or negative slope

H (horizontal) slope i.e. slope is equal to zero

M (Mild) slope i.e. slope is less than critical slope.

C (critical) slope i.e. slope is equal to critical slope.

S (steep) slope i.e. slope is greater than critical slope

$$\frac{dh}{dl} = \frac{s - i}{1 - \frac{u^2}{g\bar{h}}} \qquad \textbf{.......}(3.2)$$

where,

dh is increase in level or depth,

dl is increase in length

i is slope of the energy gradient line

s is the slope of channel bed

u is mean velocity

B is surface width of channel section

Base on the equation (3.2), the computations of gradually varied flow are done based on upstream and downstream profile.

Considering the following:

Table 4.1: Different quantities for upstream profile

Manning Constant	n	0.013
Flow through Channel	Q	0.059 m3/s
Channel width	B	0.450 m
Length of the Channel	L	8.000 m
Critical Depth	hc	$\left(\frac{q^2}{g}\right)^{1/3}$
Tail water depth	h_{tw}	From Data
Depth Inlet Sluice Gate	hi	From Data
Velocity by Inlet Sluice Gate	u_1	Q/(B*hi)
Upstream Froude number	Fr_1	u1/√(9.81* hi)
Depth of Outlet Sluice Gate	ho	From Data

Velocity of Outlet Sluice Gate	uo	Q/(B*ho)
Downstream Froude number	Fr_2	$\frac{\left(2*\sqrt{2}\right)*Fr_1}{\left(\left(\sqrt{1+8Fr_1}\right)-1\right)^{1.5}}$
Slope of the bed	s	zero

Table 4.2: Computation of Upstream of hydraulic jump Profile

1	2	3	4	5	6	7	8	9	10	11	12	13
dh	$\bar{h}$	h_1	A	u_1	P	m	$1-\frac{u}{\sqrt{g\bar{h}}}$	i	$\frac{dl}{dh}$	dl	L	LO

The Procedures for the table (4.2) are as follows.

Column No.1 Assumed dh = 0.001

Column No.2 $\bar{h}$ is Start with Critical depth, hc, and then, the column is decreased by dh/2 and so on

Compute mean depth, $\bar{h} = h_c \mp \frac{\Delta h}{2}$

Column No.3 Conjugate depth, h_2 is calculated using, $h1 = \frac{-\bar{h}}{2} + \sqrt{\left(\frac{\overline{h}^2}{4} + \frac{2\bar{h}*u_1^2}{g}\right)}$

Column No.4 Compute Cross sectional Area, A by the product of mean depth, $\bar{h}$ and bottom width B

Column No.5 Compute velocity, u_1 using $u_1 = \frac{Q}{A}$

Column No.6 Compute wetted perimeter, P using P=2$\bar{h}+B$

Column No.7 Compute hydraulic mean depth, m using m= $\frac{A}{P}$

Column No.8 Compute 1-$\frac{u_1}{\sqrt{g\bar{h}}}$

Column No.9 Compute energy gradient, i by i= $\frac{n^2 * u^2}{m^{4/3}}$ (From Manning equation)

Column No.10 Compute dl /dh by equation (3.2)

Column No.11 Compute dl by dl = (dl/dh)*dh i.e. Column No.1 is multiplied by Column No.10

Column No.12 Adding Previous value of *L* (of same column) and *dl* (of the same row)

Column No.13 It is actually column number 12 in reverse manner. It starts from the length and then decrease.

Downstream computation will be almost same to the procedure written above i.e. for upstream profile. There is only one difference that the downstream profile, column number 2 will start with tail water depth, while the upstream profile started with critical depth.

The detail computation of upstream profile and downstream profiles are shown in the Annexure I and Annexure II.

4.4.1 THEORETICAL CALCULATION PROCESS FOR THE LOCATION OF HYDRAULIC JUMP

Annexure I and Annexure II contain theoretical calculation by using upstream profile and downstream profile.

The jump takes place between a regulating inlet sluice gate and outlet sluice gate in a Prismatic horizontal rectangular channel. In the figure (4.10), the profiles AGB and A1F1B are of H2 and H3 type (figure 4.9) and a graph between H2 curve and LO was drawn as h_1 Versus LO and h_2 Versus LO from Table 3.2 Computation of Upstream of hydraulic jump Profile.

The location of the Sluice gates is very important. For locating the gate positions, Vena Contracta position is main parameter and it should be fixed first. By using inlet sluice gate opening and Coefficient of contraction, Cc = 0.61, we mark the line QQ using the depth of Vena Contracta i.e. h_{vc} = Cc*hi where hi is opening of inlet sluice gate[10]. Vena contracta thickness is the vertical position the point of intersection between AGB and QQ. By moving backward from vena-contracta by a distance equal to hi, the Inlet Sluice gates can be located. Outlet sluice gate can be located by adding the length of the channel to inlet sluice gate,

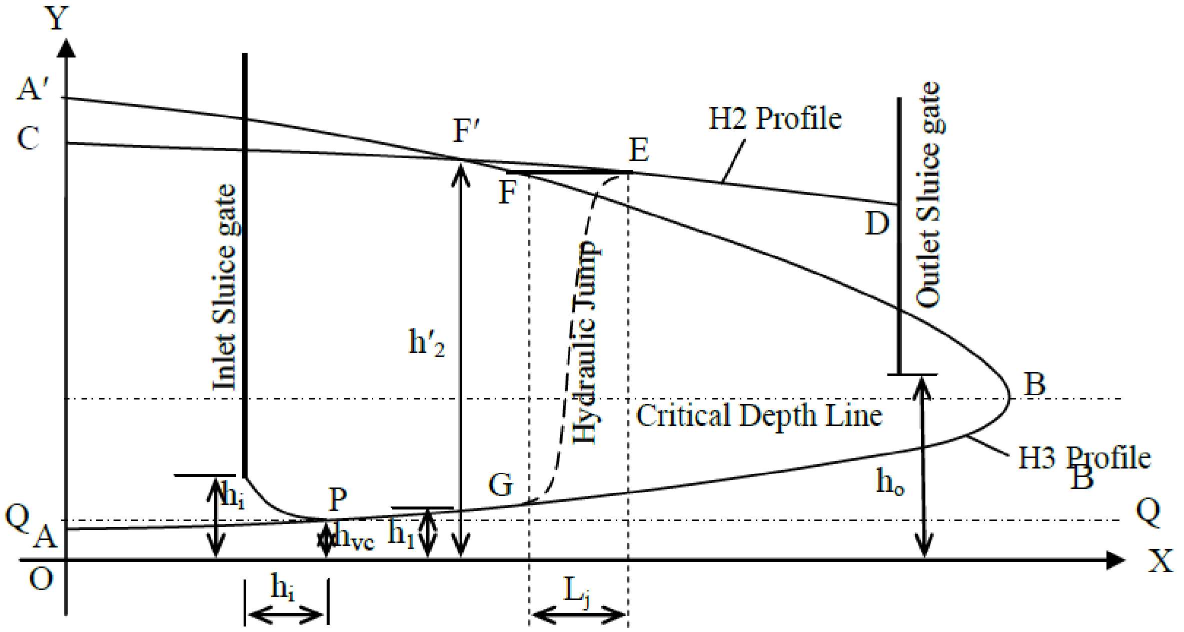


Fig. 4.10: Location of Hydraulic jump (by theoretical)

Now, the curve A′F′B is a plot of the depths sequent to AGB it can be easily drawn by using the conjugate depth. By using the downstream flow profile, the curve CF1D is plotted. The point of intersection between A′F′B and CF′D is named as F′. The initial depth of flow at Fr_1 is then found from H3 profile. The corresponding Froude number is also found from computation of the upstream flow profile and by using that Froude Number, Lj/h_2 can be found easily from the figure (4.11). The length of the jump is $Lj=\frac{Lj}{h2}$ h'_2 at Fr_1 which is to be equal EF here $\frac{Lj}{h2}$ is already known from figure 4.11. The sequent depth of flow at E will be h_2.

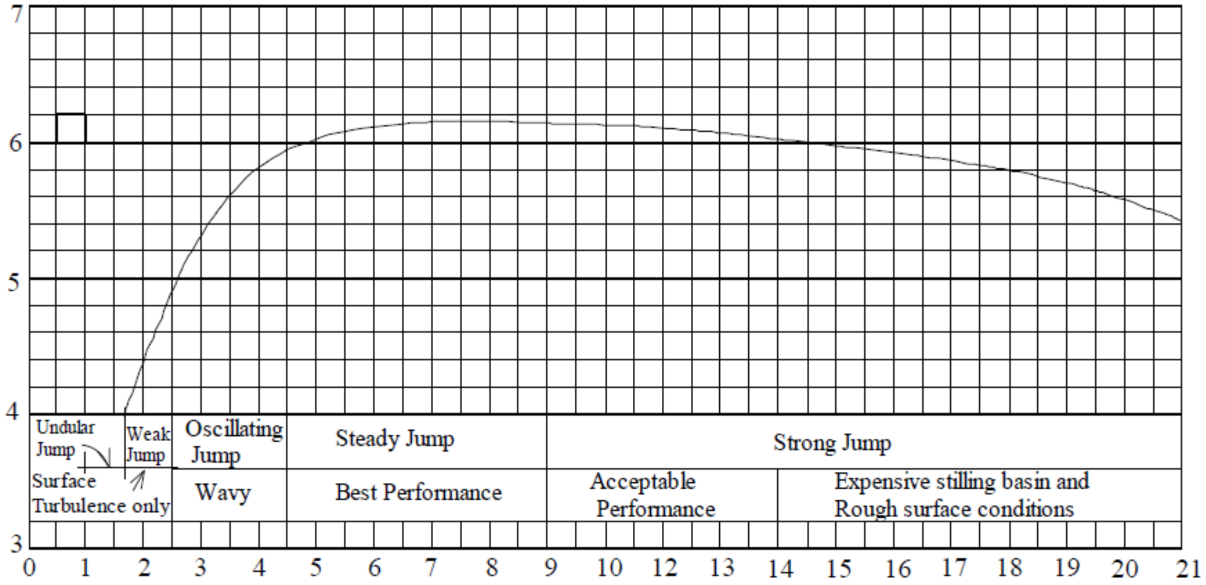
4.4.1.1 LOCATION OF THE POINT E AND F

The position of points E and F in fig (4.11) were found out by Trial and error method (Chow 1959). By using equation of linear trend lines of curves A′F′B and CF′D Now, we have modified the process. Let the points be E(x_1,y_1) and F(x_2,y_2) and $y_1$and y_2 will be same because they are at the same level. Initially a best fit curve equation is found for both the intersecting curve. Equating the y value of both the curves as it is same for both. Now we will get a equation in x_1 and x_2. Now another equation in x1 and x2 will be obtained as $x_1 = x_2 + L_J$. Therefore, equating the two equations one can calculate the values of x_1 and x_2 . Then, the position of E and F will be obtained.

The corresponding points of E and F on the datum line are the new position of h_1 and h_2 considering the length of hydraulic jump.

4.4.1.2 METHOD OF COMPUTATION OF FROUDE NUMBER FOR EXPERIMENT AND THEORETICAL CALCULATION

The velocity u1 is calculated from u1=Q/A where Q is flow rate which is measured in the channel and A is area of cross section where A = Bh1 for experimental and $A=B\bar{h}$ for theoretical computation. For getting Froude number, we have used $Fr_1 = u_1 / \sqrt{(g * h\ i)}$ for experimental and $Fr_1 = \frac{u_1}{\sqrt{(g\bar{h})}}$ for theoretical where g is acceleration due to gravity , h_1 is depth just before the jump flow and $\bar{h}$ is mean depth.



Length in terms of sequent depth y_2 of jumps in horizontal channels.

(Based on data and recommendations of U.S. Bureau of Reclamations)

Fig. 4.11: Length in terms of sequent depth y 2 in horizontal channel (Chow 1959)

CHAPTER-V

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

Experimental data were used for the study. These data were compared with theoretically predicted results. Many comparisons were done like positions of jump, surface profiles and ratio of, with the theoretically predicted results. The setup contains an adjustable inlet sluice gate at starting of the channel and an adjustable outlet sluice gate at the end of the channel. By adjusting these two gates, the jump conditions are created. For that it is essential to keep the inlet sluice gate below the critical depth. The jump location is dependent on the inlet sluice gate opening, outlet sluice gate opening and also the flow rate. But in the experiment, the jump was controlled by controlling the inlet sluice gate opening while keeping the outlet sluice gate opening and discharge fixed. Also the experiments were done on two different opening of outlet sluice gate while keeping the discharge fixed throughout the experiment. When the jump is stabilized, the reading were taken carefully for the location of jump, length of jump, sequent depths

In the previous research, researchers used weir or blocks for creating the hydraulic jump. The previous researchers used. So by using this, it can be seen that sequent depth is more than the tail water depth and the surface profile can be seen clearly. So, there is an influence of tail water depth on the hydraulic jump problem.

In the present experiments, the hydraulic jump is created with outlet sluice gate and it also helped the tail water depth to rise up. Here the tail water depth is not less than the sequent depth.

No hydraulic jump will not take place when the outlet sluice gate opening is more than or equal to the critical depth

These observations done are on the basis of experiment

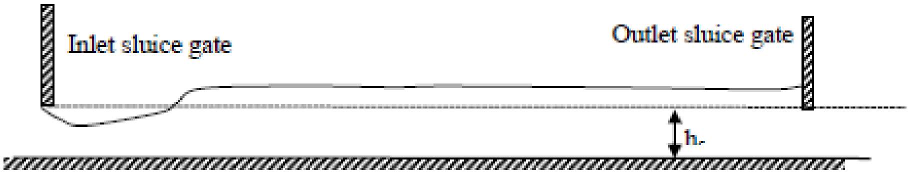


Fig 5.1: A simple sketch of free hydraulic jump when inlet sluice gate and outlet sluice gate are at critical depth

- Free hydraulic jump will take place when both the gates i.e. inlet and outlet, are at the critical height. If the inlet sluice gate opening is less than critical height, free jump takes place.
- If the inlet sluice gate is opening is less than critical depth and outlet sluice gate is less than critical depth, submerge hydraulic jump occurred.

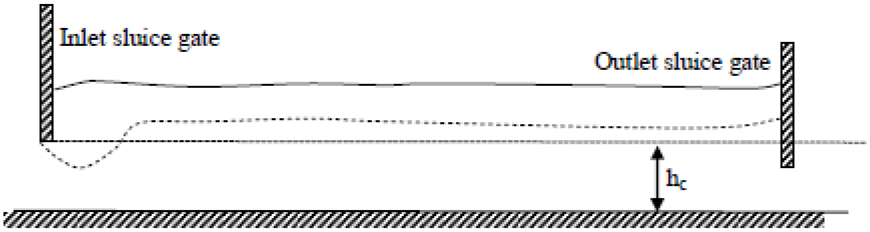


Fig 5.2: Simple sketch of submerged jump hydraulic jump in when inlet sluice gate at critical depth and outlet sluice gate is below critical depth.

- If the inlet sluice gate opening is very less i.e. than half of critical depth and outlet gate opening is more than the critical depth, hydraulic jump will not take place. The water coming out of the inlet gate goes out without formation of jump. In this situation an obstruction can be used for getting a hydraulic jump. For very long channel, the jump can take place for this situation.

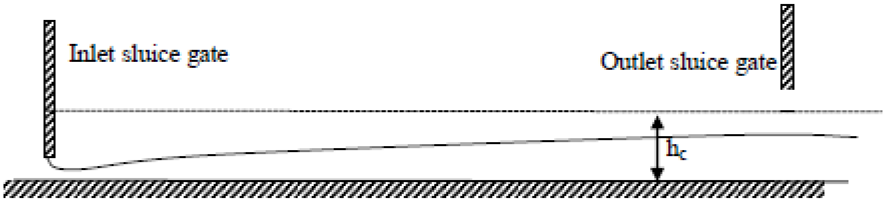


Fig 5.3: Simple sketch of no jump in between when inlet sluice gate below critical depth and outlet sluice gate is above critical depth.

The outlet gate opening is 9.0cm, 9.5cm, 10.0cm and 10.5cm in the experiment and all these values are more than critical depth. And also the inlet gate opening is kept less than the critical depth. Thus the sufficient condition for hydraulic jump is satisfied and the jump takes place.

The present study involves the comparison of experimental results with the theoretically predicted results.

- Depth ratio for the jump with Froude number
- Length of jump with Froude number
- Flow profiles based on location

5.2 DEPTH RATIO

Comparison of depth ratio (h_2/h_1) to the Froude Number is done for both Experimental and Theoretical results for different outlet sluice gate opening. The graphical representations of comparison are plotted in the graph below. Usually we can observe that the depth ratio for the experiment is less than the depth ratio of theoretical computation. It is due to the friction in the channel, varying head in the tank. By improving the channel setup, it can come closer to the theoretical computed value. It can be observed that the theoretical computed values follow a trend while the experimental results shows a few variation at some points and it become zig zag. It is also due to the irregularity in the channel. In the theoretically predicted profile, the channel is assumed to be smooth while it is rough in the actual practice.

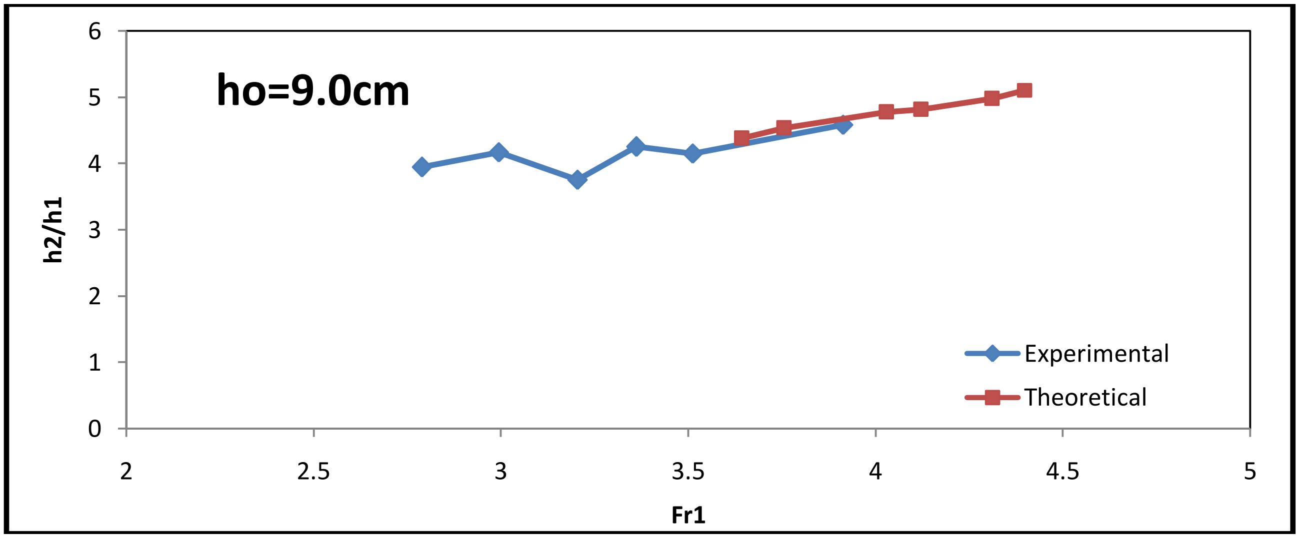


Fig 5.4: Comparison of Relative jump length of Experimental results and Theoretical Predictions

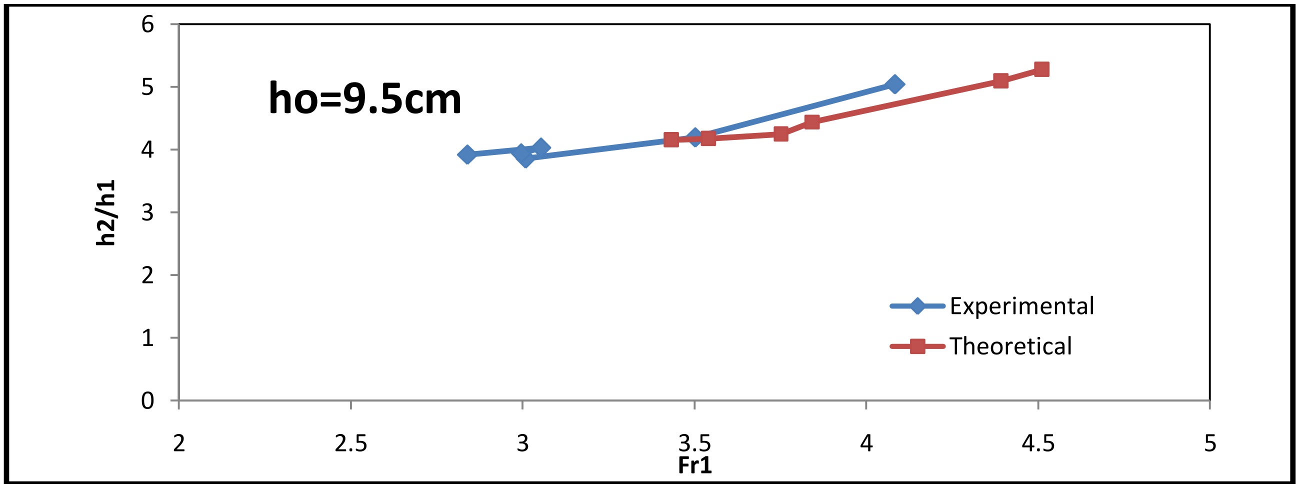


Fig 5.5: Comparison of Depth ratio for Experimental results and Theoretical Predictions

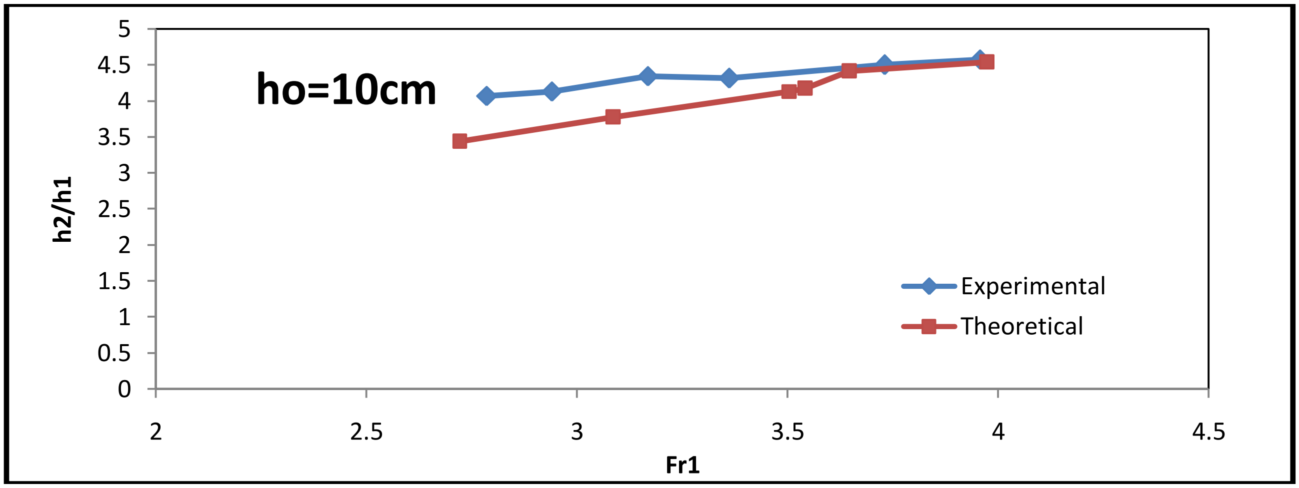


Fig. 5.6: Comparison of Depth ratio for Experimental results and Theoretical Predictions

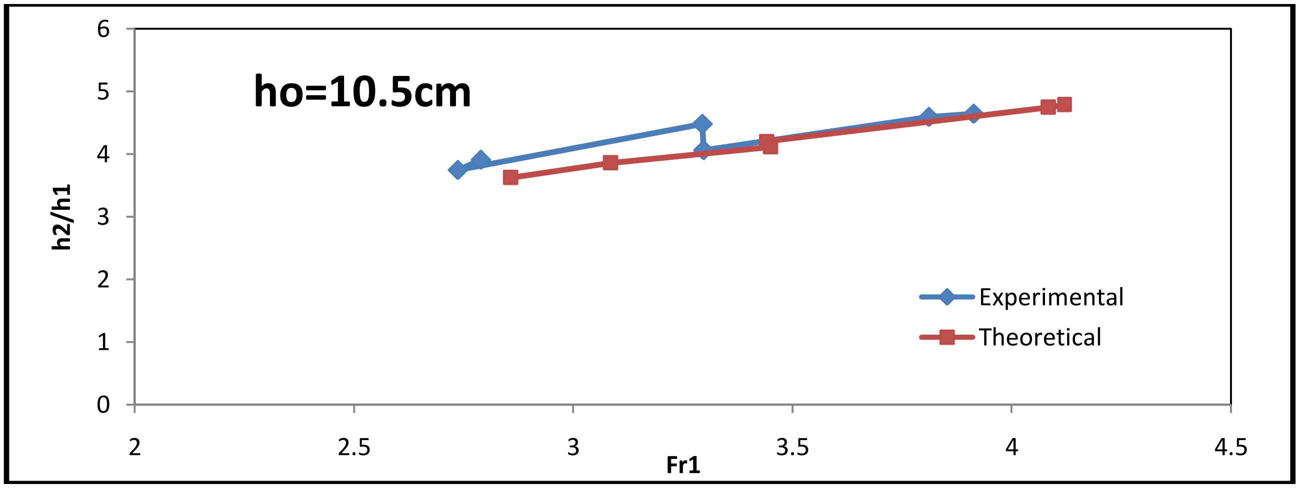


Fig. 5.7: Comparison of Depth ratio for Experimental results and Theoretical Predictions

Table 5.1: Experimental measurements in the Rectangular Channel

h_o (m)	h_i (m)	L_x (m)	L_j (m)	h_1(m)	h_2 (m)	h_{tw} (m)	Fr_1	Flow Profile
0.090	0.050	3.71	0.79	0.048	0.220	0.230	3.914	Fig 5.12
	0.055	3.01	0.80	0.051	0.212	0.230	3.512	Fig 5.13
	0.060	2.26	0.77	0.051	0.217	0.225	3.362	Fig 5.14
	0.065	1.87	0.85	0.054	0.203	0.224	3.205	Fig 5.15
	0.070	1.13	0.73	0.053	0.221	0.225	2.995	Fig 5.16
	0.075	6.10	0.71	0.054	0.213	0.220	2.789	Fig 5.17
0.095	0.050	4.43	0.82	0.043	0.217	0.222	4.084	Fig 5.18
	0.055	3.89	0.78	0.051	0.214	0.225	3.503	Fig 5.19
	0.060	3.27	0.79	0.057	0.220	0.225	3.008	Fig 5.20
	0.065	2.96	0.75	0.055	0.217	0.225	2.995	Fig 5.21
	0.070	2.21	0.70	0.052	0.210	0.220	3.053	Fig 5.22
	0.075	1.14	0.74	0.054	0.212	0.221	2.840	Fig 5.23
0.100	0.050	4.95	1.03	0.047	0.215	0.215	3.957	Fig 5.24
	0.055	4.35	1.01	0.048	0.216	0.221	3.731	Fig 5.25
	0.060	3.60	0.91	0.051	0.220	0.220	3.362	Fig 5.26
	0.065	2.55	0.98	0.052	0.226	0.223	3.168	Fig 5.27
	0.070	1.95	0.83	0.054	0.223	0.225	2.940	Fig 5.28
	0.075	1.55	0.81	0.055	0.224	0.220	2.786	Fig 5.29
0.105	0.050	5.65	0.86	0.048	0.223	0.225	3.914	Fig 5.30
	0.055	4.70	0.85	0.047	0.216	0.224	3.811	Fig 5.31
	0.060	3.86	0.90	0.052	0.211	0.220	3.298	Fig 5.32
	0.065	2.94	0.82	0.050	0.224	0.225	3.295	Fig 5.33
	0.070	2.11	0.91	0.058	0.217	0.224	2.737	Fig 5.34
	0.075	1.45	0.85	0.055	0.215	0.223	2.789	Fig 5.35

Where,

hi = Depth of Opening in Inlet Sluice gate

ho = Depth of outlet in Inlet Sluice gate

h_1 = Depth of supercritical flow of Hydraulic Jump

h_2 = Depth of subcritical flow of Hydraulic Jump

Fr_1 = Froude Number of Supercritical flow

h_{tw} = Tail water Depth

Lj = Length of Hydraulic Jump

Lx = Location of Hydraulic Jump from inlet gate

Table 5.2: Theoretical computation results for the rectangular Channel

h_o (m)	h_i (m)	L_x (m)	L_j (m)	h_1 (m)	h_2 (m)	h_{tw} (m)	Fr_1	Flow Profile
0.090	0.050	4.11	1.13	0.045	0.230	0.223	4.400	Fig 5.12
	0.055	3.52	1.07	0.045	0.224	0.224	4.312	Fig 5.13
	0.060	3.02	1.01	0.047	0.221	0.222	4.122	Fig 5.14
	0.065	2.25	0.98	0.046	0.220	0.220	4.031	Fig 5.15
	0.070	1.63	0.95	0.050	0.217	0.218	3.757	Fig 5.16
	0.075	0.34	0.95	0.051	0.218	0.220	3.644	Fig 5.17
0.095	0.050	4.86	1.22	0.043	0.227	0.223	4.511	Fig 5.18
	0.055	4.40	1.17	0.044	0.224	0.220	4.392	Fig 5.19
	0.060	3.92	1.15	0.050	0.222	0.220	3.643	Fig 5.20
	0.065	3.14	1.10	0.052	0.221	0.219	3.751	Fig 5.21
	0.070	2.26	1.04	0.052	0.217	0.217	3.542	Fig 5.22
	0.075	1.43	0.96	0.052	0.216	0.215	3.433	Fig 5.23
0.100	0.050	5.32	1.10	0.048	0.218	0.215	3.974	Fig 5.24
	0.055	4.85	1.07	0.051	0.225	0.217	3.647	Fig 5.25
	0.060	4.10	1.05	0.052	0.217	0.209	3.542	Fig 5.26
	0.065	3.20	1.02	0.052	0.215	0.218	3.504	Fig 5.27
	0.070	2.15	0.99	0.057	0.215	0.215	3.086	Fig 5.28
	0.075	1.43	0.96	0.062	0.213	0.216	2.721	Fig 5.29
0.105	0.050	6.23	1.27	0.047	0.225	0.219	4.120	Fig 5.30
	0.055	5.31	1.20	0.047	0.223	0.220	4.084	Fig 5.31
	0.060	4.48	1.18	0.053	0.223	0.214	3.442	Fig 5.32
	0.065	4.04	1.11	0.052	0.214	0.215	3.451	Fig 5.33
	0.070	3.37	1.10	0.057	0.220	0.210	3.086	Fig 5.34
	0.075	2.56	1.12	0.060	0.217	0.217	2.858	Fig 5.35

Where,

hi = Depth of Opening in Inlet Sluice gate

ho = Depth of outlet in Inlet Sluice gate

h_1 = Depth of supercritical flow of Hydraulic Jump

h_2 = Depth of subcritical flow of Hydraulic Jump

Fr_1 = Froude Number of Supercritical flow

h_{tw} = Tail water Depth

Lj = Length of Hydraulic Jump

Lx = Location of Hydraulic Jump from inlet gate

5.3 RATIO OF LENGTH OF HYDRAULIC JUMP (L_j) TO THE SEQUENT DEPTH

Comparison of ratio of length of hydraulic jump and sequent depth is done in the study for both experimental results and theoretical computed results. The comparisons are done for different values of outlet sluice gate opening. It is observed from comparison that the theoretical computed values are more. In other language it can be observed that the graph of theoretical computed values are always above the graph of experimental results. It is due to irregularity in the channel. Usually the length of jump is higher in smooth channel. A channel with friction reduces the length of jump. The experiment was done in a channel which was not very smooth and in theoretical computation the channel is observed as smooth channel. So the Lj/h2 value of theoretical computation is always more than experimental results.

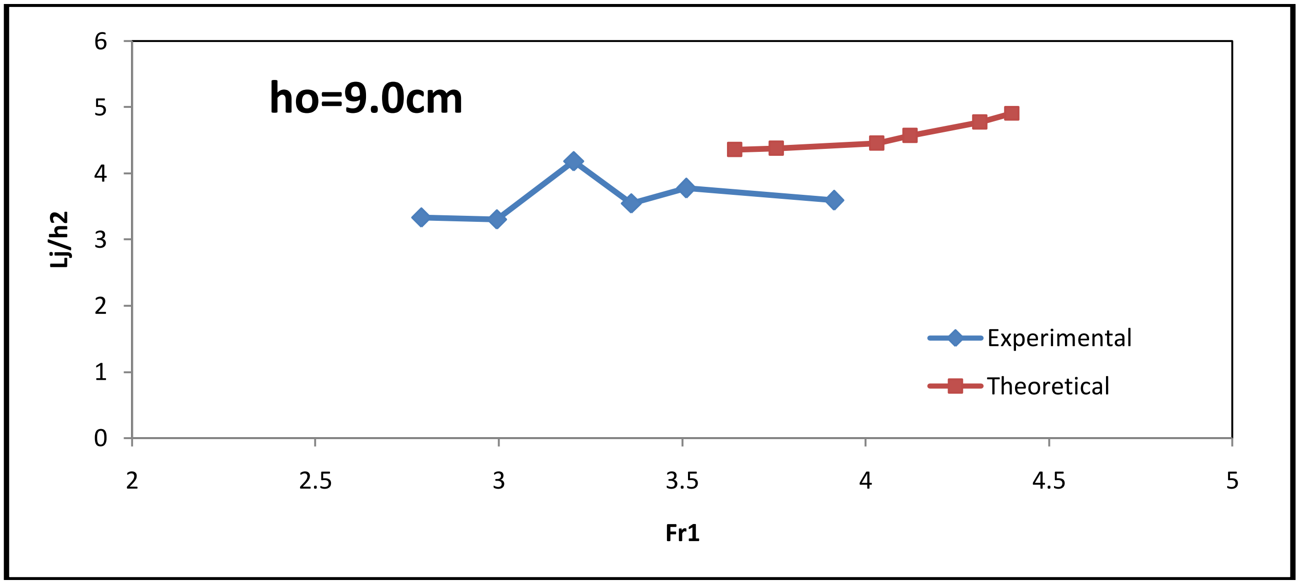


Fig. 5.8: Comparison of Relative jump length of Experimental results and Theoretical Predictions

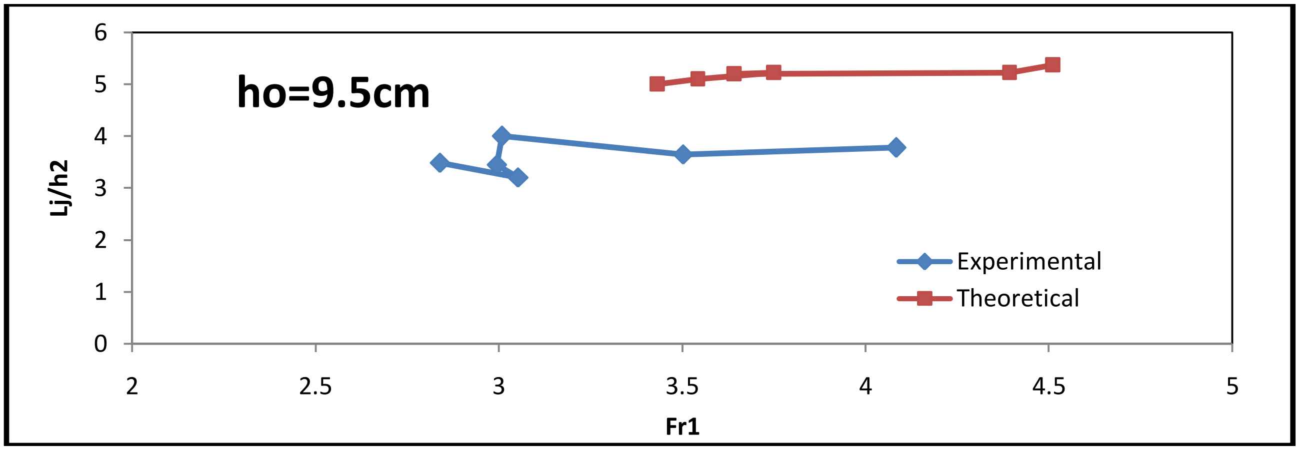


Fig. 5.9: Comparison of Relative jump length of Experimental results and Theoretical Predictions

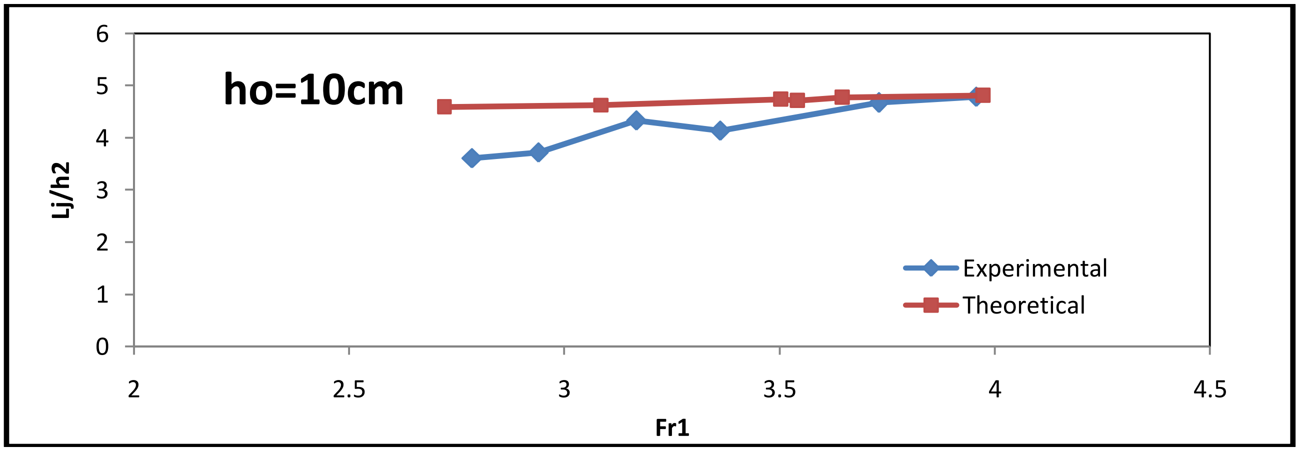


Fig. 5.10: Comparison of Relative jump length of Experimental results and Theoretical Predictions

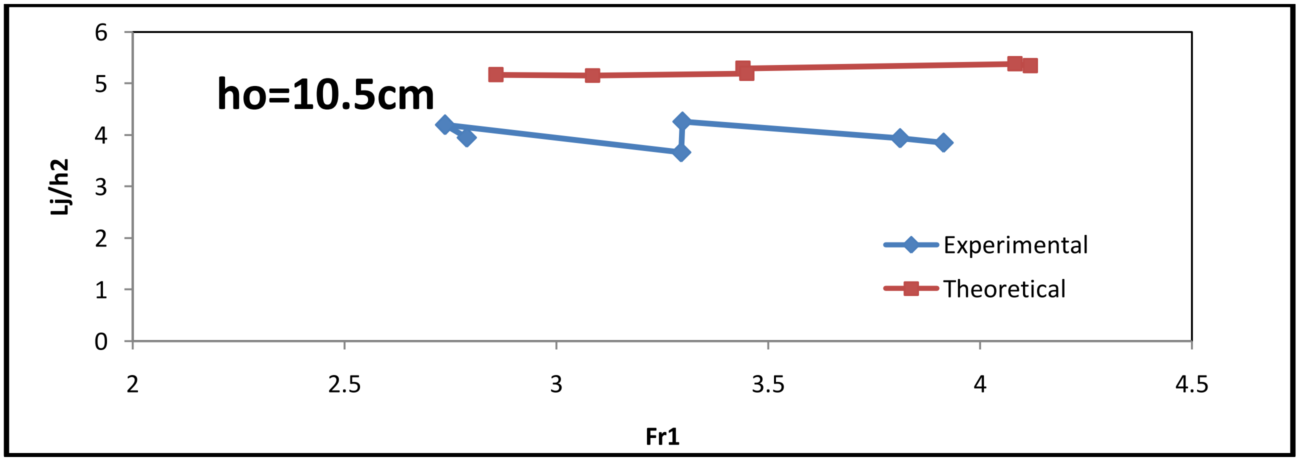


Fig. 5.1: Comparison of Relative jump length of Experimental results and Theoretical Predictions

5.4 COMPARISON OF FLOW PROFILE

Comparison of flow profile for both experimental results and theoretical computed data are plotted. These plots indicate the comparison of jump parameters e.g. location and height of jump, tail water depth etc. from these plots we can observe that just after the inlet sluice gate, vena contracta is formed. Thus the water level is comparatively lower than the inner gate opening. After that is starts rising very slowly. It is also observed that near outlet sluice gate, the water depth is becoming higher, the water flow try to follow the H2 profile but sluice gate is introduced, that create a pool. The location of the jump and also the length of jump is higher in theoretical computed profile. It is also due to the surface roughness of the channel. In the experimental results, surface roughness plays a vital role while in the theoretical we get the computed results, assuming the channel is smooth. The method of theoretical computation has already been discussed. Although the theoretical location of the jump is a little ahead of that of the experimental jump, still the two profiles are in reasonable agreement. The graphs of comparisons are made for every outlet sluice gate opening. The experiment was performed for four different opening of the outlet sluice gate i.e. 9.0cm, 9.5cm, 10cm, 10.5cm and for every opening of outlet sluice gate opening, there are 6 different inlet gates opening. Inlet gate is kept at 5.0cm, 5.5cm, 6.0cm, 6.5cm, 7.0cm, and 7.5cm. So it makes a combination of 24 graphs. These 24 graphs for experimental results and theoretical computed results are shown in the thesis.

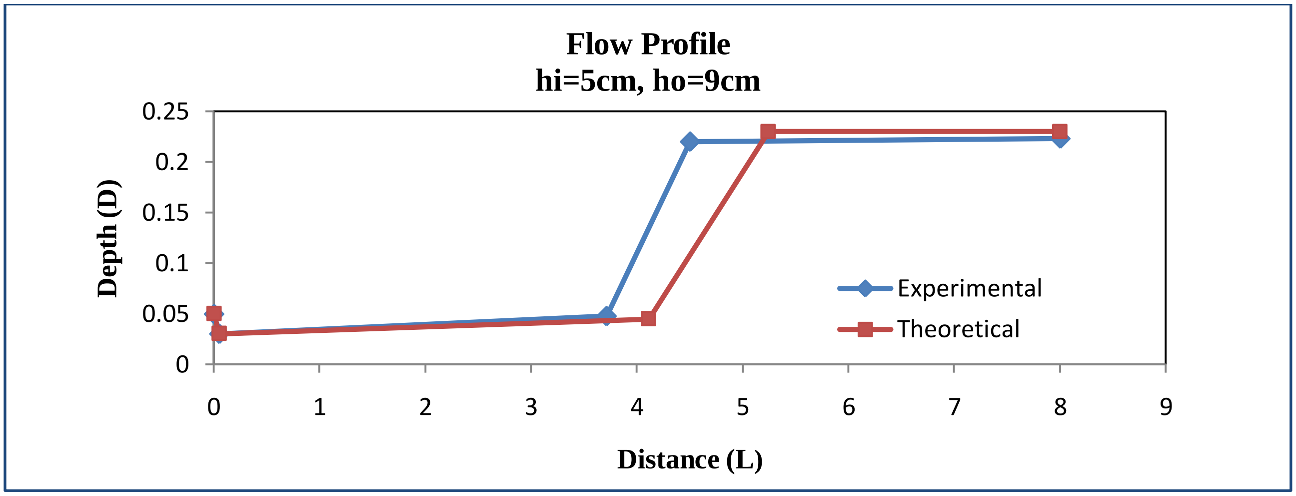


Fig 5.12: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

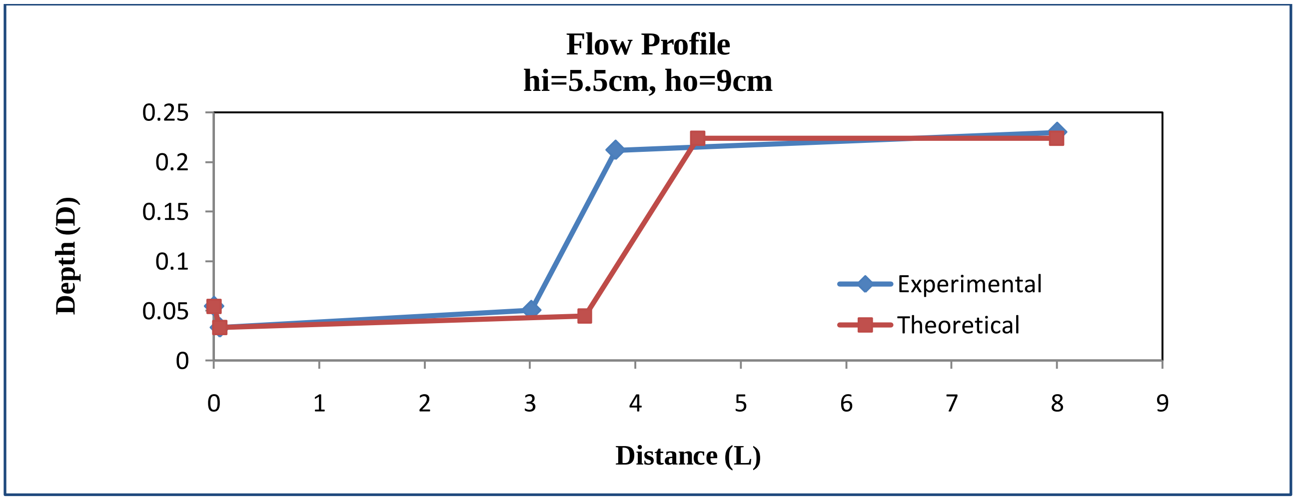


Fig 5.13: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

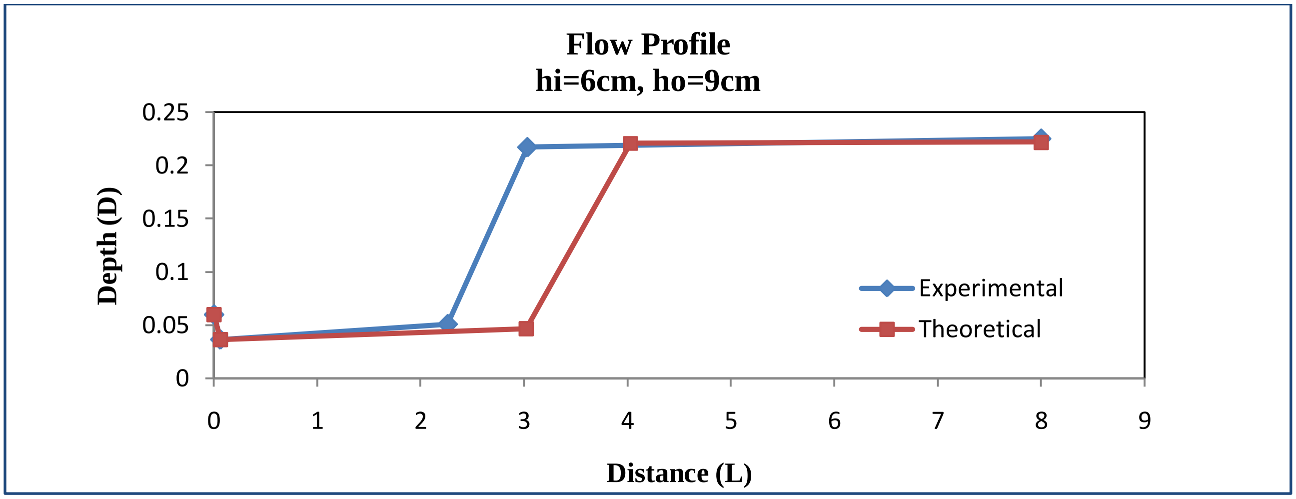


Fig 5.14: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

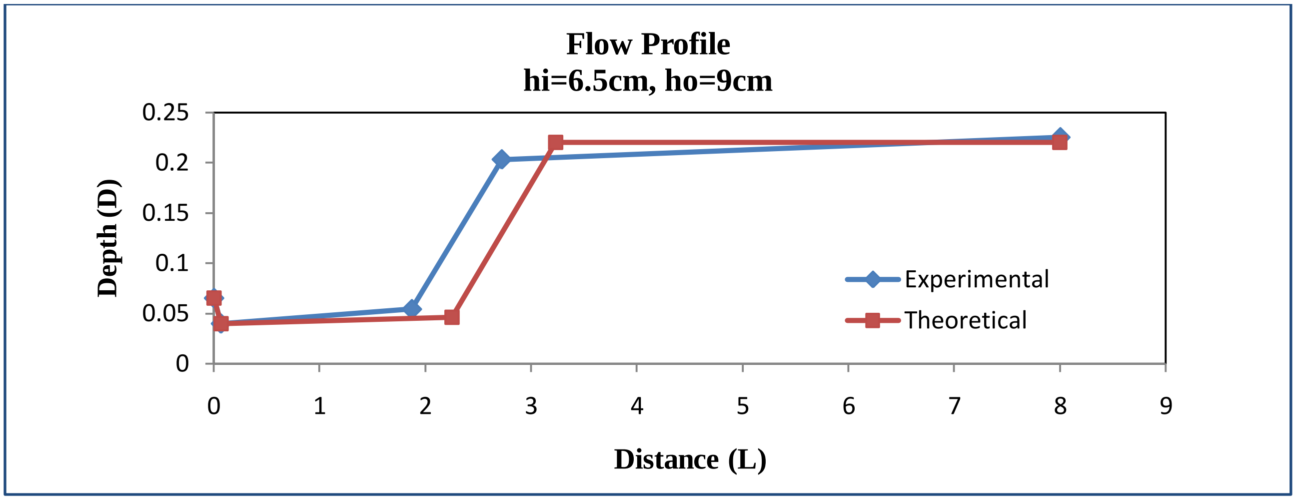


Fig 5.15: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

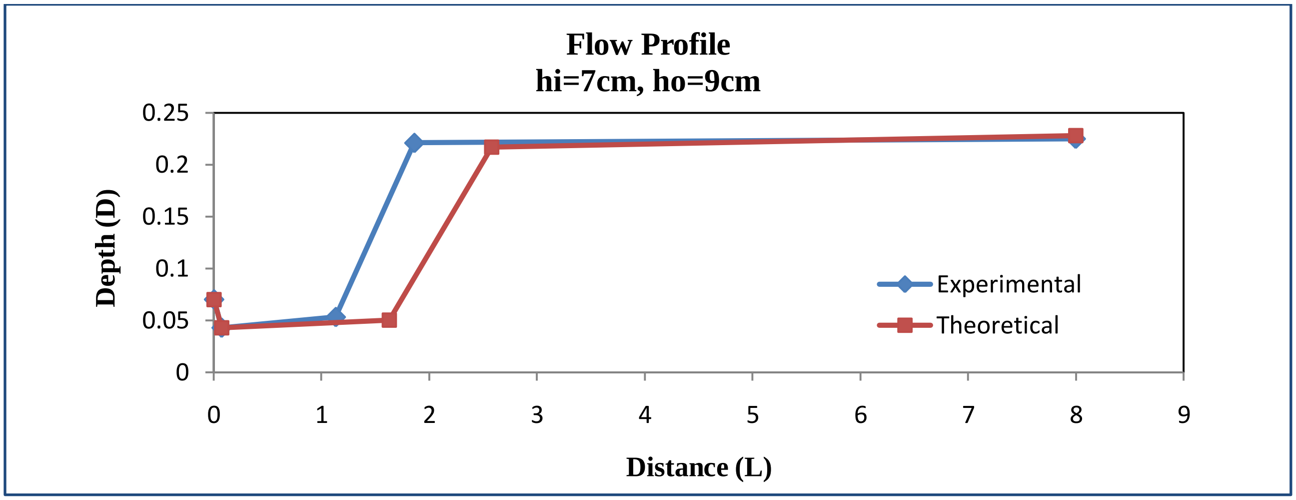


Fig 5.16: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

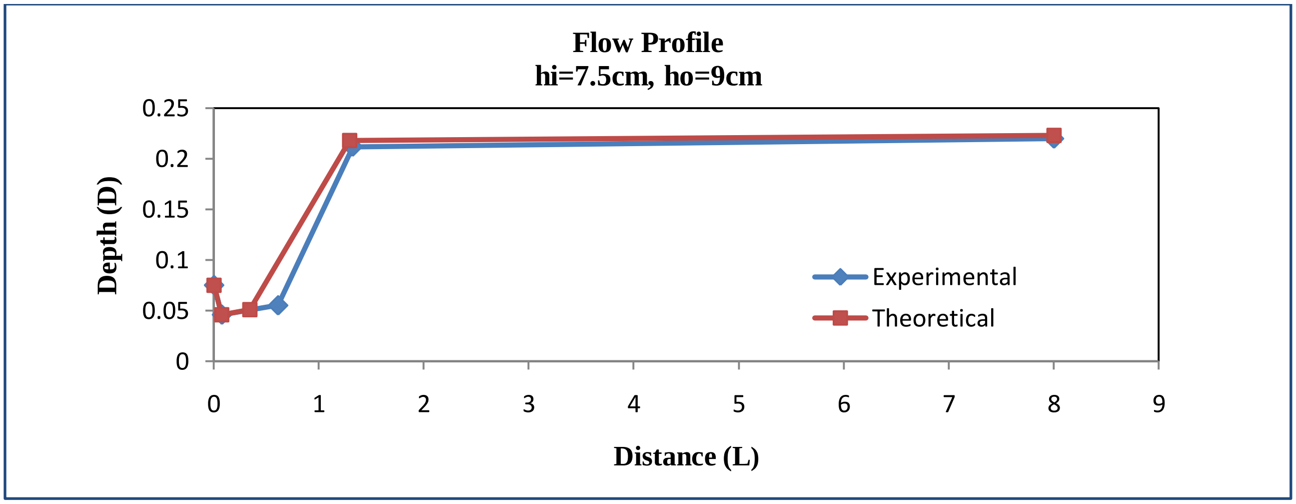


Fig 5.17: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

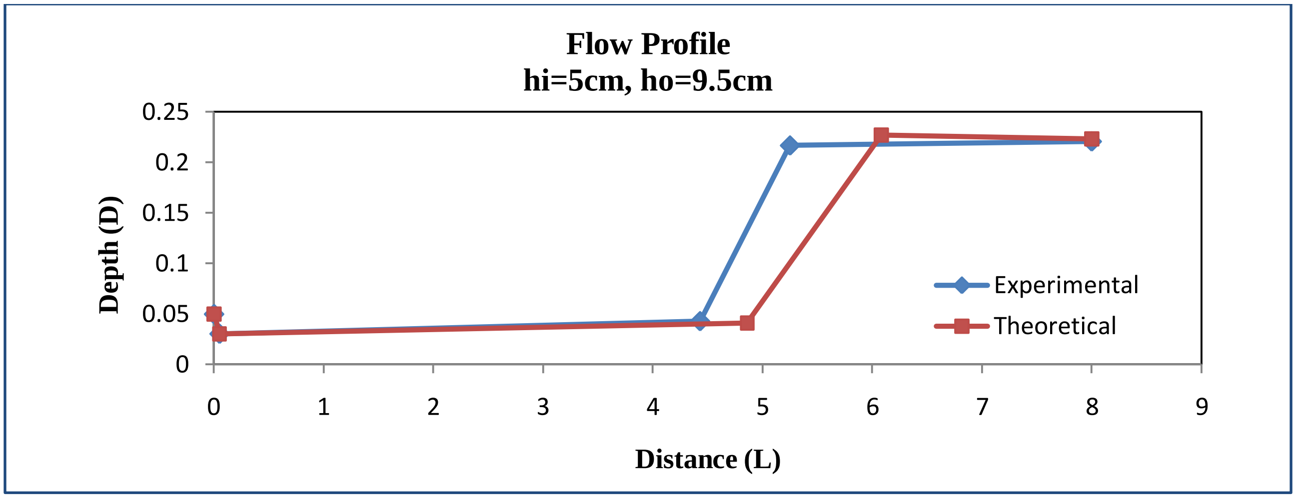


Fig 5.18: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

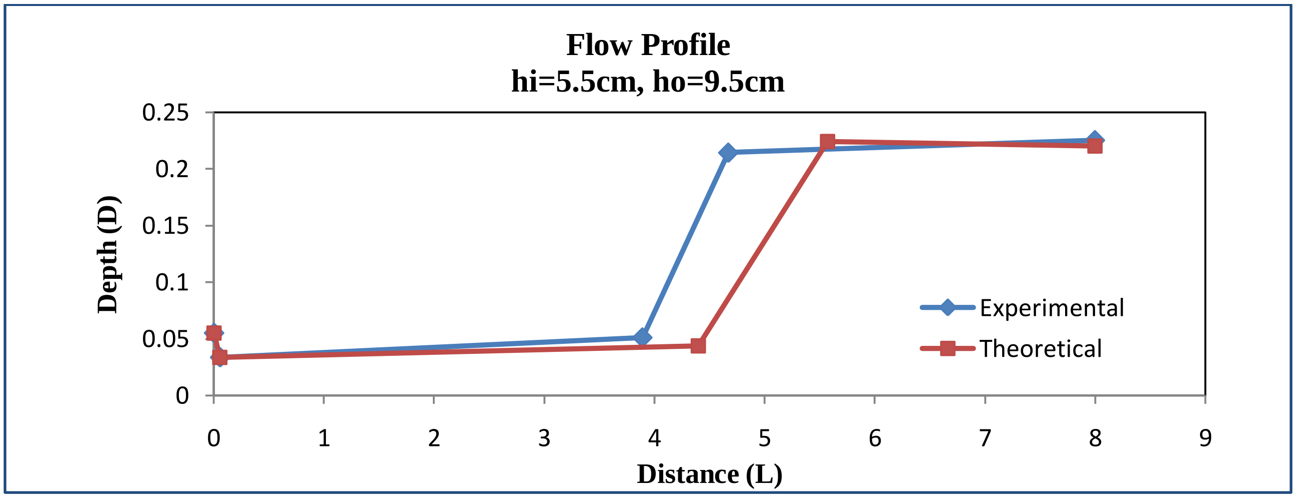


Fig 5.19: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

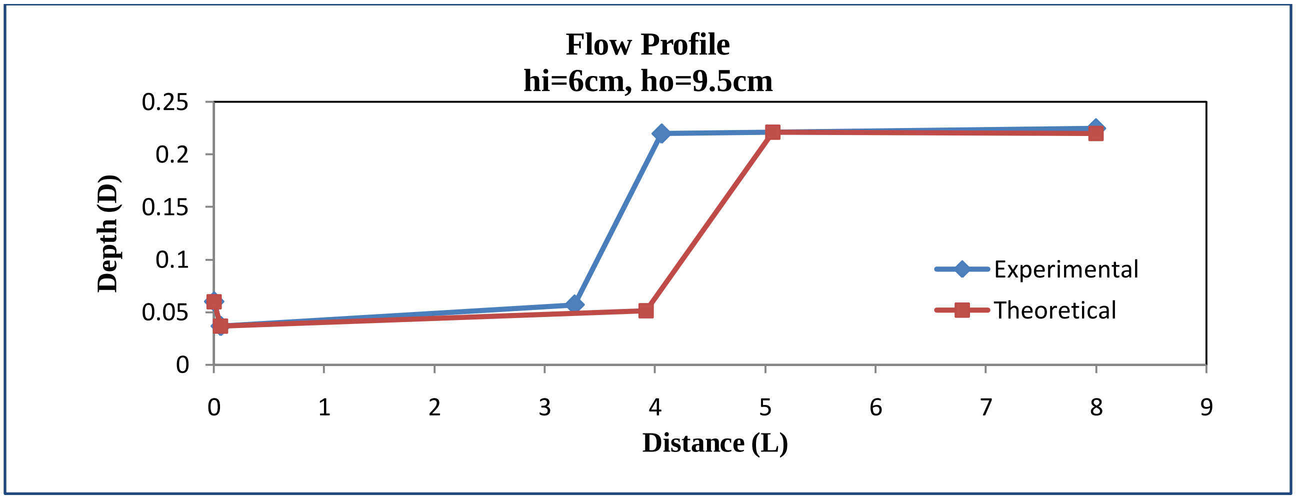


Fig 5.20: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

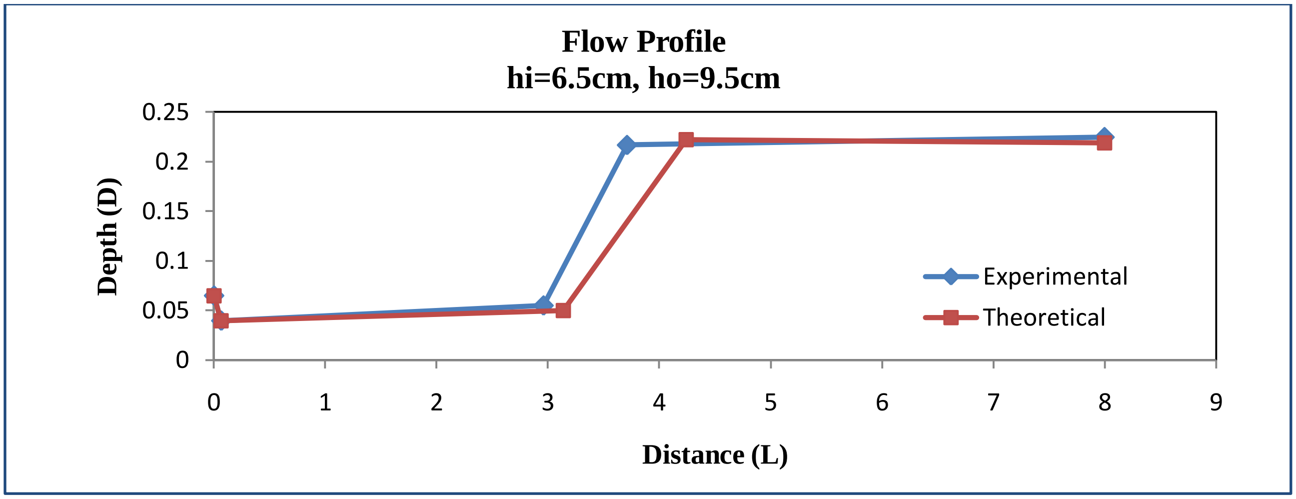


Fig 5.21: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

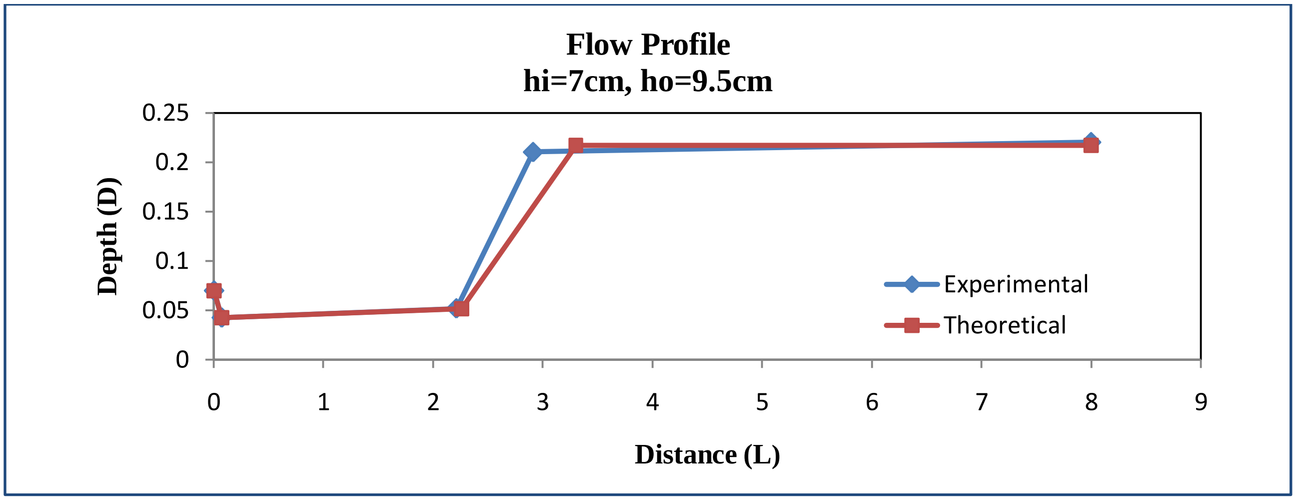


Fig 5.22: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

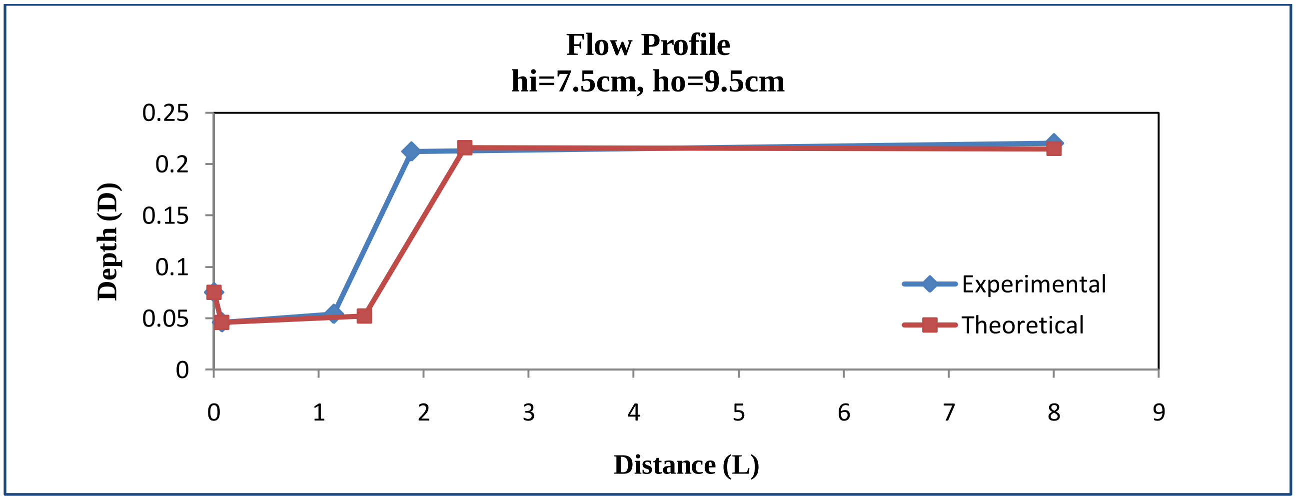


Fig 5.23: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

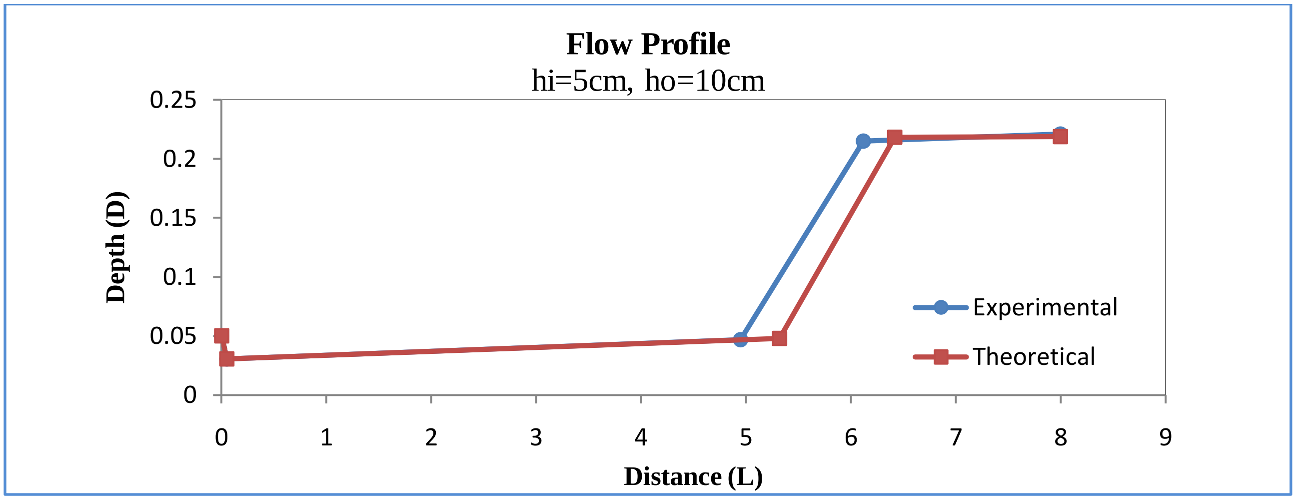


Fig 5.24: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

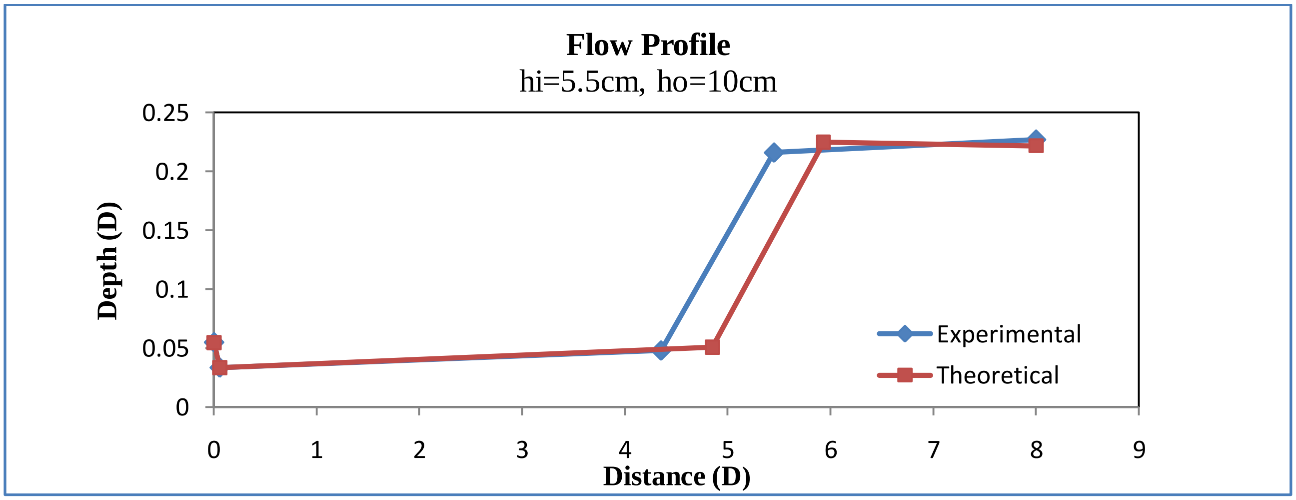


Fig 5.25: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

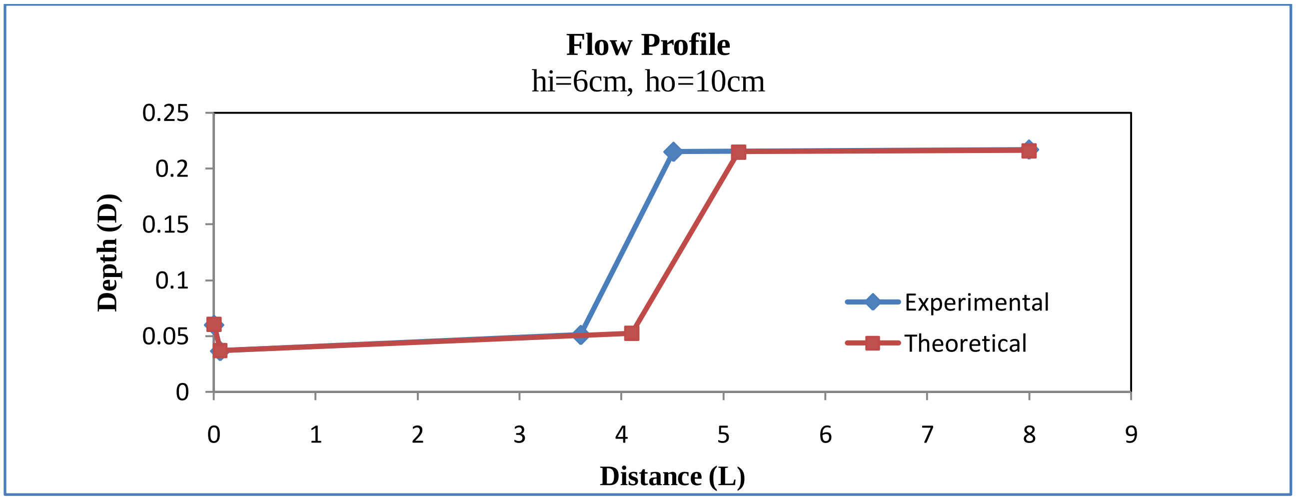


Fig 5.26: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

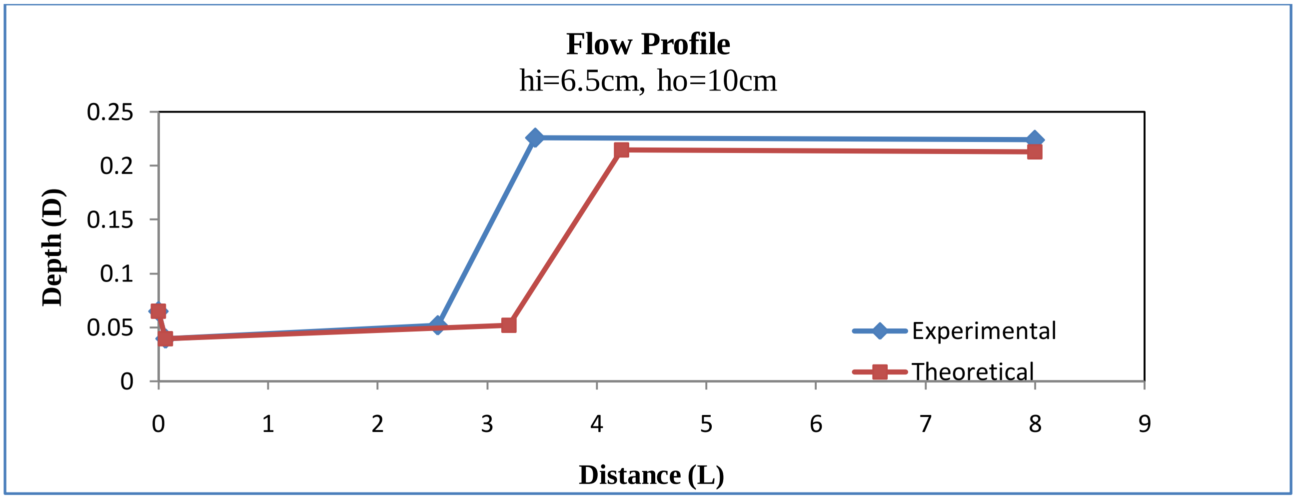


Fig 5.27: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

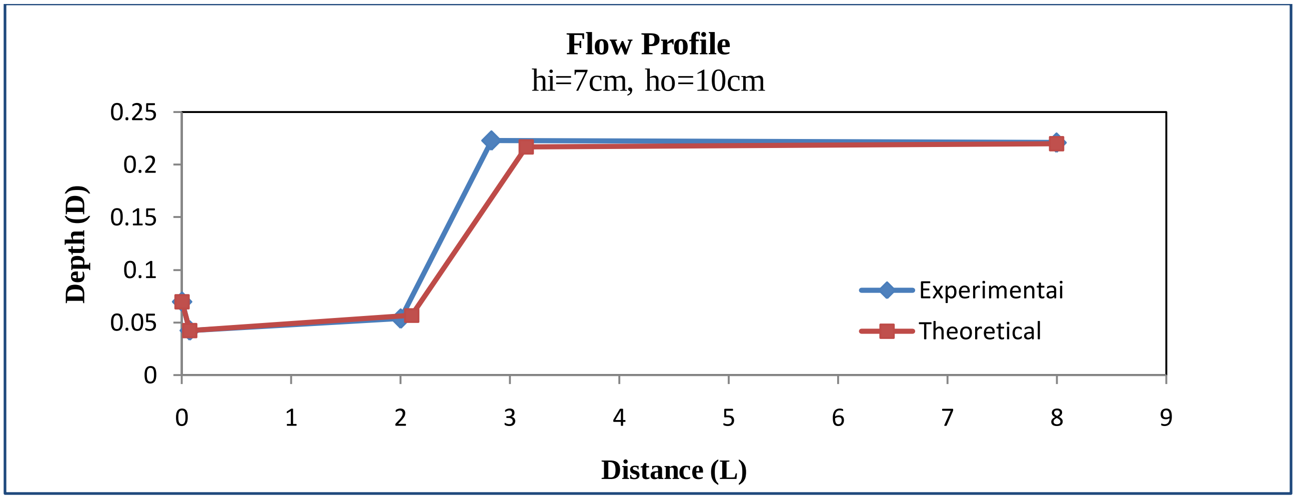


Fig 5.28; Comparison between Experimental Flow Profile and Theoretical Flow Profile.

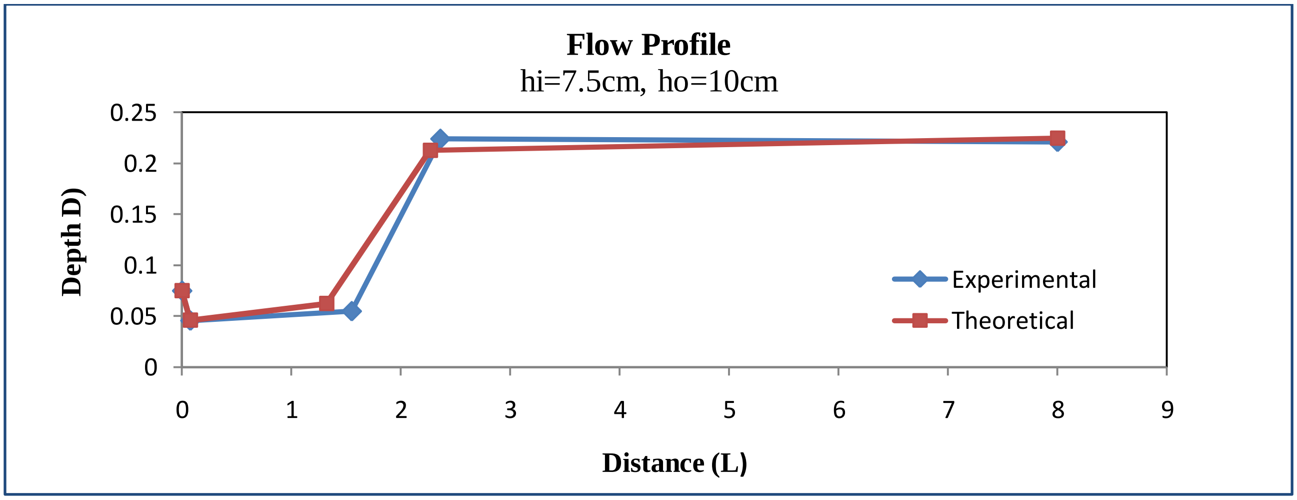


Fig 5.29: Comparison between Experimental Flow Profile and Theoretical Flow Profile.

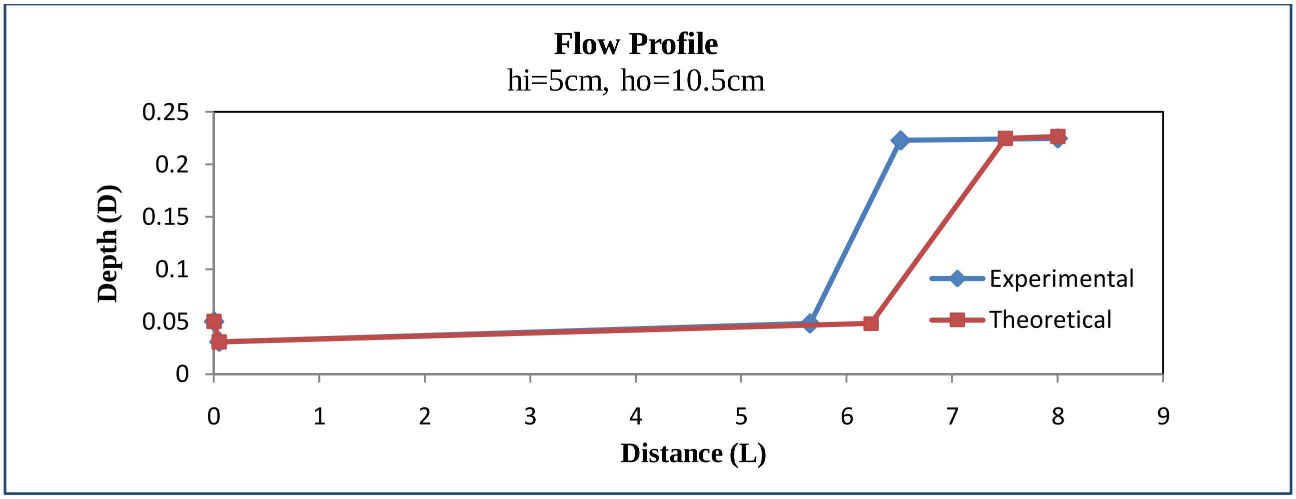


Fig 5.30; Comparison between Experimental Flow Profile and Theoretical Flow Profile.

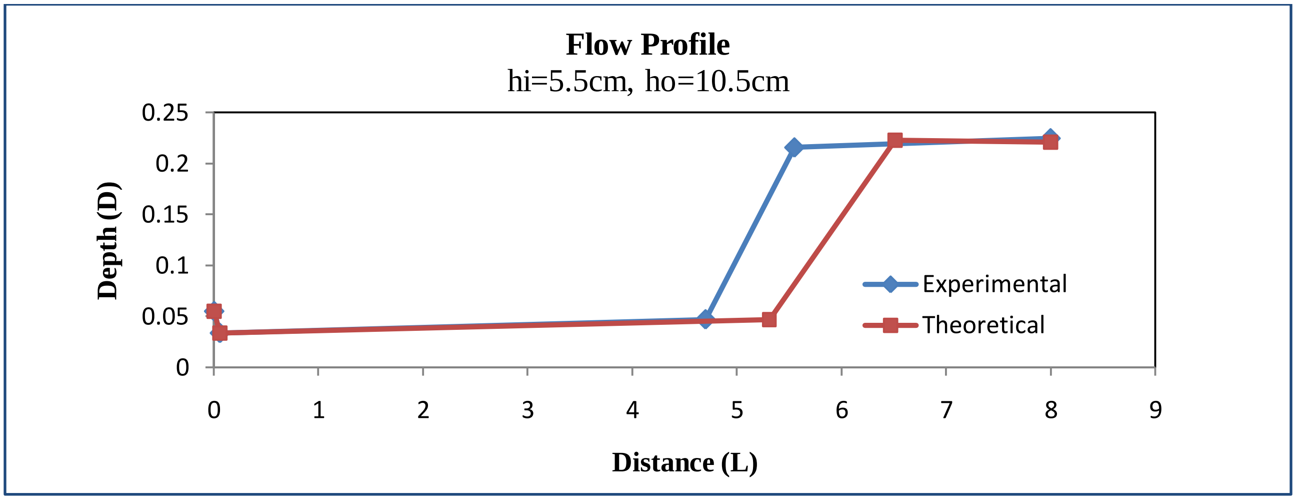


Fig 5.31: Comparisons between Experimental Flow Profile and Theoretical Flow Profile.

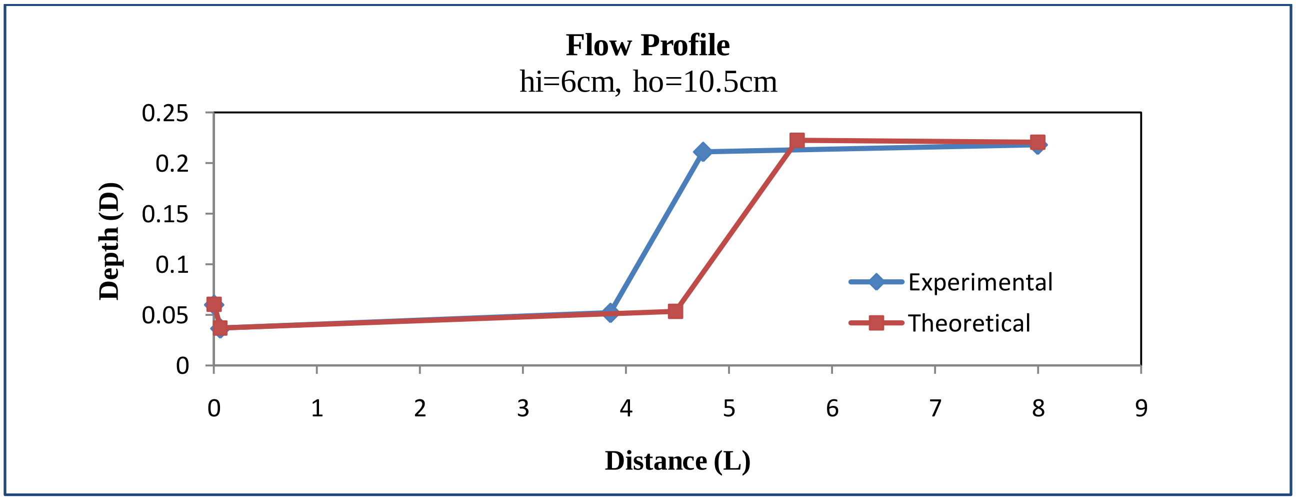


Fig 5.32: Comparisons between Experimental Flow Profile and Theoretical Flow Profile.

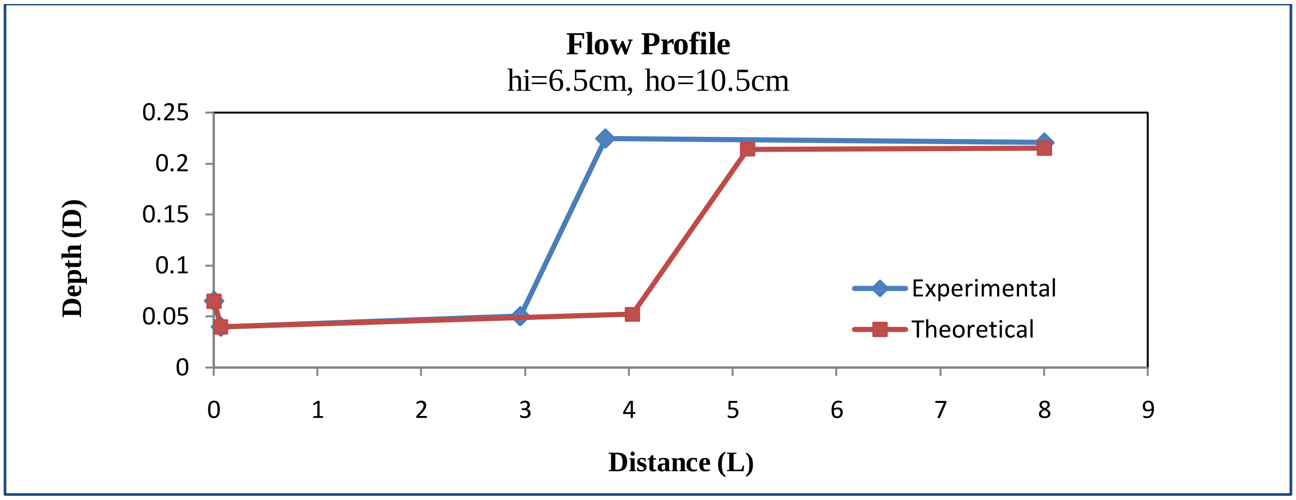


Fig 5.33: Comparisons between Experimental Flow Profile and Theoretical Flow Profile.

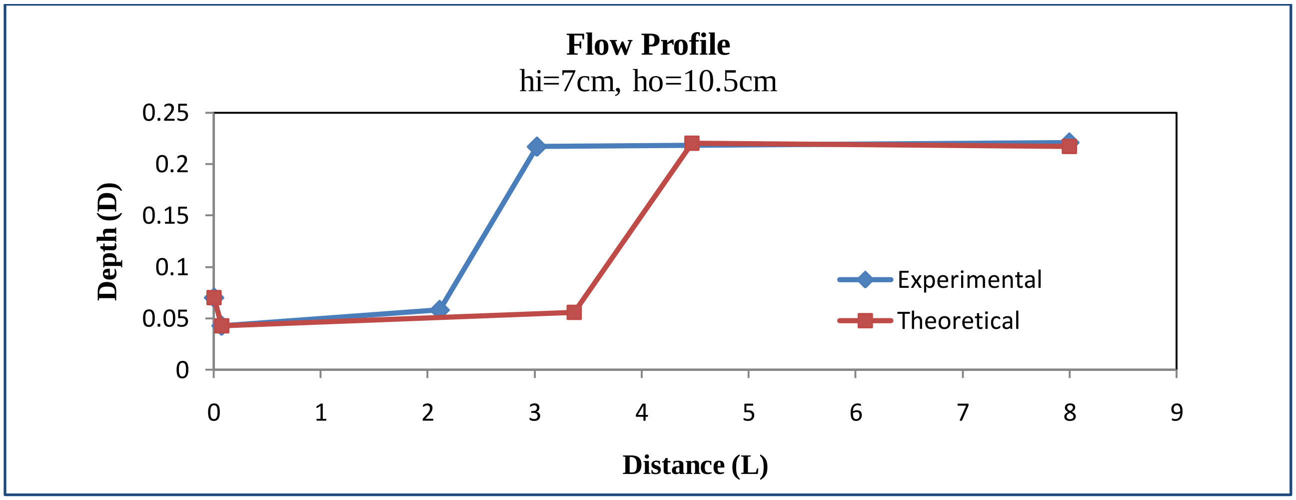


Fig 5.34: Comparisons between Experimental Flow Profile and Theoretical Flow Profile.

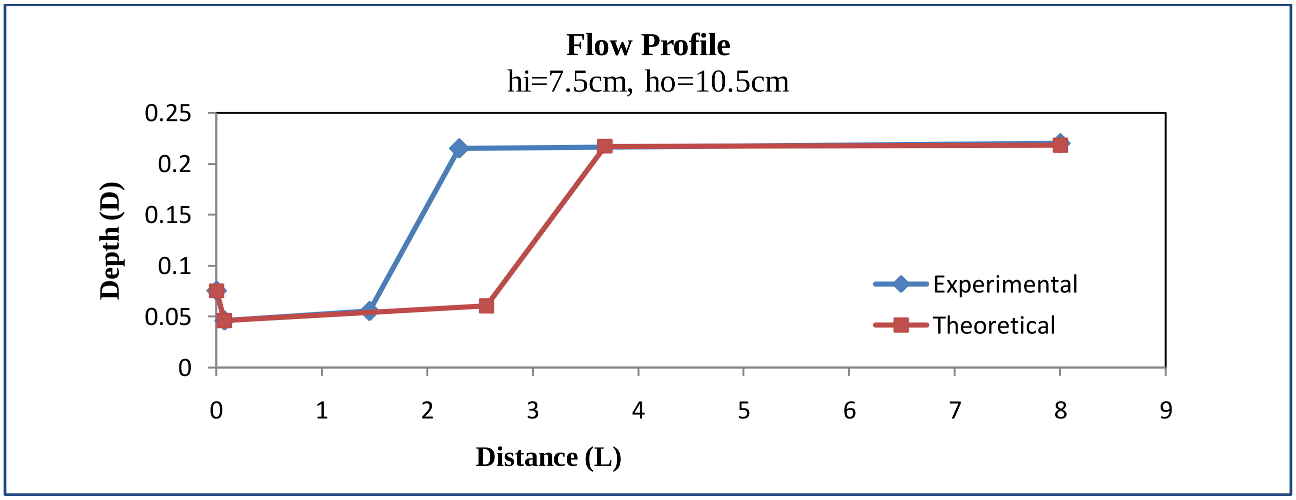


Fig 5.35: Comparisons between Experimental Flow Profile and Theoretical Flow Profile.

CHAPTER VI

CONCLUSION AND FUTURE SCOPE OF WORK

5.1 CONCLUSIONS

The phenomenon of Hydraulic Jump in a rectangular channel is done in this study. The experiment was performed for a constant volume flow rate. Vary high Froude Number was not possible due to overflow limitations. Still the experiments were performed keeping in mind that maximum Froude Number which was possible by that channel setup, could be achieved. Very smooth channel bed and constant head tank can be used to improve the experimental results with accuracy. Higher Froude number could also be achieved by using this.

The computation of flow profile graphical representation may not be the exact profile of the water surface as there are only few points used for making the graph and downstream profile seems to be horizontal. But it is approximate profile of the jump.

Hydraulic jump is very useful at many places specially in the dissipation of energy. For the dissipation of energy, free jump is the best suited.

The flow of jump is unsteady in nature so it is very difficult to determine the length of jump, location of jump and height of jump. A data acquisition system could be a better option in these situations.

Due to many practical difficulties, this present work could not be more comprehensive. But a lot of work that can be carried out in the directions described. However some important conclusions can be drawn from the present study. They are as follows

Adjustments for two-gate control become difficult and tail water rise of level becomes an issue. Baffles are more suitable for creating hydraulic jump.

- The setup should contain a constant head tank and it should also be smooth for better results.
- The dimensionless length of jump is independent of initial Froude number
- Theoretical results give more value of length of jump
- There is a reasonable agreement in the experimental results and theoretically predicted results.

5.2 FUTURE SCOPE OF WORK

The result of the study was very positive however it can be much more accurate by using more accurate setup. There are many numbers of things that were possible with this experiment but it will take more time and more accurate apparatus. They were not possible because of constraints on time, setup and apparatus. The hydraulic jump study can be continued with the present set up with some modifications in he setup and apparatus. In the present study, high Froude number was not possible due to overflow limitation. With some modification in setup and apparatus, the experiments can be carried out over a much wider range of Froude number. High speed imaging system can be used for measuring the length and location of jump more accurately. The study of the effect of roughness on jump in the channel can also be done by using a calibrated rough surface and may be pasted on the bottom surface. It can be done various times to give a conclusion. The study of jump can also be done in a gradually varying slope of channel bed, gradually changing area of channel. For better agreement with experimental results comprehensive CFD simulation for the flow can also be performed.

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ANNEXTURE I

COMPUTATION OF UPSTREAM PROFILE

Mannings constant, n	0.013
Channel width b, (m)	0.45
Height of water level over rectangular notch (m)	0.15
Flow through channel, Q (m^3/s)	0.05927
Length of channel (m)	8
Height of rectangular notch (m)	0.355
Coefficient of contraction, Cc	0.61
Critical depth, hc (m)	0.1208

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	Energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.1208	0.05436	0.120892	1.08922	0.6916	0.0786	-0.00057	0.005955	-0.00065	-1545.97	-1.54597	0	1.00057	28.28567
0.001	0.1203	0.054135	0.121394	1.093747	0.6906	0.078388	-0.00681	0.006026	0.440646	2.269396	0.002269	0.002269	1.006815	28.24536
	0.1198	0.05391	0.121898	1.098312	0.6896	0.078176	-0.01312	0.006099	0.230828	4.332227	0.004332	0.006602	1.013124	28.18963
	0.1193	0.053685	0.122405	1.102915	0.6886	0.077963	-0.0195	0.006172	0.156736	6.380136	0.00638	0.012982	1.0195	28.12431
	0.1188	0.05346	0.122915	1.107557	0.6876	0.077749	-0.02594	0.006247	0.118862	8.41315	0.008413	0.021395	1.025943	28.05171
	0.1183	0.053235	0.123428	1.112238	0.6866	0.077534	-0.03245	0.006324	0.095865	10.43129	0.010431	0.031826	1.032455	27.97316
	0.1178	0.05301	0.123944	1.116959	0.6856	0.077319	-0.03903	0.006401	0.080421	12.4346	0.012435	0.044261	1.039035	27.88954
	0.1173	0.052785	0.124463	1.12172	0.6846	0.077103	-0.04569	0.00648	0.069333	14.42309	0.014423	0.058684	1.045685	27.80147
	0.1168	0.05256	0.124984	1.126522	0.6836	0.076887	-0.05241	0.00656	0.060988	16.39679	0.016397	0.075081	1.052407	27.70942
	0.1163	0.052335	0.125509	1.131365	0.6826	0.07667	-0.0592	0.006641	0.054479	18.35573	0.018356	0.093436	1.059201	27.61379
	0.1158	0.05211	0.126036	1.13625	0.6816	0.076452	-0.06607	0.006724	0.049261	20.29994	0.0203	0.113736	1.066069	27.51487
	0.1153	0.051885	0.126567	1.141178	0.6806	0.076234	-0.07301	0.006809	0.044985	22.22944	0.022229	0.135966	1.073011	27.41293
	0.1148	0.05166	0.127101	1.146148	0.6796	0.076015	-0.08003	0.006894	0.041418	24.14426	0.024144	0.16011	1.080028	27.30818
	0.1143	0.051435	0.127637	1.151162	0.6786	0.075796	-0.08712	0.006982	0.038396	26.04443	0.026044	0.186154	1.087123	27.20082
	0.1138	0.05121	0.128177	1.156219	0.6776	0.075576	-0.0943	0.007071	0.035804	27.92998	0.02793	0.214084	1.094296	27.09102
	0.1133	0.050985	0.12872	1.161322	0.6766	0.075355	-0.10155	0.007161	0.033556	29.80093	0.029801	0.243885	1.101547	26.97891
	0.1128	0.05076	0.129266	1.16647	0.6756	0.075133	-0.10888	0.007253	0.031588	31.65731	0.031657	0.275543	1.10888	26.86463
	0.1123	0.050535	0.129815	1.171663	0.6746	0.074911	-0.11629	0.007347	0.029852	33.49915	0.033499	0.309042	1.116294	26.7483
	0.1118	0.05031	0.130367	1.176903	0.6736	0.074688	-0.12379	0.007442	0.028307	35.32647	0.035326	0.344368	1.12379	26.63003
	0.1113	0.050085	0.130923	1.18219	0.6726	0.074465	-0.13137	0.007539	0.026926	37.13931	0.037139	0.381508	1.131372	26.50991
	0.1108	0.04986	0.131482	1.187525	0.6716	0.074241	-0.13904	0.007638	0.025682	38.93769	0.038938	0.420445	1.139038	26.38803
	0.1103	0.049635	0.132044	1.192908	0.6706	0.074016	-0.14679	0.007739	0.024557	40.72164	0.040722	0.461167	1.146792	26.26447
	0.1098	0.04941	0.132609	1.19834	0.6696	0.07379	-0.15463	0.007841	0.023534	42.49118	0.042491	0.503658	1.154635	26.13931
	0.1093	0.049185	0.133178	1.203822	0.6686	0.073564	-0.16257	0.007946	0.022601	44.24635	0.044246	0.547904	1.162566	26.01262
	0.1088	0.04896	0.13375	1.209355	0.6676	0.073337	-0.17059	0.008052	0.021745	45.98717	0.045987	0.593892	1.17059	25.88447
	0.1083	0.048735	0.134326	1.214938	0.6666	0.07311	-0.17871	0.00816	0.020958	47.71367	0.047714	0.641605	1.178706	25.75491
	0.1078	0.04851	0.134905	1.220573	0.6656	0.072882	-0.18692	0.00827	0.020232	49.42587	0.049426	0.691031	1.186916	25.624

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.1073	0.048285	0.135488	1.226261	0.6646	0.072653	-0.19522	0.008383	0.01956	51.12382	0.051124	0.742155	1.195222	25.4918
	0.1068	0.04806	0.136074	1.232002	0.6636	0.072423	-0.20362	0.008497	0.018937	52.80752	0.052808	0.794963	1.203625	25.35836
	0.1063	0.047835	0.136663	1.237797	0.6626	0.072193	-0.21213	0.008614	0.018356	54.47702	0.054477	0.84944	1.212127	25.22373
	0.1058	0.04761	0.137257	1.243646	0.6616	0.071962	-0.22073	0.008733	0.017815	56.13234	0.056132	0.905572	1.22073	25.08795
	0.1053	0.047385	0.137853	1.249552	0.6606	0.07173	-0.22943	0.008854	0.017309	57.7735	0.057773	0.963345	1.229435	24.95106
	0.1048	0.04716	0.138454	1.255513	0.6596	0.071498	-0.23824	0.008977	0.016835	59.40054	0.059401	1.022746	1.238244	24.81311
	0.1043	0.046935	0.139058	1.261532	0.6586	0.071265	-0.24716	0.009103	0.01639	61.01348	0.061013	1.083759	1.247158	24.67413
	0.1038	0.04671	0.139666	1.267609	0.6576	0.071031	-0.25618	0.009231	0.015971	62.61236	0.062612	1.146372	1.25618	24.53417
	0.1033	0.046485	0.140278	1.273744	0.6566	0.070797	-0.26531	0.009362	0.015577	64.19719	0.064197	1.210569	1.265312	24.39325
	0.1028	0.04626	0.140893	1.279939	0.6556	0.070561	-0.27455	0.009495	0.015205	65.76801	0.065768	1.276337	1.274554	24.25142
	0.1023	0.046035	0.141512	1.286195	0.6546	0.070325	-0.28391	0.009631	0.014853	67.32485	0.067325	1.343662	1.28391	24.10871
	0.1018	0.04581	0.142136	1.292513	0.6536	0.070089	-0.29338	0.00977	0.014521	68.86773	0.068868	1.41253	1.293381	23.96514
	0.1013	0.045585	0.142763	1.298892	0.6526	0.069851	-0.30297	0.009911	0.014205	70.39669	0.070397	1.482926	1.302968	23.82075
	0.1008	0.04536	0.143394	1.305335	0.6516	0.069613	-0.31268	0.010056	0.013906	71.91174	0.071912	1.554838	1.312675	23.67557
	0.1003	0.045135	0.144029	1.311842	0.6506	0.069374	-0.3225	0.010203	0.013622	73.41292	0.073413	1.628251	1.322503	23.52962
	0.0998	0.04491	0.144668	1.318415	0.6496	0.069135	-0.33245	0.010353	0.013351	74.90026	0.0749	1.703151	1.332454	23.38294
	0.0993	0.044685	0.145311	1.325053	0.6486	0.068895	-0.34253	0.010506	0.013093	76.37379	0.076374	1.779525	1.342531	23.23555
	0.0988	0.04446	0.145959	1.331759	0.6476	0.068653	-0.35273	0.010662	0.012848	77.83353	0.077834	1.857358	1.352735	23.08747
	0.0983	0.044235	0.146611	1.338533	0.6466	0.068412	-0.36307	0.010822	0.012614	79.2795	0.07928	1.936638	1.363069	22.93873
	0.0978	0.04401	0.147266	1.345376	0.6456	0.068169	-0.37354	0.010985	0.01239	80.71175	0.080712	2.01735	1.373535	22.78936
	0.0973	0.043785	0.147926	1.35229	0.6446	0.067926	-0.38414	0.011151	0.012176	82.1303	0.08213	2.09948	1.384136	22.63937
	0.0968	0.04356	0.148591	1.359275	0.6436	0.067682	-0.39487	0.011321	0.011971	83.53517	0.083535	2.183015	1.394874	22.4888
	0.0963	0.043335	0.14926	1.366332	0.6426	0.067437	-0.40575	0.011494	0.011775	84.92639	0.084926	2.267942	1.405752	22.33766
	0.0958	0.04311	0.149933	1.373463	0.6416	0.067191	-0.41677	0.011671	0.011587	86.304	0.086304	2.354246	1.416771	22.18597
	0.0953	0.042885	0.150611	1.380669	0.6406	0.066945	-0.42794	0.011852	0.011407	87.66801	0.087668	2.441914	1.427936	22.03376
	0.0948	0.04266	0.151293	1.387951	0.6396	0.066698	-0.43925	0.012036	0.011234	89.01847	0.089018	2.530932	1.439248	21.88105

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.0943	0.042435	0.15198	1.39531	0.6386	0.06645	-0.45071	0.012225	0.011067	90.35539	0.090355	2.621287	1.45071	21.72785
	0.0938	0.04221	0.152671	1.402748	0.6376	0.066201	-0.46232	0.012417	0.010908	91.6788	0.091679	2.712966	1.462325	21.57419
	0.0933	0.041985	0.153367	1.410266	0.6366	0.065952	-0.4741	0.012614	0.010754	92.98873	0.092989	2.805955	1.474095	21.42009
	0.0928	0.04176	0.154068	1.417864	0.6356	0.065702	-0.48602	0.012815	0.010606	94.28521	0.094285	2.90024	1.486025	21.26556
	0.0923	0.041535	0.154774	1.425545	0.6346	0.065451	-0.49812	0.013021	0.010464	95.56827	0.095568	2.995808	1.498116	21.11062
	0.0918	0.04131	0.155484	1.433309	0.6336	0.065199	-0.51037	0.013231	0.010327	96.83794	0.096838	3.092646	1.510372	20.95529
	0.0913	0.041085	0.1562	1.441159	0.6326	0.064946	-0.5228	0.013445	0.010194	98.09423	0.098094	3.190741	1.522797	20.7996
	0.0908	0.04086	0.15692	1.449094	0.6316	0.064693	-0.53539	0.013665	0.010067	99.33719	0.099337	3.290078	1.535392	20.64355
	0.0903	0.040635	0.157646	1.457118	0.6306	0.064439	-0.54816	0.013889	0.009944	100.5668	0.100567	3.390645	1.548162	20.48716
	0.0898	0.04041	0.158376	1.465231	0.6296	0.064184	-0.56111	0.014119	0.009825	101.7832	0.101783	3.492428	1.56111	20.33045
	0.0893	0.040185	0.159112	1.473435	0.6286	0.063928	-0.57424	0.014354	0.00971	102.9863	0.102986	3.595414	1.57424	20.17344
	0.0888	0.03996	0.159853	1.481732	0.6276	0.063671	-0.58755	0.014594	0.009599	104.1762	0.104176	3.69959	1.587554	20.01615
	0.0883	0.039735	0.160599	1.490122	0.6266	0.063414	-0.60106	0.01484	0.009492	105.3528	0.105353	3.804943	1.601058	19.85858
	0.0878	0.03951	0.16135	1.498608	0.6256	0.063155	-0.61475	0.015091	0.009388	106.5163	0.106516	3.911459	1.614754	19.70076
	0.0873	0.039285	0.162107	1.507191	0.6246	0.062896	-0.62865	0.015348	0.009288	107.6667	0.107667	4.019126	1.628646	19.5427
	0.0868	0.03906	0.16287	1.515873	0.6236	0.062636	-0.64274	0.015611	0.009191	108.8039	0.108804	4.12793	1.642739	19.38442
	0.0863	0.038835	0.163638	1.524656	0.6226	0.062376	-0.65704	0.015881	0.009097	109.928	0.109928	4.237858	1.657036	19.22593
	0.0858	0.03861	0.164411	1.533541	0.6216	0.062114	-0.67154	0.016157	0.009006	111.0391	0.111039	4.348897	1.671541	19.06725
	0.0853	0.038385	0.165191	1.54253	0.6206	0.061851	-0.68626	0.016439	0.008918	112.1371	0.112137	4.461034	1.68626	18.90838
	0.0848	0.03816	0.165976	1.551625	0.6196	0.061588	-0.7012	0.016729	0.008832	113.2221	0.113222	4.574256	1.701196	18.74936
	0.0843	0.037935	0.166767	1.560828	0.6186	0.061324	-0.71635	0.017025	0.008749	114.2941	0.114294	4.68855	1.716353	18.59019
	0.0838	0.03771	0.167564	1.570141	0.6176	0.061059	-0.73174	0.017329	0.008669	115.3531	0.115353	4.803903	1.731737	18.43088
	0.0833	0.037485	0.168366	1.579565	0.6166	0.060793	-0.74735	0.01764	0.008591	116.3992	0.116399	4.920303	1.747353	18.27145
	0.0828	0.03726	0.169175	1.589104	0.6156	0.060526	-0.7632	0.017958	0.008516	117.4324	0.117432	5.037735	1.763204	18.11192
	0.0823	0.037035	0.169991	1.598758	0.6146	0.060259	-0.7793	0.018285	0.008442	118.4527	0.118453	5.156188	1.779296	17.95229
	0.0818	0.03681	0.170812	1.60853	0.6136	0.05999	-0.79564	0.01862	0.008371	119.4602	0.11946	5.275648	1.795635	17.79259
	0.0813	0.036585	0.17164	1.618423	0.6126	0.059721	-0.81223	0.018963	0.008302	120.4548	0.120455	5.396103	1.812225	17.63282

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.0808	0.03636	0.172474	1.628438	0.6116	0.059451	-0.82907	0.019315	0.008235	121.4366	0.121437	5.517539	1.829073	17.473
	0.0803	0.036135	0.173315	1.638578	0.6106	0.059179	-0.84618	0.019675	0.00817	122.4056	0.122406	5.639945	1.846183	17.31315
	0.0798	0.03591	0.174162	1.648844	0.6096	0.058907	-0.86356	0.020046	0.008106	123.3619	0.123362	5.763307	1.863561	17.15327
	0.0793	0.035685	0.175016	1.659241	0.6086	0.058635	-0.88121	0.020425	0.008045	124.3054	0.124305	5.887612	1.881214	16.99338
	0.0788	0.03546	0.175877	1.669769	0.6076	0.058361	-0.89915	0.020815	0.007985	125.2362	0.125236	6.012849	1.899148	16.83349
	0.0783	0.035235	0.176745	1.680431	0.6066	0.058086	-0.91737	0.021214	0.007927	126.1543	0.126154	6.139003	1.917368	16.67362
	0.0778	0.03501	0.17762	1.691231	0.6056	0.05781	-0.93588	0.021625	0.00787	127.0598	0.12706	6.266063	1.935881	16.51378
	0.0773	0.034785	0.178502	1.70217	0.6046	0.057534	-0.95469	0.022046	0.007815	127.9526	0.127953	6.394015	1.954694	16.35399
	0.0768	0.03456	0.179391	1.713252	0.6036	0.057256	-0.97381	0.022478	0.007762	128.8328	0.128833	6.522848	1.973814	16.19424
	0.0763	0.034335	0.180288	1.724479	0.6026	0.056978	-0.99325	0.022922	0.00771	129.7004	0.1297	6.652548	1.993248	16.03457
	0.0758	0.03411	0.181192	1.735855	0.6016	0.056699	-1.013	0.023378	0.00766	130.5554	0.130555	6.783104	2.013002	15.87498
	0.0753	0.033885	0.182103	1.747381	0.6006	0.056419	-1.03309	0.023847	0.00761	131.3979	0.131398	6.914502	2.033085	15.71548
	0.0748	0.03366	0.183022	1.759061	0.5996	0.056137	-1.0535	0.024328	0.007563	132.2279	0.132228	7.04673	2.053504	15.55608
	0.0743	0.033435	0.183949	1.770899	0.5986	0.055855	-1.07427	0.024823	0.007516	133.0453	0.133045	7.179775	2.074268	15.39681
	0.0738	0.03321	0.184884	1.782897	0.5976	0.055572	-1.09538	0.025332	0.007471	133.8503	0.13385	7.313625	2.095383	15.23767
	0.0733	0.032985	0.185827	1.795058	0.5966	0.055288	-1.11686	0.025854	0.007427	134.6428	0.134643	7.448268	2.11686	15.07867
	0.0728	0.03276	0.186778	1.807387	0.5956	0.055003	-1.13871	0.026392	0.007384	135.4228	0.135423	7.583691	2.138705	14.91983
	0.0723	0.032535	0.187738	1.819886	0.5946	0.054717	-1.16093	0.026945	0.007343	136.1905	0.13619	7.719881	2.160929	14.76116
	0.0718	0.03231	0.188706	1.83256	0.5936	0.054431	-1.18354	0.027513	0.007302	136.9457	0.136946	7.856827	2.183541	14.60267
	0.0713	0.032085	0.189682	1.845411	0.5926	0.054143	-1.20655	0.028099	0.007263	137.6885	0.137689	7.994515	2.20655	14.44438
	0.0708	0.03186	0.190667	1.858443	0.5916	0.053854	-1.22997	0.028701	0.007224	138.419	0.138419	8.132934	2.229966	14.28629
	0.0703	0.031635	0.191661	1.871661	0.5906	0.053564	-1.2538	0.029321	0.007187	139.1371	0.139137	8.272072	2.253798	14.12842
	0.0698	0.03141	0.192664	1.885068	0.5896	0.053273	-1.27806	0.029959	0.007151	139.8429	0.139843	8.411915	2.278059	13.97078
	0.0693	0.031185	0.193676	1.898669	0.5886	0.052982	-1.30276	0.030616	0.007116	140.5364	0.140536	8.552451	2.302757	13.81339
	0.0688	0.03096	0.194698	1.912468	0.5876	0.052689	-1.32791	0.031293	0.007081	141.2176	0.141218	8.693669	2.327906	13.65625
	0.0683	0.030735	0.195729	1.926468	0.5866	0.052395	-1.35352	0.031991	0.007048	141.8865	0.141887	8.835555	2.353515	13.49938
	0.0678	0.03051	0.196769	1.940675	0.5856	0.0521	-1.3796	0.032709	0.007015	142.5432	0.142543	8.978098	2.379597	13.34279

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.0673	0.030285	0.19782	1.955093	0.5846	0.051805	-1.40617	0.03345	0.006984	143.1876	0.143188	9.121286	2.406165	13.18649
	0.0668	0.03006	0.19888	1.969727	0.5836	0.051508	-1.43323	0.034214	0.006953	143.8198	0.14382	9.265106	2.433231	13.0305
	0.0663	0.029835	0.19995	1.984582	0.5826	0.05121	-1.46081	0.035001	0.006923	144.4397	0.14444	9.409545	2.460808	12.87482
	0.0658	0.02961	0.201031	1.999662	0.5816	0.050911	-1.48891	0.035814	0.006894	145.0475	0.145047	9.554593	2.48891	12.71947
	0.0653	0.029385	0.202123	2.014974	0.5806	0.050611	-1.51755	0.036652	0.006866	145.6431	0.145643	9.700236	2.517551	12.56446
	0.0648	0.02916	0.203225	2.030521	0.5796	0.050311	-1.54675	0.037517	0.006839	146.2264	0.146226	9.846462	2.546745	12.40981
	0.0643	0.028935	0.204338	2.046311	0.5786	0.050009	-1.57651	0.038409	0.006812	146.7977	0.146798	9.99326	2.576509	12.25552
	0.0638	0.02871	0.205462	2.062348	0.5776	0.049706	-1.60686	0.039331	0.006786	147.3567	0.147357	10.14062	2.606856	12.10161
	0.0633	0.028485	0.206597	2.078638	0.5766	0.049402	-1.6378	0.040283	0.006761	147.9036	0.147904	10.28852	2.637804	11.94809
	0.0628	0.02826	0.207744	2.095188	0.5756	0.049097	-1.66937	0.041266	0.006737	148.4384	0.148438	10.43696	2.669369	11.79497
	0.0623	0.028035	0.208903	2.112003	0.5746	0.04879	-1.70157	0.042283	0.006713	148.9611	0.148961	10.58592	2.701568	11.64226
	0.0618	0.02781	0.210073	2.12909	0.5736	0.048483	-1.73442	0.043333	0.00669	149.4716	0.149472	10.73539	2.734421	11.48998
	0.0613	0.027585	0.211256	2.146456	0.5726	0.048175	-1.76794	0.044419	0.006668	149.97	0.14997	10.88536	2.767944	11.33814
	0.0608	0.02736	0.212452	2.164108	0.5716	0.047866	-1.80216	0.045542	0.006646	150.4563	0.150456	11.03582	2.802158	11.18675
	0.0603	0.027135	0.21366	2.182053	0.5706	0.047555	-1.83708	0.046704	0.006626	150.9305	0.15093	11.18675	2.837083	11.03582
	0.0598	0.02691	0.214881	2.200297	0.5696	0.047244	-1.87274	0.047906	0.006605	151.3926	0.151393	11.33814	2.87274	10.88536
	0.0593	0.026685	0.216115	2.21885	0.5686	0.046931	-1.90915	0.049151	0.006586	151.8426	0.151843	11.48998	2.909149	10.73539
	0.0588	0.02646	0.217362	2.237717	0.5676	0.046617	-1.94633	0.050439	0.006567	152.2805	0.15228	11.64226	2.946335	10.58592
	0.0583	0.026235	0.218624	2.256909	0.5666	0.046303	-1.98432	0.051774	0.006549	152.7063	0.152706	11.79497	2.984319	10.43696
	0.0578	0.02601	0.219899	2.276432	0.5656	0.045987	-2.02313	0.053156	0.006531	153.12	0.15312	11.94809	3.023126	10.28852
	0.0573	0.025785	0.221189	2.296296	0.5646	0.04567	-2.06278	0.054589	0.006514	153.5216	0.153522	12.10161	3.062782	10.14062
	0.0568	0.02556	0.222493	2.31651	0.5636	0.045351	-2.10331	0.056075	0.006497	153.9111	0.153911	12.25552	3.103313	9.99326
	0.0563	0.025335	0.223813	2.337083	0.5626	0.045032	-2.14475	0.057616	0.006481	154.2884	0.154288	12.40981	3.144745	9.846462
	0.0558	0.02511	0.225147	2.358025	0.5616	0.044712	-2.18711	0.059214	0.006466	154.6537	0.154654	12.56446	3.187108	9.700236
	0.0553	0.024885	0.226498	2.379345	0.5606	0.04439	-2.23043	0.060873	0.006451	155.0069	0.155007	12.71947	3.23043	9.554593
	0.0548	0.02466	0.227864	2.401054	0.5596	0.044067	-2.27474	0.062595	0.006437	155.3479	0.155348	12.87482	3.274743	9.409545
	0.0543	0.024435	0.229246	2.423163	0.5586	0.043743	-2.32008	0.064383	0.006424	155.6768	0.155677	13.0305	3.320078	9.265106

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.0538	0.02421	0.230645	2.445684	0.5576	0.043418	-2.36647	0.066241	0.006411	155.9936	0.155994	13.18649	3.366469	9.121286
	0.0533	0.023985	0.232062	2.468626	0.5566	0.043092	-2.41395	0.068171	0.006398	156.2981	0.156298	13.34279	3.413951	8.978098
	0.0528	0.02376	0.233495	2.492003	0.5556	0.042765	-2.46256	0.070179	0.006386	156.5905	0.156591	13.49938	3.462559	8.835555
	0.0523	0.023535	0.234947	2.515827	0.5546	0.042436	-2.51233	0.072266	0.006375	156.8708	0.156871	13.65625	3.512332	8.693669
	0.0518	0.02331	0.236416	2.540112	0.5536	0.042106	-2.56331	0.074438	0.006364	157.1388	0.157139	13.81339	3.563308	8.552451
	0.0513	0.023085	0.237905	2.564869	0.5526	0.041775	-2.61553	0.076699	0.006353	157.3945	0.157395	13.97078	3.61553	8.411915
	0.0508	0.02286	0.239412	2.590114	0.5516	0.041443	-2.66904	0.079054	0.006344	157.638	0.157638	14.12842	3.66904	8.272072
	0.0503	0.022635	0.240939	2.61586	0.5506	0.04111	-2.72388	0.081506	0.006334	157.8693	0.157869	14.28629	3.723883	8.132934
	0.0498	0.02241	0.242487	2.642124	0.5496	0.040775	-2.78011	0.084062	0.006326	158.0882	0.158088	14.44438	3.780106	7.994515
	0.0493	0.022185	0.244054	2.66892	0.5486	0.040439	-2.83776	0.086727	0.006317	158.2948	0.158295	14.60267	3.837759	7.856827
	0.0488	0.02196	0.245643	2.696266	0.5476	0.040102	-2.89689	0.089506	0.00631	158.489	0.158489	14.76116	3.896891	7.719881
	0.0483	0.021735	0.247254	2.724178	0.5466	0.039764	-2.95756	0.092407	0.006302	158.6708	0.158671	14.91983	3.957559	7.583691
	0.0478	0.02151	0.248886	2.752673	0.5456	0.039424	-3.01982	0.095435	0.006296	158.8402	0.15884	15.07867	4.019816	7.448268
	0.0473	0.021285	0.250542	2.781771	0.5446	0.039084	-3.08372	0.098598	0.006289	158.9971	0.158997	15.23767	4.083724	7.313625
	0.0468	0.02106	0.25222	2.811491	0.5436	0.038742	-3.14934	0.101903	0.006284	159.1415	0.159141	15.39681	4.149342	7.179775
	0.0463	0.020835	0.253923	2.841853	0.5426	0.038398	-3.21674	0.105359	0.006279	159.2733	0.159273	15.55608	4.216737	7.04673
	0.0458	0.02061	0.25565	2.872877	0.5416	0.038054	-3.28598	0.108974	0.006274	159.3926	0.159393	15.71548	4.285977	6.914502
	0.0453	0.020385	0.257402	2.904587	0.5406	0.037708	-3.35713	0.112757	0.00627	159.4991	0.159499	15.87498	4.357132	6.783104
	0.0448	0.02016	0.259181	2.937004	0.5396	0.037361	-3.43028	0.116718	0.006266	159.593	0.159593	16.03457	4.430278	6.652548
	0.0443	0.019935	0.260985	2.970153	0.5386	0.037013	-3.50549	0.120868	0.006263	159.6741	0.159674	16.19424	4.505494	6.522848
	0.0438	0.01971	0.262818	3.004059	0.5376	0.036663	-3.58286	0.125218	0.00626	159.7424	0.159742	16.35399	4.582863	6.394015
	0.0433	0.019485	0.264678	3.038748	0.5366	0.036312	-3.66247	0.129781	0.006258	159.7977	0.159798	16.51378	4.662472	6.266063
	0.0428	0.01926	0.266568	3.074247	0.5356	0.03596	-3.74441	0.134568	0.006256	159.8402	0.15984	16.67362	4.744412	6.139003
	0.0423	0.019035	0.268487	3.110586	0.5346	0.035606	-3.82878	0.139596	0.006255	159.8695	0.15987	16.83349	4.828781	6.012849
	0.0418	0.01881	0.270437	3.147794	0.5336	0.035251	-3.91568	0.144878	0.006254	159.8858	0.159886	16.99338	4.91568	5.887612
	0.0413	0.018585	0.272418	3.185903	0.5326	0.034895	-4.00522	0.150431	0.006254	159.8889	0.159889	17.15327	5.005218	5.763307
	0.0408	0.01836	0.274432	3.224946	0.5316	0.034537	-4.09751	0.156272	0.006255	159.8788	0.159879	17.31315	5.097507	5.639945

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.0403	0.018135	0.27648	3.264957	0.5306	0.034178	-4.19267	0.162421	0.006256	159.8552	0.159855	17.473	5.192667	5.517539
	0.0398	0.01791	0.278562	3.305974	0.5296	0.033818	-4.29083	0.168897	0.006257	159.8182	0.159818	17.63282	5.290825	5.396103
	0.0393	0.017685	0.28068	3.348035	0.5286	0.033456	-4.39212	0.175723	0.006259	159.7677	0.159768	17.79259	5.392116	5.275648
	0.0388	0.01746	0.282834	3.39118	0.5276	0.033093	-4.49668	0.182923	0.006262	159.7035	0.159703	17.95229	5.49668	5.156188
	0.0383	0.017235	0.285027	3.435451	0.5266	0.032729	-4.60467	0.190523	0.006265	159.6255	0.159626	18.11192	5.604668	5.037735
	0.0378	0.01701	0.287258	3.480894	0.5256	0.032363	-4.71624	0.19855	0.006268	159.5336	0.159534	18.27145	5.716239	4.920303
	0.0373	0.016785	0.289531	3.527554	0.5246	0.031996	-4.83156	0.207035	0.006272	159.4278	0.159428	18.43088	5.831561	4.803903
	0.0368	0.01656	0.291845	3.575483	0.5236	0.031627	-4.95081	0.216011	0.006277	159.3078	0.159308	18.59019	5.950813	4.68855
	0.0363	0.016335	0.294202	3.624732	0.5226	0.031257	-5.07419	0.225513	0.006282	159.1735	0.159173	18.74936	6.074186	4.574256
	0.0358	0.01611	0.296604	3.675357	0.5216	0.030886	-5.20188	0.235582	0.006288	159.0247	0.159025	18.90838	6.201882	4.461034
	0.0353	0.015885	0.299052	3.727416	0.5206	0.030513	-5.33412	0.246259	0.006295	158.8615	0.158861	19.06725	6.334116	4.348897
	0.0348	0.01566	0.301549	3.780971	0.5196	0.030139	-5.47112	0.25759	0.006302	158.6834	0.158683	19.22593	6.471116	4.237858
	0.0343	0.015435	0.304095	3.836087	0.5186	0.029763	-5.61313	0.269628	0.00631	158.4905	0.15849	19.38442	6.613127	4.12793
	0.0338	0.01521	0.306692	3.892834	0.5176	0.029386	-5.76041	0.282426	0.006318	158.2825	0.158282	19.5427	6.760409	4.019126
	0.0333	0.014985	0.309343	3.951285	0.5166	0.029007	-5.91324	0.296047	0.006327	158.0592	0.158059	19.70076	6.913241	3.911459
	0.0328	0.01476	0.312049	4.011518	0.5156	0.028627	-6.07192	0.310556	0.006336	157.8204	0.15782	19.85858	7.071919	3.804943
	0.0323	0.014535	0.314813	4.073615	0.5146	0.028245	-6.23676	0.326027	0.006347	157.566	0.157566	20.01615	7.236762	3.69959
	0.0318	0.01431	0.317637	4.137666	0.5136	0.027862	-6.40811	0.34254	0.006357	157.2957	0.157296	20.17344	7.408109	3.595414
	0.0313	0.014085	0.320522	4.203763	0.5126	0.027478	-6.58633	0.360185	0.006369	157.0092	0.157009	20.33045	7.586327	3.492428
	0.0308	0.01386	0.323473	4.272006	0.5116	0.027091	-6.77181	0.379059	0.006381	156.7064	0.156706	20.48716	7.771806	3.390645
	0.0303	0.013635	0.32649	4.342501	0.5106	0.026704	-6.96497	0.399271	0.006394	156.387	0.156387	20.64355	7.964969	3.290078
	0.0298	0.01341	0.329578	4.415362	0.5096	0.026315	-7.16627	0.42094	0.006408	156.0506	0.156051	20.7996	8.166268	3.190741
	0.0293	0.013185	0.332739	4.490709	0.5086	0.025924	-7.37619	0.4442	0.006423	155.6971	0.155697	20.95529	8.376192	3.092646
	0.0288	0.01296	0.335976	4.568673	0.5076	0.025532	-7.59527	0.469197	0.006438	155.3261	0.155326	21.11062	8.595266	2.995808
	0.0283	0.012735	0.339292	4.649391	0.5066	0.025138	-7.82406	0.496098	0.006454	154.9372	0.154937	21.26556	8.824059	2.90024
	0.0278	0.01251	0.342691	4.733014	0.5056	0.024743	-8.06319	0.525084	0.006471	154.5303	0.15453	21.42009	9.063185	2.805955
	0.0273	0.012285	0.346178	4.819699	0.5046	0.024346	-8.31331	0.55636	0.006489	154.1048	0.154105	21.57419	9.31331	2.712966

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.0268	0.01206	0.349755	4.909619	0.5036	0.023948	-8.57516	0.590156	0.006508	153.6604	0.15366	21.72785	9.575156	2.621287
	0.0263	0.011835	0.353427	5.002957	0.5026	0.023548	-8.84951	0.626728	0.006528	153.1968	0.153197	21.88105	9.849505	2.530932
	0.0258	0.01161	0.357198	5.099914	0.5016	0.023146	-9.13721	0.666366	0.006548	152.7135	0.152713	22.03376	10.13721	2.441914
	0.0253	0.011385	0.361075	5.200703	0.5006	0.022743	-9.4392	0.709395	0.00657	152.21	0.15221	22.18597	10.4392	2.354246
	0.0248	0.01116	0.365061	5.305556	0.4996	0.022338	-9.75649	0.756182	0.006593	151.6859	0.151686	22.33766	10.75649	2.267942
	0.0243	0.010935	0.369162	5.414723	0.4986	0.021931	-10.0902	0.807143	0.006616	151.1406	0.151141	22.4888	11.09018	2.183015
	0.0238	0.01071	0.373385	5.528478	0.4976	0.021523	-10.4415	0.862752	0.006641	150.5737	0.150574	22.63937	11.44149	2.09948
	0.0233	0.010485	0.377735	5.647115	0.4966	0.021114	-10.8117	0.923544	0.006667	149.9846	0.149985	22.78936	11.81175	2.01735
	0.0228	0.01026	0.382221	5.770955	0.4956	0.020702	-11.2024	0.990134	0.006695	149.3726	0.149373	22.93873	12.20241	1.936638
	0.0223	0.010035	0.386848	5.900349	0.4946	0.020289	-11.6151	1.063223	0.006723	148.7372	0.148737	23.08747	12.6151	1.857358
	0.0218	0.00981	0.391626	6.035678	0.4936	0.019874	-12.0516	1.143616	0.006753	148.0776	0.148078	23.23555	13.05159	1.779525
	0.0213	0.009585	0.396563	6.17736	0.4926	0.019458	-12.5138	1.232241	0.006785	147.3931	0.147393	23.38294	13.51384	1.703151
	0.0208	0.00936	0.401669	6.325855	0.4916	0.01904	-13.004	1.330168	0.006817	146.6829	0.146683	23.52962	14.00403	1.628251
	0.0203	0.009135	0.406953	6.481664	0.4906	0.01862	-13.5246	1.438639	0.006852	145.9462	0.145946	23.67557	14.52459	1.554838
	0.0198	0.00891	0.412428	6.645342	0.4896	0.018199	-14.0782	1.559097	0.006888	145.1821	0.145182	23.82075	15.07823	1.482926
	0.0193	0.008685	0.418105	6.817501	0.4886	0.017775	-14.6679	1.693228	0.006926	144.3896	0.14439	23.96514	15.66795	1.41253
	0.0188	0.00846	0.423997	6.998818	0.4876	0.01735	-15.2971	1.843008	0.006965	143.5678	0.143568	24.10871	16.29714	1.343662
	0.0183	0.008235	0.43012	7.190043	0.4866	0.016924	-15.9696	2.010763	0.007007	142.7155	0.142715	24.25142	16.96959	1.276337
	0.0178	0.00801	0.436489	7.39201	0.4856	0.016495	-16.6896	2.199244	0.007051	141.8315	0.141831	24.39325	17.6896	1.210569
	0.0173	0.007785	0.443122	7.605652	0.4846	0.016065	-17.462	2.411715	0.007097	140.9145	0.140915	24.53417	18.46201	1.146372
	0.0168	0.00756	0.450039	7.832011	0.4836	0.015633	-18.2923	2.652076	0.007145	139.9632	0.139963	24.67413	19.29231	1.083759
	0.0163	0.007335	0.45726	8.072256	0.4826	0.015199	-19.1868	2.925002	0.007195	138.9761	0.138976	24.81311	20.18676	1.022746
	0.0158	0.00711	0.46481	8.327707	0.4816	0.014763	-20.1525	3.236136	0.007249	137.9515	0.137951	24.95106	21.15253	0.963345
	0.0153	0.006885	0.472716	8.599855	0.4806	0.014326	-21.1978	3.592323	0.007305	136.8876	0.136888	25.08795	22.19785	0.905572
	0.0148	0.00666	0.481007	8.89039	0.4796	0.013887	-22.3322	4.001919	0.007365	135.7826	0.135783	25.22373	23.33219	0.84944
	0.0143	0.006435	0.489717	9.201243	0.4786	0.013445	-23.5665	4.475194	0.007428	134.6343	0.134634	25.35836	24.56654	0.794963
	0.0138	0.00621	0.498883	9.534622	0.4776	0.013003	-24.9137	5.024859	0.007494	133.4405	0.133441	25.4918	25.9137	0.742155

Δh	Average depth	Area, A	Conjugate Depth	Velocity (u1)	Perimeter, P	hyd. Depth (m)	1-u/sq(gh)	energy gradient, i	dh/dl	dl/dh	dl	L	Fr1	LO
	0.0133	0.005985	0.508547	9.893066	0.4766	0.012558	-26.3886	5.666763	0.007564	132.1986	0.132199	25.624	27.38865	0.691031
	0.0128	0.00576	0.518758	10.27951	0.4756	0.012111	-28.009	6.420828	0.007639	130.9058	0.130906	25.75491	29.00902	0.641605
	0.0123	0.005535	0.529572	10.69738	0.4746	0.011662	-29.7957	7.312318	0.007718	129.559	0.129559	25.88447	30.79572	0.593892
	0.0118	0.00531	0.54105	11.15066	0.4736	0.011212	-31.7737	8.373571	0.007803	128.1548	0.128155	26.01262	32.77367	0.547904
	0.0113	0.005085	0.553265	11.64405	0.4726	0.01076	-33.9728	9.6464	0.007893	126.6894	0.126689	26.13931	34.9728	0.503658
	0.0108	0.00486	0.566303	12.18313	0.4716	0.010305	-36.4294	11.18547	0.00799	125.1585	0.125159	26.26447	37.42936	0.461167
	0.0103	0.004635	0.580261	12.77454	0.4706	0.009849	-39.1876	13.06312	0.008093	123.5573	0.123557	26.38803	40.18761	0.420445
	0.0098	0.00441	0.595256	13.4263	0.4696	0.009391	-42.3021	15.37632	0.008205	121.8804	0.12188	26.50991	43.3021	0.381508
	0.0093	0.004185	0.611425	14.14815	0.4686	0.008931	-45.8407	18.25695	0.008325	120.1215	0.120122	26.63003	46.84073	0.344368
	0.0088	0.00396	0.628933	14.95202	0.4676	0.008469	-49.889	21.8873	0.008455	118.2737	0.118274	26.7483	50.88901	0.309042
	0.0083	0.003735	0.647978	15.85274	0.4666	0.008005	-54.556	26.52372	0.008596	116.3286	0.116329	26.86463	55.55599	0.275543
	0.0078	0.00351	0.668802	16.86895	0.4656	0.007539	-59.9826	32.53397	0.008751	114.2769	0.114277	26.97891	60.98263	0.243885
	0.0073	0.003285	0.691707	18.02435	0.4646	0.007071	-66.3541	40.45739	0.00892	112.1073	0.112107	27.09102	67.35406	0.214084
	0.0068	0.00306	0.717066	19.34967	0.4636	0.006601	-73.9177	51.10499	0.009107	109.8067	0.109807	27.20082	74.91774	0.186154
	0.0063	0.002835	0.745358	20.88536	0.4626	0.006128	-83.0112	65.73159	0.009315	107.3591	0.107359	27.30818	84.01121	0.16011
	0.0058	0.00261	0.777203	22.68582	0.4616	0.005654	-94.1056	86.34348	0.009547	104.7453	0.104745	27.41293	95.10559	0.135966
	0.0053	0.002385	0.81342	24.826	0.4606	0.005178	-107.877	116.2735	0.00981	101.9415	0.101942	27.51487	108.8765	0.113736
	0.0048	0.00216	0.85512	27.41204	0.4596	0.0047	-125.324	161.3136	0.010109	98.91773	0.098918	27.61379	126.3241	0.093436
	0.0043	0.001935	0.903854	30.59948	0.4586	0.004219	-147.986	232.0878	0.010456	95.63543	0.095635	27.70942	148.986	0.075081
	0.0038	0.00171	0.961867	34.62573	0.4576	0.003737	-178.338	349.412	0.010864	92.04368	0.092044	27.80147	179.3381	0.058684
	0.0033	0.001485	1.032555	39.87205	0.4566	0.003252	-220.604	557.5749	0.011354	88.07289	0.088073	27.88954	221.6038	0.044261
	0.0028	0.00126	1.121353	46.99206	0.4556	0.002766	-282.538	961.3613	0.011958	83.62381	0.083624	27.97316	283.5378	0.031826
	0.0023	0.001035	1.237645	57.20773	0.4546	0.002277	-379.852	1846.637	0.012731	78.54671	0.078547	28.05171	380.852	0.021395
	0.0018	0.00081	1.399419	73.09877	0.4536	0.001786	-549.097	4168.286	0.013775	72.59716	0.072597	28.12431	550.097	0.012982
	0.0013	0.000585	1.6471	101.2137	0.4526	0.001293	-895.258	12296.36	0.015308	65.32641	0.065326	28.18963	896.2579	0.006602
	0.0008	0.00036	2.100078	164.4722	0.4516	0.000797	-1855.58	61850.1	0.017944	55.72956	0.05573	28.24536	1856.577	0.002269
	0.0003	0.000135	3.429916	438.5926	0.4506	0.0003	-8083.74	1621633	0.02481	40.30694	0.040307	28.28567	8084.742	0

ANNEXTURE I

COMPUTATION OF UPSTREAM PROFILE

Mannings constant, n	0.013
Channel width b, (m)	0.45
Height of water level over rectangular notch (m)	0.15
Flow through channel, Q (m^3/s)	0.05927
Length of channel (m)	8
Height of rectangular notch (m)	0.355
Coefficient of contraction, Cc	0.61
Critical depth, hc (m)	0.1208

Δh	Avg Depth	Conjugate Depth	Velocity,u1	Area, A	Perimeter, P	Hyd deapth, m	1-u/sq(gh)	Energy Grad, i	dh/dl	dl/dh	dl	L
	0.215	0.189002	0.61199	0.09675	0.88	0.109943	0.578604	0.001202	-0.00146	-684.352	-0.68435	17.5
0.001	0.2155	0.188245	0.61057	0.096975	0.881	0.110074	0.58007	0.001194	-0.00145	-689.66	-0.68966	16.81034
	0.216	0.187492	0.609156	0.0972	0.882	0.110204	0.581527	0.001187	-0.00144	-694.987	-0.69499	16.11535
	0.2165	0.186743	0.60775	0.097425	0.883	0.110334	0.582976	0.00118	-0.00143	-700.333	-0.70033	15.41502
	0.217	0.185997	0.606349	0.09765	0.884	0.110464	0.584416	0.001172	-0.00142	-705.698	-0.7057	14.70932
	0.2175	0.185254	0.604955	0.097875	0.885	0.110593	0.585849	0.001165	-0.00141	-711.082	-0.71108	13.99824
	0.218	0.184515	0.603568	0.0981	0.886	0.110722	0.587273	0.001158	-0.0014	-716.484	-0.71648	13.28176
	0.2185	0.183779	0.602187	0.098325	0.887	0.110851	0.588688	0.001151	-0.00139	-721.905	-0.7219	12.55985
	0.219	0.183047	0.600812	0.09855	0.888	0.11098	0.590096	0.001144	-0.00137	-727.345	-0.72734	11.83251
	0.2195	0.182317	0.599443	0.098775	0.889	0.111108	0.591496	0.001137	-0.00136	-732.804	-0.7328	11.0997
	0.22	0.181592	0.598081	0.099	0.89	0.111236	0.592888	0.00113	-0.00135	-738.281	-0.73828	10.36142
	0.2205	0.180869	0.596725	0.099225	0.891	0.111364	0.594272	0.001123	-0.00134	-743.778	-0.74378	9.617644
	0.221	0.18015	0.595375	0.09945	0.892	0.111491	0.595648	0.001116	-0.00133	-749.293	-0.74929	8.868351
	0.2215	0.179434	0.594031	0.099675	0.893	0.111618	0.597016	0.00111	-0.00132	-754.827	-0.75483	8.113523
	0.222	0.178722	0.592693	0.0999	0.894	0.111745	0.598377	0.001103	-0.00132	-760.38	-0.76038	7.353143
	0.2225	0.178012	0.591361	0.100125	0.895	0.111872	0.59973	0.001096	-0.00131	-765.952	-0.76595	6.58719
	0.223	0.177306	0.590035	0.10035	0.896	0.111998	0.601075	0.00109	-0.0013	-771.543	-0.77154	5.815647
	0.2235	0.176603	0.588715	0.100575	0.897	0.112124	0.602413	0.001083	-0.00129	-777.153	-0.77715	5.038494
	0.224	0.175904	0.587401	0.1008	0.898	0.112249	0.603744	0.001077	-0.00128	-782.782	-0.78278	4.255711
	0.2245	0.175207	0.586093	0.101025	0.899	0.112375	0.605067	0.001071	-0.00127	-788.43	-0.78843	3.467281
	0.225	0.174514	0.58479	0.10125	0.9	0.1125	0.606383	0.001064	-0.00126	-794.097	-0.7941	2.673184
	0.2255	0.173823	0.583493	0.101475	0.901	0.112625	0.607691	0.001058	-0.00125	-799.783	-0.79978	1.873401
	0.226	0.173136	0.582203	0.1017	0.902	0.112749	0.608992	0.001052	-0.00124	-805.488	-0.80549	1.067913
	0.2265	0.172452	0.580917	0.101925	0.903	0.112874	0.610286	0.001046	-0.00123	-811.212	-0.81121	0.256701
	0.227	0.171771	0.579638	0.10215	0.904	0.112998	0.611573	0.001039	-0.00122	-816.955	-0.81695	-0.56025