EXPERIMENTAL STUDY ON HYDRAULICS OF LABYRINTH WEIR OF DIFFERENT SHAPES

A DISSERTATION
Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
WATER RESOURCES DEVELOPMENT

By

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December, 2002

"DEDICATED TO MY PARENTS WHO

HAVE TAUGHT ME THE EARLY

LESSONS OF LIFE"

CANDIDATE'S DECLARATION

I hereby certify that the work which is being persecuted in the dissertation entitled, **"EXPERIMENTAL STUDY ON HYDRAULICS OF LABYRINTH WEIR OF DIFFERENT SHAPES"** in partial fulfillment of the requirement for the award of the Degree of Master of Technology in WRD(Civil) submitted in the Department of Water Resources Development Training Centre, (WRDTC) Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out during the period from July 16, 2002 to the date submission under the supervision of Dr. Nayan Sharma, professor WRDTC, Indian Institute of Technology, Roorkee.

I have not submitted the mater embodied in this dissertation for the award of any other degree.

Dated: Dec.12 ,2002 **(Rajive Nandan Mourya)**

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ACKNOWLEDGEMENT

I take this opportunity to record my sincere gratitude and indeteмess to Dr. Nayan Sharma, Professor, Water Resources Development Training Centre, IIT-Roorkee for his expert guidance, constant encouragement constructive co-operation in scrupulously scrutinizing the manuscript and very fruitful discussion at various stage of the dissertation work presented in this thesis.

I also grate fully acknowledge Mr. F. Lemperiere, Chariman, Hydrocrop France from where relevant reference have been drawn in this thesis.

I am also grateful to Rajesh Shukla who assisted me in one way or the other at times. Thanks to other friends for their help and cooperations during the experimental phase.

Last but not the list I express my thanks from the core of my heart to Neeraj Saini (WRDTC) without whose co-operation it was difficult to compete this report in time.

On the top of everything I acknowledge the discipline my parents Mr. Thakur Prasad and Mrs. Drupti Devi imbibed in me and the immerse love, encouragement and sacrifice given by my wife Mrs. Bimala Mourya to go ahead at all the stages.

But in my whole effort the angetic soul who suffered the most at my hands is my darling of all, elder son Master Nick who could not get enough love end care from my side which was due to him at his age and a little burnt was beared by my younger brother Raghawendera Ratna Mourya.

(RAJIVE NANDAN MOURYA)

ABSTRACT

In current practice, the two primary approaches for spillway design can be short-listed as gated and ungated free-flow spillways.

Gated spillways have been used for the most dam spillways over 1000 m^3/s. They were greatly favoured before 1980, but experience has underlined the recurring overhead cost of permanent operators, the need for careful maintenance and the downstream risks associated with gate operation or gate failure. The risk of some or all of the gates jamming during exceptional conditions corresponding to large floods has been emphasized by several dam accidents. Consequently, in many countries, this solution is used essentially for very large spillways.

Free-flow ungated spillways have been used for more than 80 per cent of the spillways with discharge capacities of less than 1000 m^3/s and about 20 per cent of larger ones. Their safety is well acknowledged ; their drawback is the loss of storage or the increased height (and cost) of the dam corresponding to the depth of the overtopping nappe over the sill. It is thus advisable to reduce this nappe depth : this has been achieved, partly by long spillways over concrete dams or side spillways for many earthfill dams, but the nappe depth often remains in the range of 2 or 3 m and may be more than 5m for large design floods. Consequently, the reservoir depth is often reduced by more than 10 per cent and the live storage volume by more than 30 per cent.

Alternatively, or in addition to these solutions, labyrinth weirs have been used to a limited extent in a few countries. Using it more extensively in many countries, particularly those with low labour costs, could save 10 per cent of the overall cost of many new dams, or could increase their storage by more than 10 per cent. It could also improve many existing ones.

Labyrinth weirs are polygonal walls designed to provide a much longer overtopped crest than the usual linear length of the spillway. Although many shapes and specific flows have been used or studied, the great majority of existing labyrinths have the following characteristics :

Discharge coefficient (and then the flow for the same nappe depth) surpasses two to three times the discharge coefficient of an ogee crest.

Total length of labyrinth walls stands between 2.5 to 5 times the usual linear spillway length.

Most often, the average height of walls is between 1.5 and 2 times the maximum nappe depth.

The flow downstream of a labyrinth weir is considerably aerated as per a system of air injection. Consequently the risks of erosion or cavitation are considerably reduced and the cost of new downstream structures or the maintenance of existing ones is reduced. To avoid vibrations in labyrinth spillways, it is advisable and cheaper to aerate the nappe.

Model tests and case histories show that floating debris do not create serous problems for labyrinth weirs.

As compared to a usual free flow linear spillway, labyrinths require less concrete but more reinforcing steel (about 50 K/m^3/s) and more labour for wall forms (10 hours per m^3/s) and higher cost of engineering. The low labour cost in countries such as India should help reduce the extra cost to 50 or 100 US$/m^3/s (to be spent in local currencies) and make it very attractive. And designs could be optimized and standardized for various heights (i.e. for various specific flows from 5 m^3/s/m up to 50 m^3/s/m or more).

Hydraulic operation and discharge coefficients have been studied in many laboratories, particularly in Portugal (IST Lisbon), the USA, Spain, Turkey and France (LNH Chatou) for various solutions ; but the optimization of a labyrinth weir should take into account not only hydraulic data, but also structural strains (specially for large spillways and high walls), construction facilities and the possibilities to place the weir on top of existing or new concrete gravity structures.

The purpose of the present study (model tests) is to examine to optimization of a shape which may be well adopted to large or small specific flows and may be palced on up on eisting of new gravity dams.

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NOTATIONS

The following symbols are used in this dissertations

Alphabetical

SYMBOL		Description
L	-	Crest length of labyrinth element
W	-	Effective Linear width of element of labyrinth weir
Cd	-	Co-efficient of discharge
θ	-	Angle of V-notch
α	-	Angle of Side Walls to main flow direction
H	-	Depth of water over V-notch
B	-	Width of channel
h	-	Head over the crest
p	-	Wall height of labyrinth weir
Q_L	-	Labyrinth discharge
Q_N	-	Discharge through linear weir
r	-	Ratio of labyrinth discharge and to linear weir discharge
z	-	Height of crest
p	-	Intensity of pressure in kg/m^2 due to water current
k	-	Constant for different shapes of piers
v	-	Velocity of current in m/sec at the point where pressure intensity is calculated.
W → n	-	Number of weir cycles in plan
z	-	
ρ_w	-	Mass density of water unit mass of water (kg/m^3)
F_d	-	Water current force per unit width of flume (kg/m)
F_n	-	Hydrostatic force per unit width of flume (kg/m)
μ_w	-	Undimensional discharge coefficient
L/W	-	Length magnification ratio

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INTRODUCTION

1.1 GENERAL

The world has witnessed tremendous developments in the field of science and engineering in the past 100 years. In the field of hydraulics also the progress has been nonetheless important and valuable. The technique of hydraulic model studies developed with the systematic and organised research work carried out in the Hydraulic laboratories all over the world. The technique has been so effectively developed by now that for each major work whether it be an intricate irrigation or flood control structure or a navigation canal or harbour, experiments on a model of the prototype render great assistance and provide very useful information pertaining to the work.

1.2 IMPORTANCE OF LABYRINTH WEIR

Labyrinth weirs are polygonal walls, designed to provide a much longer overtopped crest than the length of the spillway. The labyrinth spillway is particularly well-suited for cases where the length of the structure has to be restricted or for rehabilitation of existing spillways. The concept involves a structure where the crest length is developed by triangular or trapezoidal elements which are much longer than the spillway chute width.

This type of spillway is characterized by a broken-axis weir in plan, generally with the same polygonal pattern repeated periodically. Hence, for the same total width, the labyrinth weir spillway will present larger crest lengths than the same solution.

A labyrinth weir can pass large discharge at a relatively low head. Its advantage include relatively low construction and maintenance costs, and more reliable operation, compared with gated spillways.

In addition, for a given maximum operation head, a labyrinth spillway can be an economical alternative in terms of dam crest elevation and reservoir storage volume. Although it has a broad range of applications, its complex flow conditions and design have been considered a drawback by designers.

1.3 HYDRAULIC ENGINEERS FACING PROBLEM IN TRADITIONAL METHODS

Spillways represent a substantial portion of total project costs and they play a major role in ensuring safety. Insufficient spillway capacity has been the cause of the third of all dam failures.

Gated spillways have been used for most spillway over 1000m^3/sec. They were greatly favoured before 1980 but experience has underlined the cost of permanent operators, the need for careful maintenance and the downstream risks associated with gate operation or gate failure. The risk of some or all of the gates jamming during exceptional conditions corresponding to large floods can affect dam safety considerably. Consequently in many countries, this solution is used essentially for very large spillways and in many new designs in the event of a gate jamming.

Free flow ungated spillways have been used for more than 80 percent of spillways with discharge capacities of less than 1000 m^3/sec and about 20 percent for larger ones. Their safety is well acknowledged, their drawback is the loss of storage or the increased height of the dam corresponding to the depth of overtopping nappe over the sill. It is thus advisable to reduce this nappe depth. This has been achieved partly by long spillways over concrete dams or side spillways for many earthfill dams but the nappe depth often remains in the range of 2 or 3m and may be more than 5m for large design floods. Consequently, the reservoir depth is often reduced by more than 10 percent and the live storage volume by more than 30 percent.

In above circumstances the freeboard over the gates should be at least 50 percent of the gate and labyrinth weir or mixed solution may be more attractive. Even labyrinth is to reduce the spillway length while keeping the ogee weir nappe depth. The length reduction should be between 50 to 70 percent. A labyrinth weir can pass large discharge at a relatively low head. Its advantages include relatively low construction and maintenance costs, and more reliable operation compared with gated spillways.

1.4 THEORETICAL CONCEPT OF LABYRINTH WEIR

Labyrinth weirs are polygonal walls in reinforced concrete such as to provide much larger overtopped crest than the length of the linear spillway and thus to increase the flow for same maximum reservoir levels.

The labyrinth spillway is particularly well suited for cases where the length of the structure has to be restricted or for the rehabilitation of existing spillways. A labyrinth weir can pass large discharge at a relatively low head. Its advantages include relatively low construction and maintenance costs and more reliable operation, compared with gated spillways.

In addition for a given maximum operation head, a labyrinth spillway can be an economical alternative in terms of dam crest elevation and reservoir storage volume.

The ability of the labyrinth weir to pass large flows at comparatively low heads has led to many applications. The labyrinths primary use has been as a spillway for dams. It is particularly suited for use where the spillway width is restricted or where the flood surcharge space is limited.

Labyrinth walls may be used for increasing by 50% the capacity of a spillway of a maximum nappe depth.

A labyrinth spillway has advantages compared with the straight overflow weir and the standard ogee crest. The total length of the labyrinth weir is typically three to five times the spillway width. Its capacity varies with head and is typically about twice that of a standard weir or overflow crest of the same width. Labyrinth weirs can be used to increase outlet capacity for a given spillway crest elevation ad length or to increase storage by raising the crest while maintaining spillway capacity.

The labyrinth spillway has the ability to discharge up to three times the volume of water that a conventional linear weir can handle. This feature allowed the engineers to replace the existing unsafe spillway in its same location.

The flow downstream of a labyrinth weir is considerably aerated as per a system of air injection. Consequently the risks of erosion or cavitation are considerably reduced and the cost of new downstream structures or the maintenance of existing ones is reduced. To avoid vibrations in labyrinth spillways it is advisable to aerete the nappe.

1.5 LABYRINTH CYCLES

The upstream total head, the total spillway width W and the economics of the design determine the number of labyrinth cycles. A spillway can be designed using only one cycle but would be very uneconomical. Alternatively for the same total spillway width, the labyrinth can be constructed with so many cycles not nappe interference severely reduce the spillway width, the number of cycles and the crest height P, determine the cycle width W and vertical aspect ratio W/P. The number of cycles selected should combine hydraulic efficiency by minimizing nappe interference with economical construction.

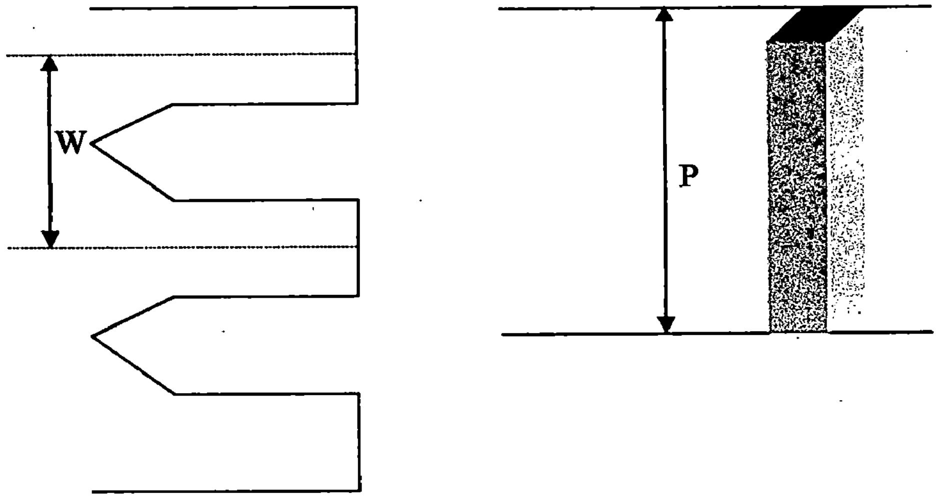


Fig. 1.1 Labyrinth Weir Models

1.6 BRIEF STATEMENT OF THE EXPERIMENTAL WORK DONE IN THE DISSERTATION

The primary aim of the present exploratory campaign of the flume experiments has been to investigate into the suitability of the selected model variants of labyrinth weir, keeping in view its efficiency at different flow ranges represented by the non-dimensional n/p ratio here. The findings of this study are promising enough to warrant further work for the potential applications of the labyrinth spillways for dam safety in India in the context of adverse hydrological consequences due to global warming phenomenon.

1.7 OBJECTIVES OF THE STUDY

Keeping the above mentioned points in mind, following objectives are decided for the present study.

1. To perform laboratory experiments to investigate the labyrinth effect at varying discharge for the different models.

2. To assess the hydraulic performance of the selected element shapes from the stand point of labyrinth effect.
3. To study the effect of full end partial morter filling of elements from hydraulic end structural considerations.
4. To study the interaction at higher discharge on labyrinth effect.
5. To study the (L/w) length a magnification ratio and w/p ratio on the labyrinth effect.

1.8 LIMITATIONS OF THE STUDY

The labyrinth spillway uses simple shapes linked in a repetitive manner to form the labyrinth structure. These two concepts, simplicity and repetition, makes design and construction of labyrinths easy, saving time, materials and money. The low labour cost in countries line India should help to reduce the extra cost and make it very attractive.

The present investigations were limited in scope due to number of non dimensional ratios had to be held constant. In the present study, due to constrains of the lab infrastructure, experimentation at desired higher levels of h/p ratios in the range of 0.5 to 1 were left out presently.

REVIEW OF LITERATURE

2.1 GENERAL

Spillways represent a substantial portion of total project costs and they play a major role in ensuring safety. Insufficient spillway capacity has been the cause of one third of all dam failures as per literatures. As projects are reassessed for safety, provision for an increased estimate of the probable maximum flood has to be made in many cases. It is therefore necessary to provide more flood sterage and/ or larger capacity for spillways to pass the PMF safely. If the dam can not adequately pass the updated flood, the structure requires modification by increasing the flood storage space, increasing the spillway capacity or using combinations of these two solutions. An innovative and effective way of increasing the spillway capacity is to use a labyrinth weir. The concept of the labyrinth weir is to vary the plan shape of the crest to increase the effective crest length. This increases the discharge per unit width of the spillway for a given operating head.

The ability of the labyrinth to pass large flows at comparatively low heads has led to many applications. The labyrinth primary use has been as a spillway for dams. It is particularly suited for use where the spillway width is restricted, or where the flood surcharge space is limited. The labyrinth is relatively low cost when compared with – gated spillways and this has led to its use in conjunction with the raising of dams for increased. Storage space of labyrinth spillways can be highly effective in many circumstances.

A Labyrinth spillway has advantages compared to the straight over flow weir and the standard ogee crest. The total length of labyrinth weir is typically three to four times the spillway width. Its capacity varies with head and is typically about twice that of a standard weir or over flow crest of the same width. Labyrinth weirs can be used to increase outlet capacity for a given spillway crest elevation and length or to increase storage by raising the crest while maintaining spillway capacity.

2.2 REVIEW OF THE EXISTING MODELS

A number of researchers worked on hydraulic models that have been tested in order to learn about the design by labyrinth spillways. A review of the models tested pertaining to labyrinth spillways is presented in the following paras.

An extensive investigation and behavior of labyrinth weirs was studied by missing Taylor (1968) in terms of a magnification ratio of the labyrinth flow for a sharp-crested linear weir having the same channel width. As follow up to that Hay and Taylor (1970) worked for design procedure for labyrinth weirs, including criteria for estimating the discharge over the triangular or trapezoidal labyrinth weirs. Taylor (1968) described that when head increases, the tail water depth increases particularly between the nappe and the labyrinth wall. Due to convergence of opposing nappes the higher tail water depths and the restricted area at the upstream apexes, aeration under the nappe at these apexes becomes difficult.

Hay and Taylor (1970) limited the application of their results to situations having the same approach. Condition as tested that is rectangular flumes with no side wall contractions. This is due to the piezometric head having a single unique value given the discharge in the flume and the flume cross section and assuming sub-critical flow.

By changing the upstream definition from piezometric head h to total specific head Ho in order to apply Talor's labyrinth model results to differing approach conditions, this method can no longer be used for the following reasons.

1. The flow in the labyrinth is three-dimensional in nature. Observations show that the flow over the crest is not perpendicular to the crest at all sections as with linear weirs.
2. At increasing head the flow over the labyrinth is not fully aerated due to nappe interference and submergence. The linear weir equations apply only to fully aerated flow.
3. The method does not provide an indication where nappe interference or loss of aeration occurs.

Darvas (1971) tested a number of hydraulic models in order to learn about the design of labyrinth spillways and experimental results of the model studies of Woronera and Avon weirs in Australis and develop curves for designing labyrinth weirs.

Mayer (1980) studied the model in Bartletts Ferry project for effect on mi discharge of a proposed labyrinth weir spillway. The conceptual design of the structure was based on the approach of Hay and Taylor (1970) and was found to be inadequate, as the structure would not pass the required flow.

missing

Kathlen, et al. (1982), Houston (K.I) (1982) and ~~A. N.~~ Cold (1980) studied a labyrinth weir operating with low head for non-aerated clinging nappe. On this flow conditions, he observed that nappe oscillation and noise are produced by alternating atmospheric and sub-atmospheric pressures in the nappe. Sub atmospheric pressures help to increase the flow ratio, but can create structural problems as a result of vibrations and resonance. He also observed for transitional flow as a discontinuity in the discharge co-efficient and ratio for certain L/W values. This insatiable flow condition can also cause structural problems. This can be avoided with the installation of splitter piers or installation of an air gallery through the weir wall. The splitter piers do not have to be high enough to aerate the flow under the full range of upstream heads but may be submerged during higher flows. Splitter piers can accumulate waste material resulting in a decrease in the effective overflow length. He suggested that aeration through the weir wall is considered a safer and more effective way in all flow conditions.

More ever U. S. Bureau of Reclamation completed a model of Ritschard Dam labyrinth weir spillway based on Vermeyen (1991) model study results which were ? used to design labyrinth for standley lake Tullis (1973).

Several experimental programme were completed at the Utah Water Research Laboratory to evalute the crest co-efficient for labyrinth weirs, Amanian (1987), Basiri et al. (1972) and Waldran (1974). These experimental studies resulted in the development of a data base and design procedure. It is based on a specific crest geometry. The procedure allows complete flexibility in selecting the number of cycle and the angle of the side legs. Limitations are same of the design variables, such as height of the weir and the width to length ratio of the labyrinth. The final choice should be based on over all layout of the project which is cost effective.

The proposed method for designing a labyrinth weir using the basic equation for linear weirs is

$$Q = 2/3 \ Cd \, L \sqrt{2g} \ H_t^{1/2}$$

Where Cd = dimensionless crest coefficient.

g = Accelaration of gravity.

L = effective length of weir

H_t = Total head on the crest.

2.3 CHARACTERISTICS OF LABYRINTH FLOW

The distinguishing characteristic of this spillway is that the plan shape is not linear but varies using a repeating plan form. The repeating plan forms that have been used are U, V and trapezoidal shape. Using these plan form shapes for spillways result in a complex flow pattern. Ideally the discharge passing over the labyrinth should increase in direct proportion of an increase in crest length. However this is only the case for labyrinth spillways with low design heads. Qualitatively, as the upstream head increases, the flow pattern using a labyrinth spillway sequentially passes through four basic phases. These phases are fully aerated, partially aerated, transitional and suppressed.

The fully aerated condition occurs at low upstream heads when the flow falls freely over the entire length of the labyrinth crest. In this flow condition, the thickness of the nappe and depth of fall of water do not affect the discharge capability of the spillway. As a result, the labyrinth behaves almost ideally when compared to a linear weir with the same vertical cross section.

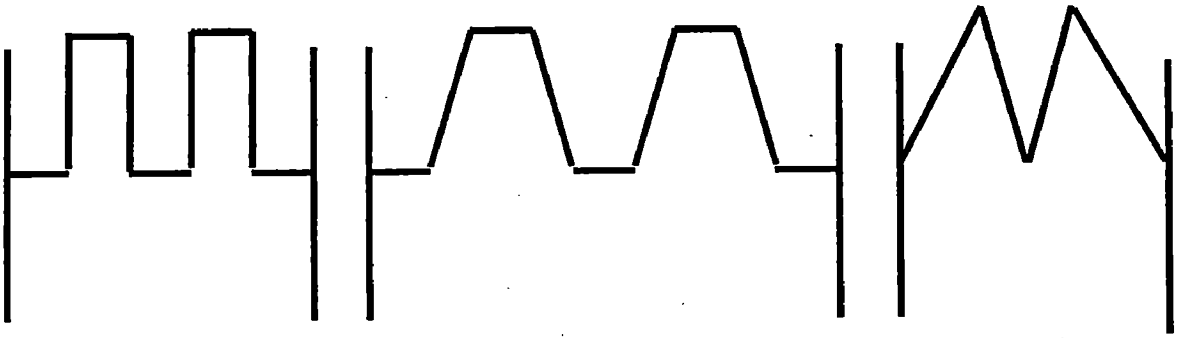
In partially aerated phase when head increases, the tail water depth increases particularly between the nappe and the labyrinth wall, due to convergence of opposing nappes. The higher tail water depths and restricted area at the upstream apexes aeration under the nappe is maintained. A stable air pocket is formed along each side wall and downstream apex of the labyrinths.

In the transitional phase, the nappe is alternating between intermittent air entrainment and solid water flows. It is difficult at times to distinguish between the partially aerated and transitional phases but transitional region can be easily identified as a discontinuity in the discharge co-efficient curve.

On the suppressed phase, the flow over the labyrinth crest forms a solid non aerated nappe. The thickness of the nappe and the depth of tail water do not allow air to be drawn under the nappe. As the upstream head increases, this last flow condition eventually leads to full submergence of the labyrinth spillway. Complete submergence of the labyrinth usually occurs when the flow depth over the crest is greater than the height of the labyrinth.

2.4 PLAN GEOMETRY OF LABYRINTH WEIR SPILLWAYS

In plan, the labyrinth weirs may present many forms as given below –



(a) (b) (c)

Fig. 2.4(a),(b)&(c) Plan Geometry of Labyrinth Weir

The shape of such a plan form is completely defined by l/w (length magnification) α and n. For a given length magnification, α varies from zero rectangular form to a certain maximum triangular form. The most used being the symmetric trapezoidal form.

2.5 DIFFERENT THEORY OF LABYRINTH WEIR DISCHARGE CO-EFFICIENT

Methods presented by Hay and Taylor, (1970) and Darvas (1971) respectively, have been generally used to compute the theoretical values of the discharge co-efficient.

Hay and Taylor's approach (1970) enable the evaluation of the labyrinth – weir performance, Q_L/Q_N, as a function of the undimensional parameters h/p. w/p. l/w, α/α_{max} and n.

Where, QL = discharge over the labyrinth weir (m^3/sec)

QN = discharge over the corresponding straight weir (m^3/sec)

h = upstream head over crest (m) αmax – arc sin (w/l)

When hydraulic model tests proved that the actual discharges are smaller than those value given by Hay and Taylor's in particular for high values of h/p. Cassidy [illegible] et al. (1983) tested a model for Cartys dam labyrinth spillways and obtained a discharge co-efficient 20 + 25% smaller than the values given by Hay and Taylor (1970).

Darvas (1971), presents a design chart to determine cw = $Q_L/wh^{3/2}$ as a function of the parameters l/w and h/p with cw being expressed in ft 0.5 /sec. This chart was obtained from model tests, under the following condition labyrinth weir trapezoidal in plan, with horizontal bed and quarter of a circle section (crest profile).

Free flow over the weir

$$1 \leq l/w \leq 8$$

$$0.2 \leq n/p \leq 0.6$$

$$\alpha/\alpha max \geq 0.80$$

$$w/p \geq 2$$

Darvas (1971) chart was modified in Magalhaes (1993) by using an undimensional discharge coefficient.

?

$$\mu w = Q_L \, W\sqrt{2g}\, h^{3/2}$$

Model tests confirmed that the actual discharge are in general, smaller than those indicated by Darvas (1971) in particular for high values of h/p.

missing Amarian (1987), Basin et al. (1972), Tullis (1993) and Waldron (1994) have given value for nonaerated flows of crest coefficient values Cd = 0.75 for small h/p values. The crest coefficients for a labyrinth weir varies for different labyrinth angles between 6^0 to 35^0. The value of Cd does not vary significantly with a small change spelling
missing of α. Amerian (1987) has suggested that sharp-crest and flat-crest weirs are generally not preferred because their crest coefficients are measurably less than those for rounded crested weirs. The most efficient and practical shape appears to be the quarter round. Even though the quarter-round crest has a smaller Cd at Low head h/p < 0.5 compared to a full half round crest which is easier to construct.

2.6 REVIEW OF RECENTLY – BUILT LABYRINTH SPILLWAYS

Hydraulic model studies have been conducted at the Portuguese National Laboratory for Harrezza dam (Algeria) in 1980, Dungo dam (Angola) in 1981 and Keddara dam (Algeria) in 1984 , and the details are narrated below.

1. Harrezza dam

Harrezza dam is a 41 m high earthfill dam. Initial design included an ogee spillway of straight crest, without gates, with three bridge piers and its was located next to the left abutment. At the foot of the spillway there was stilling basin, connected downstream to a 700 m long excavated, rather steep transition channel to the natural river. The weir width was 64.50 m (Four 15 m wide spans and three 1.50 m thick piers)

The model tests indicated an upstream head over crest of 2.08 m for a design discharge of 350m^3/sec. The downstream transition channel to the natural river was to be built in a very soft clay soil. In consequence, the hydraulic model tests led the way to include in the design an armored blanket to protect the transition channel. The existence of this apron made the initially designed spillway non economic solution.

Therefore, a new spillway was designed, next to the right abutment. The downstream transition to the river becoming significantly shorter, but the available width for the entrance zone and spillway weir becoming rather smaller, due to topographical constraints.

The new spillway presents a labyrinth weir followed by a 230 m long steep channel with variable width (30, 40 to 20 m), a 35 m long stilling basin and finally a transition channel which become almost horizontal.

The labyrinth weir has three cycles with a total length of 90 m and width 30 and 40 m , includes on the upstream side, three piers, which serve as splitters also.

Model test indicated, for this new solution a quite good behaviour, with an upstream head over crest of 1.90 m for a design discharge of 350 m^3/sec.

2. Dungo Dam

Dungo dam is a 19 m high earth fill dam. The initial design included a straight ogee crest spillway to be built next to the dam right abutment, without gates, with four bridge piers, and followed downstream by a canal and a stilling basin. The weir total width was approximately 72.50 m. The design discharge of 576 m^3/sec would correspond to an upstream head over crest of 2.50 meter.

A large flood occurred during the spillway construction, destroyed the spillway crest and the canal. To rebuild the same spillway was too expensive, so a new spillway was designed located now at the dam left abutment.

The new spillway, much narrower than the initial one, has a labyrinth weir, followed, similarly, by a canal and a stilling basin. The labyrinth weir has a total length of 115.50 m and total width of 40.10 m, it has four cycles, and includes splitter piers at both sides upstream and downstream.

The model test confirmed the excellence of this solution, which was finally adopted for construction. The design discharge of 576 m^3/sec was set to an upstream head over crest of 2.40 meter.

3. Keddara dam

Keddara dam is a 108 m high rockfill dam. the spillway was designed for a 250 m^3/sec discharge and it includes, essentially a labyrinth weir, a canal and a stilling basin.

In this case the labyrinth weir was adopted since the beginning as the most economical solution. It consists of two cycles ahs a total length of 53.77 in and a total width of 19.00 m and it includes two bridge splitter piers at the upstream end.

The model tests confirmed a well behaved solution with an upstream head ove crest of 2.46 m for a design discharge of 250m^3/sec.

For dams in operation it is sometime required to increase the spillway discharge capacity, this may be done either by proposing another spillway or by changing the spillway in weir form. In few cases the following alternative has taken into consideration.

1. Avon dam

Avon dam, a 72 m high masonry dam was concluded in 1927. The spillway presented a fan shape weir with a total length of 146 m designed for a maximum discharge of 765 m^3/sec corresponding to a upstream head over crest of 2.80 m subsequent hydrological studies showed that the maximum expected flowed discharge was much larger than the one initially adopted. Thus after some hydraulic model tests, it was decided to substitute the original spillway by a labyrinth weir spillway for the same total width.

This was done in 1970. The labyrinth weir consisting of ten trapezoidal cycles has a total length of 264 m for the same 2.80 m upstream head over crest the discharge was increased to 1790 m^3/s which is a much larger value (2.3 times) than the initial solution.

2. Ute Dam

Ute dam is a 37 m high earth fill dam. completed in 1962. Its original spillway presented an ogee straight crest, 256 m – long and it was designed to allow gates to be added in the future. But some years later, when the gates implementation becomes advisable to increase the reservoir storage capacity, the corresponding updated cost was unacceptably high. Alternative solutions were studied and the most economical being to raise the dam by 3.35 m and substitute the existent spillway by a labyrinth weir spillway. Hence a labyrinth weir spillway was constructed for the same width of 256 m with fourteen cycles and total length of 1024 m. This alternative solution which was completed in 1983 allows a discharge of 15574 m^3/sec for a upstream head over crest of 5.79 m.

2.7 CONCLUDING REMARKS

In this chapter various studies related to labyrinth spillway mechanisms and their applications have been reviewed. It is obvious that labyrinth weir spillway performance depends on a number of factors including shape geometry, flow pattern and related variables. The opinion defers regarding the relative importance of these factors on performance of labyrinth weir spillway.

A design procedure gives an accurate analysis of the labyrinth's capacity. However it is still advisable to verify the performance of the spillway with a model study. The models accounts for site specific factors outside the scope of the spillway design, such as flow conditions in the approach and discharge channels, inlet losses, scour, submergence and energy dissipation. If the flow in the discharge channel is super critical the model can also provide valuable information on wave heights and super elevation caused by channel convergence or bends.

The labyrinth spillway uses simple shapes linked in a repetitive manner to form the labyrinth structure. These two concepts, simplicity and repetition make design and construction of labyrinth easy. Having the labyrinth should be considered as a viable spillway alternative.

However, there is no literature available on this shape and also there is no published work available on this. This emphasizes the importance of the present study. The labyrinth weirs used world wide for one hundred dams with various shapes and most often the flow was double of the flow of an usual ereager spillway. It has not yet been used in India where available efficient engineering and low cost labour would favour it.

EXPERIMENTAL PROGRAMME

3.1 INTRODUCTION

The experiments as envisaged under the objectives have been conducted in the River Engineering Laboratory of Water Resources Development Training Centre of Indian Institute of Technology Roorkee. The experimental programme was organised in three phases. In the first phase, experiments were performed in a 50cm wide flume using models of Labyrinth Weir. In this phase of laboratory experiments elements were not filled with cement mortar to investigate its effect on the labyrinth effect as well as structural stability. In the second phase of experiments conducted in a 50cm wide flume, the elements were filled up with half filling by cement mortar to investigate the above effects. In the third phase of experimental study, elements were fully filled by cement mortar

The main aim of this proposed model experiments is to optimize size which appears well adapted to Indian condition of large flows and may be used for existing as well for new dams.

3.2 OBJECTIVES OF THE EXPERIMENTAL STUDY

(i) Investigation of labyrinth effect at higher discharge.

(ii) Determination of discharge at which labyrinth discharge is almost equal to the linear rectangular weir discharge.

(iii) Hydraulic performance of element size on the labyrinth effect.

(iv) Study of effect of full and partial mortar filling of elements on hydraulic and structural stability

(v) Measurement of 3-D velocity components at the element for study of effect of 3-D velocity on labyrinth.

(vi) Study of jet interaction on labyrinth effect.

(vii) Study of (L/W) ratio and (Ho/P) ratio on the labyrinth effect.

With the above objectives, this background, the details of the experimental programme are presented below.

3.3 LABORATORY FLUME AND OTHER ACCESSORIES

The experimental set-up consists of (a) measuring device and equipment and (b) dampening device.

3.3.1 Flume Used For Experiment

This 50cm wide, and 55cm deep flume is flitted with an inbuilt upstream tank. All three parts of the flume are made up of panted mild steel. The down stream tank is attached with a pump which is 10HP (horse power) in capacity. 10cm diameter pipes connect this pump to the upstream tank of the flume which is deeper of the upstream tank are 50cm and 100cm respectively while the width and depth of the flume are 50cm×50cm respectively. This flume has side walls made up of transparent perspex sheet in 240cm length up to 25cm before the labyrinth weir model. An evenly perforated perspex sheet of one cm diaholes and 1cm thickness separates the upper tank from the channel portion of flume at 50cm distance from the upstream face of the upstream tank. The purpose of this sheet is to stabilize the flow and make it uniform. The upstream pipe drops the water right at the base of the upstream tank to minimize all disturbances.

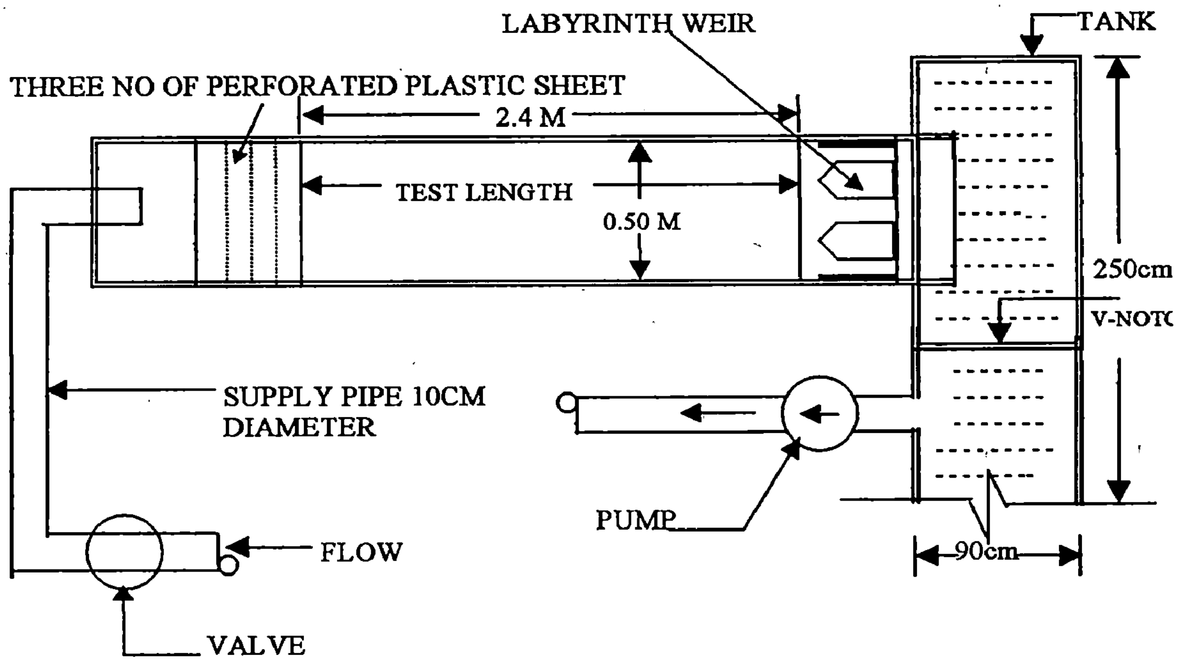
A V-notch is fixed in the down stream tank for discharge measurements. The down stream tank is 90cm wide, 90cm deep 250cm long internally. The tail end of the flume is placed roughly 15cm above the top of the upstream end of tank. This tank is bifurcated into two stories in first 160cm length on the flume end side, the depth of the upper portion being 40cm. A v-notch is fixed at he end of upper storey with its vertex placed 15cm from the base of upper portion at the end of upper portion. Three baffle wall is placed to carb all the disturbances of the water falling from the flume into the tank. It is 90cm away from upstream end of the tank. In the bottom portion is placed the opening of the pump close the base of tank 5cm above it.

The flume is mounted on two R.C.C. blocks 65cm in height from the floor, 66cm wide and 39cm in length. A threaded rod is grouted in the lower and block. The lower end of the flume is merited over this threaded rod with the help of a very strong nut with handles is such away not the lower portion of flume could be mov3ed up or down maximum of 4% creating the desired slope. The plan of this flume is given in Fig 3.1.

Two railings are mounted on the top edges mot is left and right sides of the flume over which are placed all the required equipment for measurement of velocity, depths and levels, etc. Pitot tubes and Pointer gauges are placed on the railings. By adjustment of the screw on which the pipe rails rested it was possible to level them accurately and to make them parallel to the flume.

3.3.2 Pipe Network and Pump

Downstream of V-Notch and upstream of labyrinth weir, network is connected through a simple pipe. Pump in connected in the pipe for recirculation of water.



PLAN VIEW

Fig. 3.1 Schematic Diagram of Experimental Setup for Labyrinth Weir

NOT TO SCALE

3.3.3 Proposed Labyrinth Weir Model

For experiments relevant model tests should be adapted to an existing flume 50cm wide and 50cm deep.

It proposed to represent 2 labyrinth element 25cm wide, 16cm high and 32cm long. These elements should by fixed upon a single steel basis and placed upon a masonry basis about 10cm high plate form. Four models having different internal widths and shapes shown in photographs 3.1 to 3.6. In this case number of weir cycles (n) is two.

The models should include the vertical walls and the downstream inclined part and the steel horizontal basis 20cm × 50cm supporting the whole model and laid upon the masonry support. Details given in drawing and Fig. 2(a) and 3.2 (b)

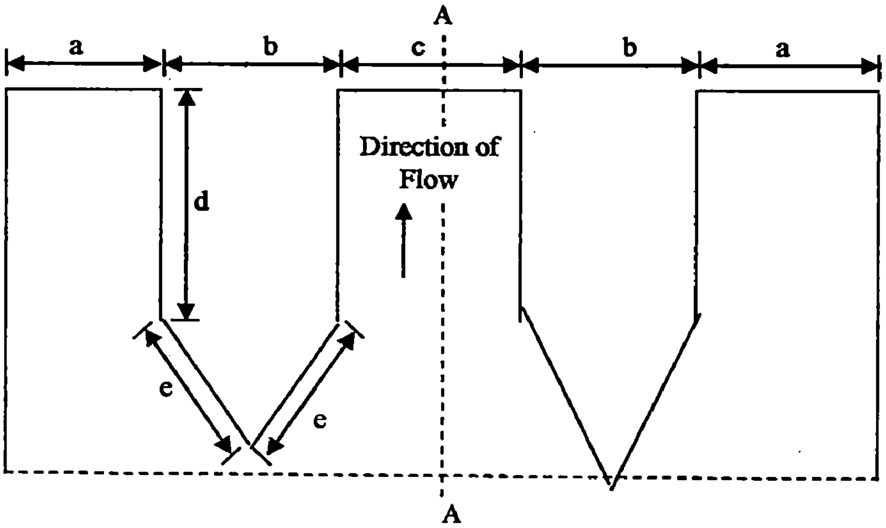
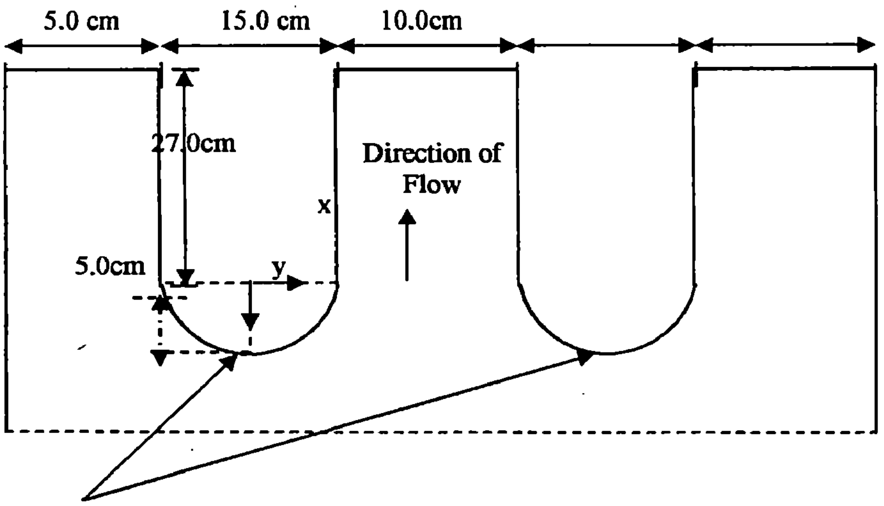


Fig. 3.2(a). Plan Showing Dimension of Labyrinth Weir for Model No.s 1-4

Model With Dimensions In Cm.				
	M_1	M_2	M_3	M_4
a =	7	9	8.1	5.9
b =	11	7	9.15	15
c =	14	18	15.5	8.2
d =	27	27	27	27
e =	7.5	6	7	9



Parabola (Governing equation is, $y=5(1-x^2/7.5^2)$)

Fig. 3.2 (b). Plan Showing Dimension of Labyrinth Weir for Model No. 5

3.3.4 V-Notch

It was used to measure the discharge through labyrinth weir. The formula used for discharge is v-notch is $\frac{8}{15} cd\sqrt{2g}.\tan\theta/2.H^{5/2}$ where it is the depth of water above vertex of V-notch at the upstream of v-notch.

3.3.5 Pointer Gauge

It was used to measure the nappe height at the upstream of labyrinth weir and head over the v-notch.

3.3.6 Acoustic Doppler Velocimeter (ADV)

ADV was used to measure the 3D velocities at elements of the labyrinth weir. The Acoustic Doppler Velocimeter is a versatile, high precision instrument that measures all three flow velocity components. The measurements are insensitive to water quality, which allows for a wise range of applications. ADVs is used in laboratories, wave basins, river, estuaries end oceanographic research.

The instruments consists of three modules, the measuring probe, the conditioning module and the processing module. The measurements probe is attached to the water proof conditioning module, .which contaings low noise electronic circuit. The housing and cable attachment are rugged and can be deployed upto 30 m in the standard configuration.

The down looking probe (Standard for all systems) Cannot meausre the velocity in the upper 5 cm of the water column. It the main interast is to meausre th esurface layer to measure under structure may be very useful.

For taking reading 3-D down looking probe have been used for collecting data in three direction Vx, Vy and Vz, where velocity Vx refers to the velocity along the x-axis. The direction of y-axis and z-axis are based on the definition of a right-handed coordinate system where z is pointing upwards. For collecting data high-frequency cable from the single conditioning module is connected to the processor. Explorer V, Version 1.5 and version 2.7 have been used for running program and for collecting data, version 3.2 has been used.

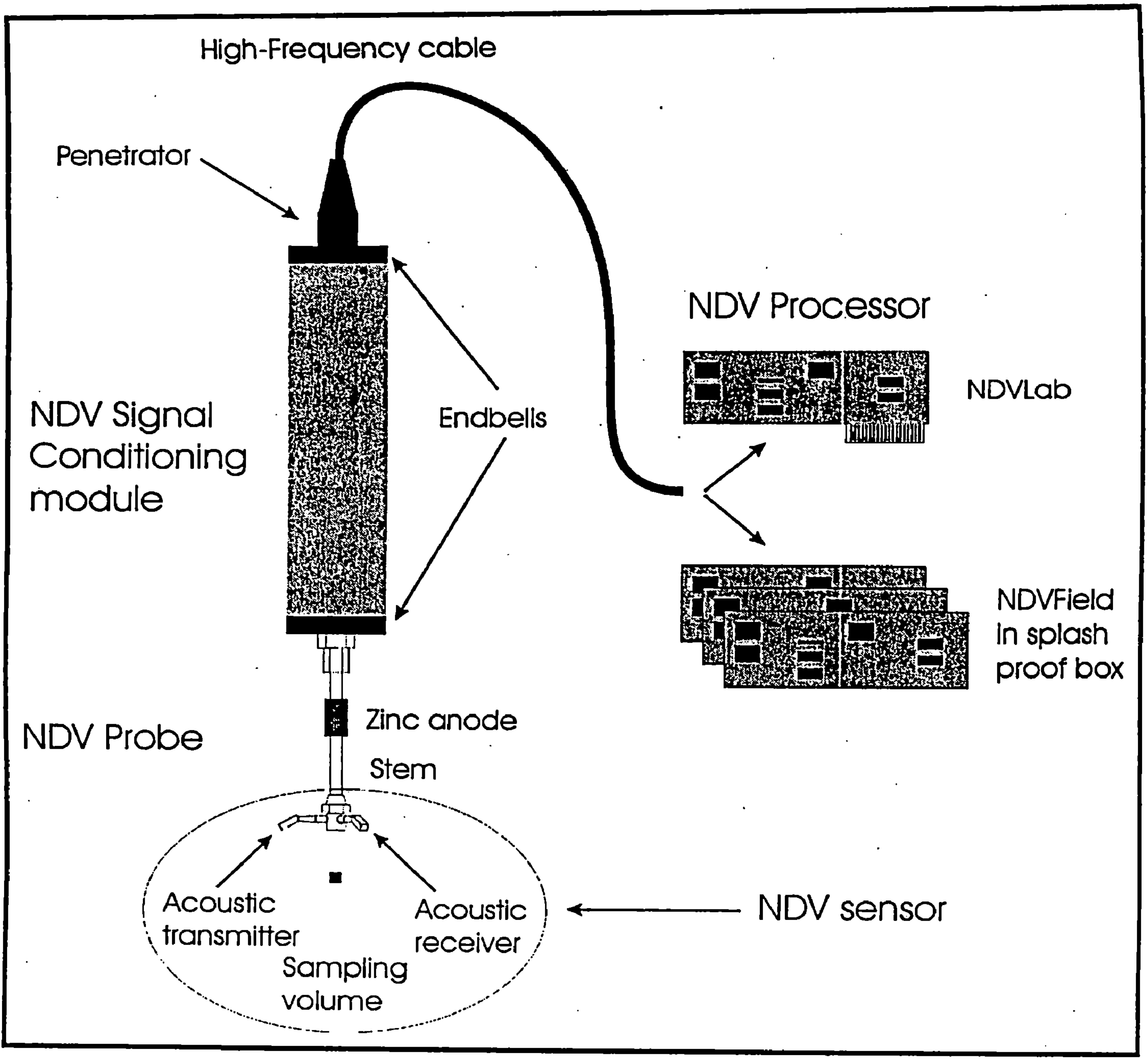


Fig. 3.3 3-D Down Looking Proble Acovsitc Doppler Velocimeter

3.4 EXPERIMENTAL PROCEDURE

Experiments were conducted in the flowing schematic way:

(1) A schematic view of the experimental setup is shown in Photograph 3.9 to 3.11.

(2) Before starting the experiment the side rails of the flume were adjusted and were kept parallel to each other and parallel to the bottom of channel.

(3) The water was supplied to the flume by means of 10cm discharge. Supply pipe connected to the pump and the discharge was controlled by a regulating valve.

(4) Three row of perforated plastic sheet wall was provided to damper the surface disturbances/destroy the excess energy of inflow and distribute it uniformly in the entire width of the flume.

(5) A steel labyrinth weir was provided at the down stream and of the flume at 12cm base platform was made. The models were placed at the platform (pre determined location).

(6) The water which discharges into the tail box was allowed to flow over 90 degree v-notch. After flowing over the notch the water was discharge into the sump form where it was re-circulated by pump.

(7) For the measurement of initial and different nappe depth the pointer gauge fixed to a vertical graduated rod was used. The difference of initial reading and different nappe depth readings gave the nappe depth of different discharge.

(8) After the labyrinth weir introduced on the plat form discharge was slowly allowed into the flume and goes upto maximum discharge. The experiment was run for 10 to 12 different nappe height and Accoustic Doppler Velocimeter was taken only for higher discharge (maximum discharge). For proper operation all three acoustic receivers and the transmitter must be submerged.

(9) The experiments were repeated for all the Models M1, M2, M3, M4 and M5 with different shapes of labyrinth weir. The data collected and data analysis have mention in Tabular form.

3.5 TIME OF RUN OF EACH MODELS

In the present investigation models of different water ways were installed one by one in the flume and trail runs were made of investigate the point where the nappe height and velocity are to measured and establish the minimum V-notch reading. Nappe height and corresponding v-notch readings were measured by using pointer gauge from minimum to maximum discharge values and about 10 to 15 readings were taken.

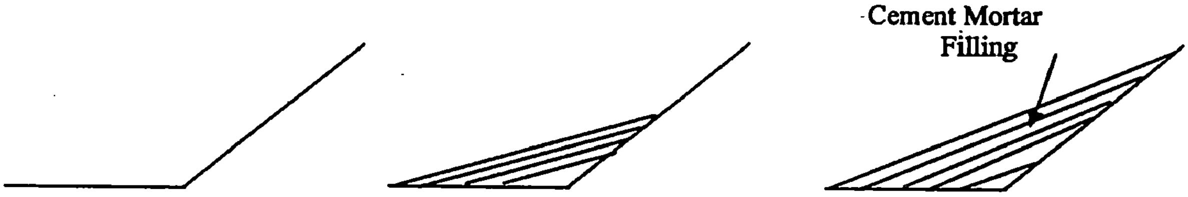
All the above readings were repeated for empty, half filled and full filled with cement mortors in elements.

In the present investigation on exploratory run was conducted but due to the infrastructural constraints, readings at higher discharge could not be taken.

ADV was used to measure velocity at max available discharge to asses the max hydrodynamic fore for structural stability.

3.6 LIST OF CASES TESTED

The various case for labyrinth weir like, without cement mortor filling half concrete tilling, and full concrete filling, which had been tested in the present study are given in Fig. (a), (b), (c):

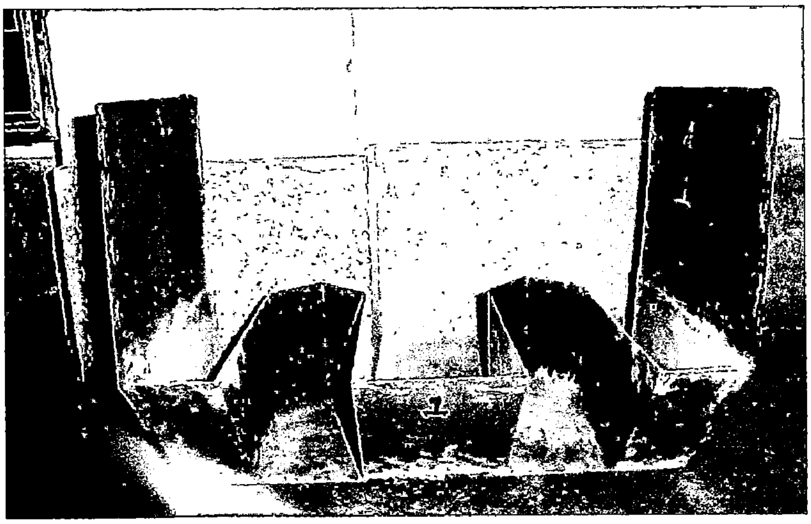


(a) empty or without
with

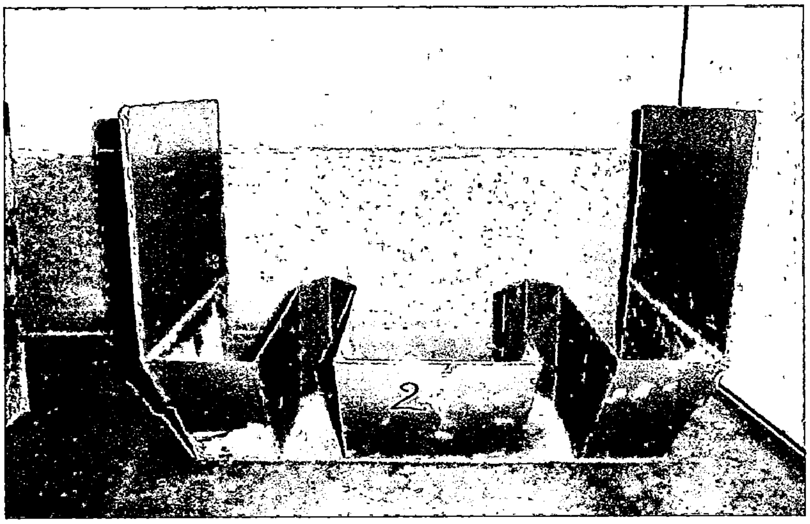
(b) half filled case and
filling case

(c) fully filled case
cement mortar

Fig. 3.4 Section A-A of Labyrinth Weir

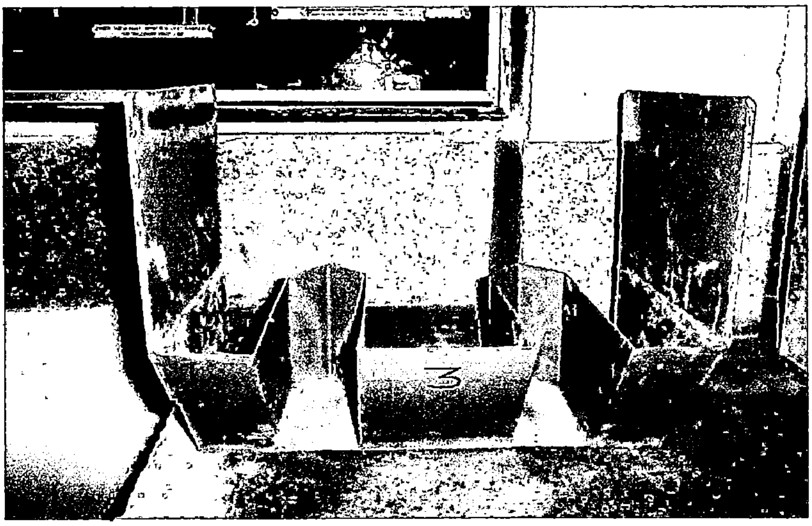


Photograph - 3.1 Showing Model -1

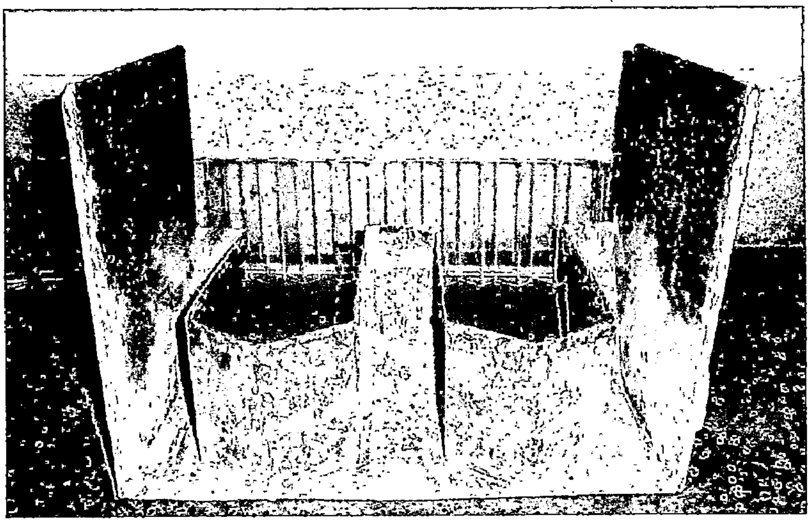


Photograph - 3.2 Showing Model -2

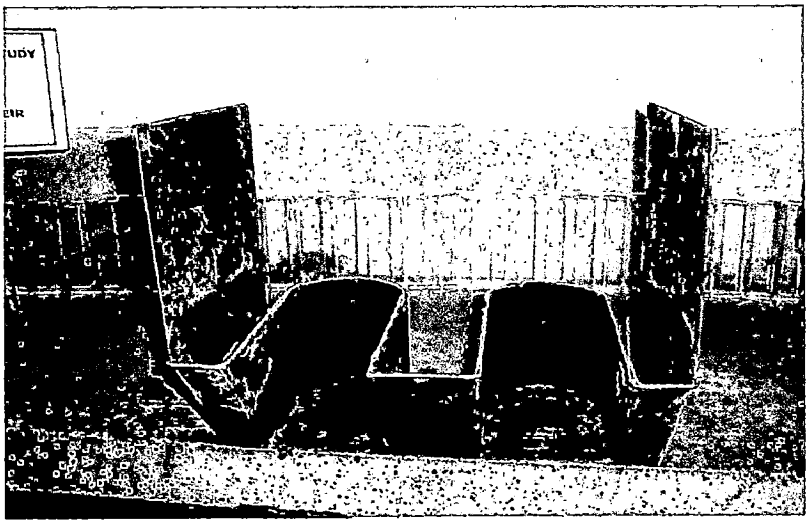
Photograph - 3.3 Showing Model -3



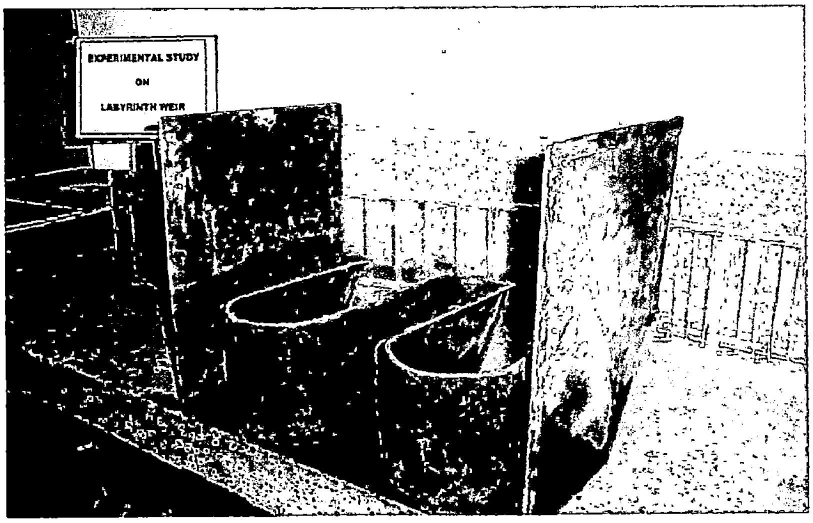
Photograph - 3.4 Showing Model -3



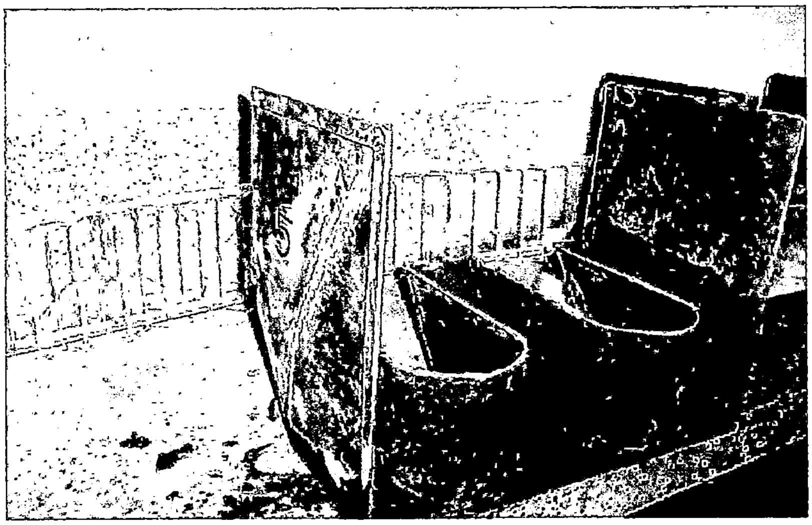
Photograph - 3.5 Showing Model -4



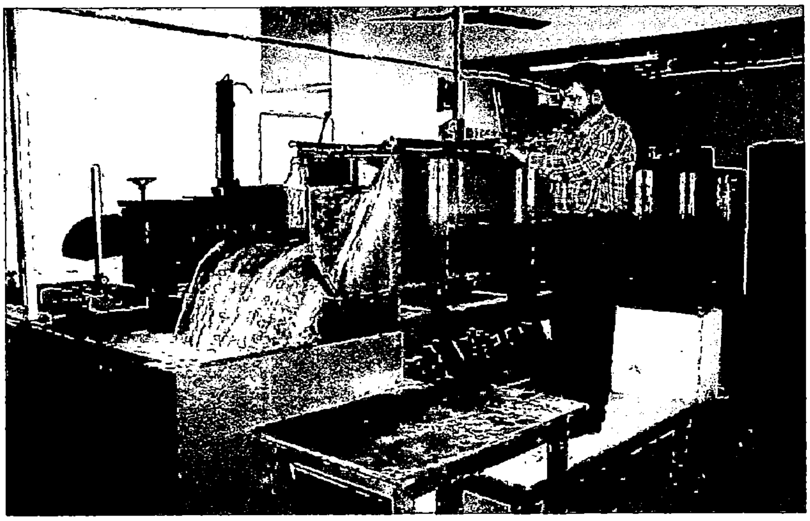
Photograph - 3.6 Showing Model -5



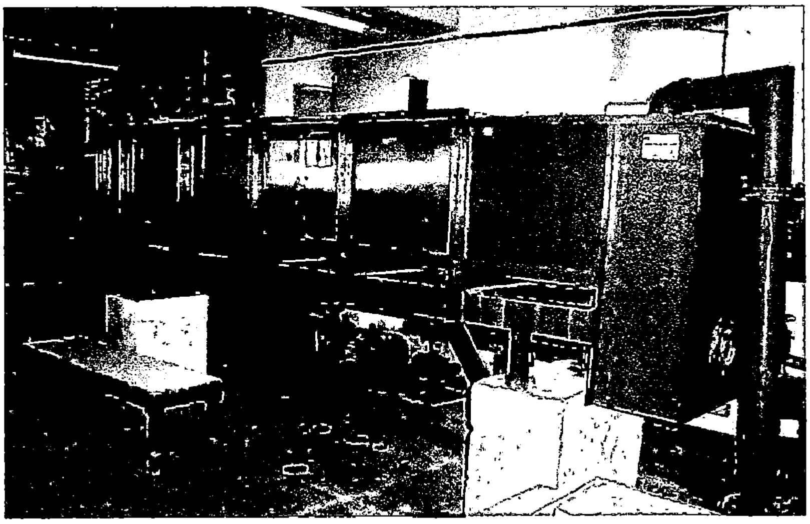
Photograph - 3.7 **Showing Model -5**



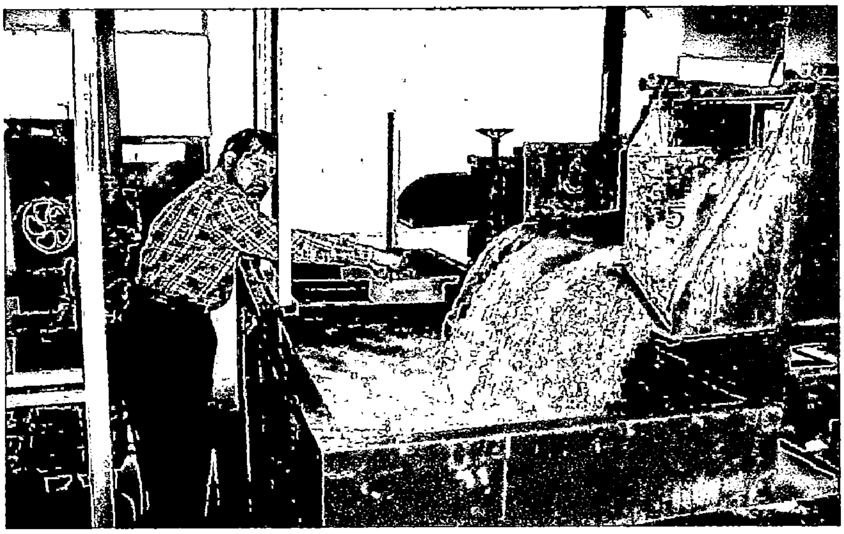
Photograph - 3.8 **Showing Model -5**



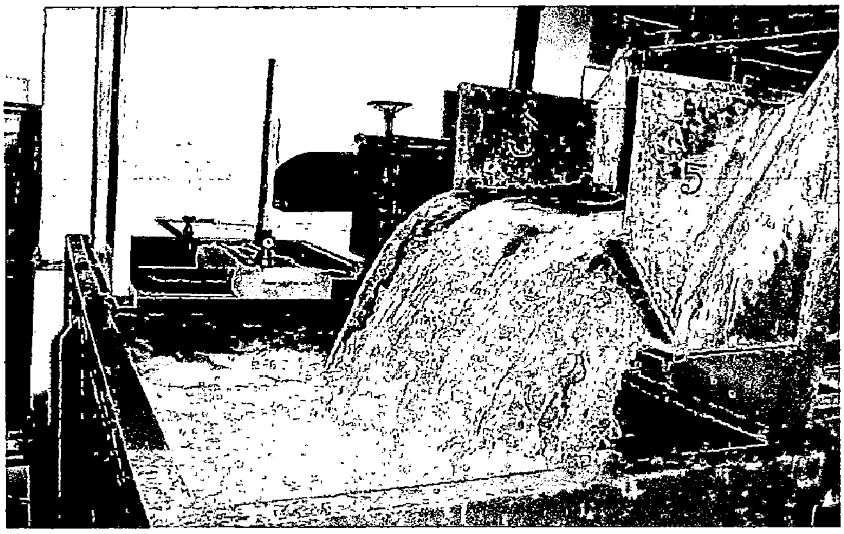
Photograph - 3.9 Showing Experimental Setup



Photograph - 3.10 Showing Experimental Setup



Photograph - 3.11 Showing Experimental Setup



Photograph - 3.12 Showing Experimental Setup

ANALYSIS OF DATA

Table 4.1 to 4.20 based on laboratory experiment represent different Q_L, Q_N, r and h/p values calculated as follows.

The method for calculations made for discharge, h/p and L/W from the experimental data are as indicated below.

(i) Calculation of discharge through linear weir is made by the formula,

$Q_N = \frac{2}{3} Cd\sqrt{2g}.Bh^{3/2}$ where h is the head over the crest and Cd is co-efficient of discharge, B is the width of channel

$Cd = \left[0.605 + \frac{0.08h}{z} + \frac{0.001}{h}\right]$, z is height of crest

Formula used for calculation of labyrinth discharge Q_L through the V-notch is as below-

$Q_L = \frac{8}{15} Cd\sqrt{2g}\tan(\theta/2)H^{5/2}$ where H is head over the V-notch and Cd is co-efficient of discharge, taken as 0.6 θ is angle of V-notch which is 90^0 in this case.

Ratio of labyrinth discharge and linear discharge (r) is

$$r = \left(\frac{Q_L}{Q_N}\right)$$

(ii) Calculation of (h/p)

h is the head over the crest (at one meter u/s of the labyrinth weir) and P is height of labyrinth weir which is equal to 16 cm for all the models.

(iii) Calculation of length magnification ratio: (L/W)

L is the length of labyrinth weir crest and W is the effective linear width of element of labyrinth weir with reference to Fig. 3.2.

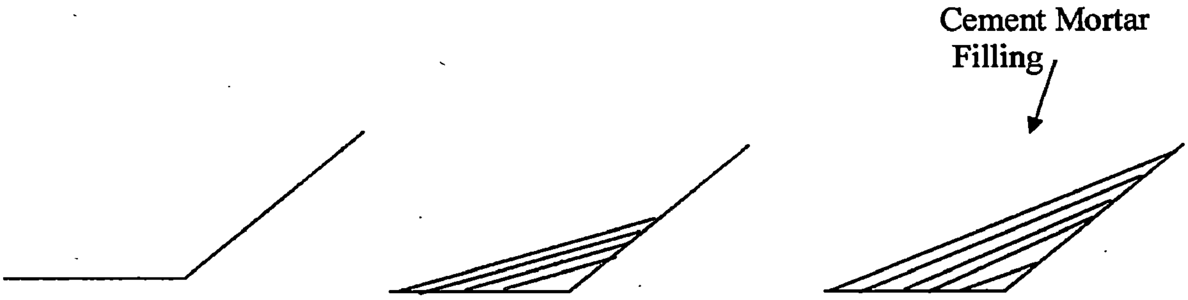
$$L = 2a + c + 4d + 4e$$

$$W = 2a + 2b + c$$

Data processing and analysis have been done for the three cases in each model i.e.

(a) empty or without filling case
(b) partial filled or half filled case and
(c) fully filled case with cement mortar

as shown in the Fig.s 4.1 (a), (b), (c) respectively, which are taken as section A-A in Fig. 1.



(a) (b) (c)

?

Fig. 4.1. Section A-A of Labyrinth Weir

The pattern for stepped mortar filling is shown in the Fig. 4.2.

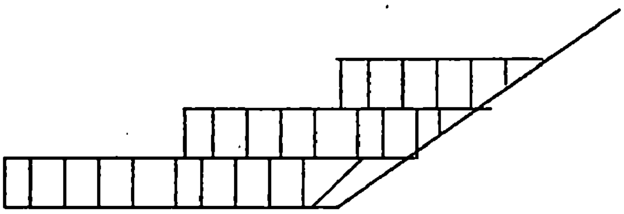


Fig. 4.2 Stepped mortar filling

4.1 CALCULATIONS FOR HYDRODYNAMIC AND HYDROSTATIC FORCES ON LABYRINTH WALL

An exercise was made to calculate from the experimental data the water current and hydrostatic forces on the labyrinth wall

$K = 47.3$ say 47.5

$H = 0.16$ m

$V = 0.394$ m/s → Empty or without filling

$= 0.4443$ m/s → Half filled with mortar

$= 0.4917$ m/s → Fully filled with mortar

Empty Case $P = KV^2$

Water current force $(F_d) = \frac{1}{2} KV^2 H$
$= \frac{1}{2} \times 47.5 \times 0.394^2 \times 0.16$
$= 0.589$ kg/m

Half Filled Case -

$F_d = \frac{1}{2} \times 47.5 \times 0.4443^2 \times 0.750$
$= 0.750$ kg/m

$\rho_w = 1000$ kg/m^3

Corresponding hydrostatic force

$F_n = \frac{1}{2} \rho_\omega H^2$
$= \frac{1}{2} . 1000 . 0.16^2$
$= 12.8$ kg/m

From the above exercise made on experimental data, it could be seen that for all cases, the hydrostatic force is the dominating force as compared to the water current force.

Filling of elements by mortar increases the water current force which is still very-much less than the hydrostatic force.

The dominating force is therefore hydrostatic which is constant for all the three cases.

Therefore, filling of the elements by mortar may be advantageous from structural nsideration to counter hydrostatic force, provided there is no adverse hydraulic effects.

In Table 4.20 (a) a comparison of the values of different length magnification ratios W with the ratio 'r' is presented for perusal of the results at a glance. The varying ranges of p ratio has yielded varying values of 'r' which are broadly categorized in Table 4.20 (a) as aximum, average and minimum for a closer comparison of the performance by different odels in the present experimental study, the resulting values of 'r' for the same value of h/p e presented in Table 4.20 (b)

Based on laboratory experiments several plots have been made to get an insight into haviour of labyrinth effect. The Graphic plots have been developed from the experimental ta collected from the five models of labyrinth with different sizes and flow conditions.

In the first set of graphical plots fig. 4.3 to fig. 4.7 the trend of variations between tio r and h/p for different models considering empty, half-filled and fully filled with cement ortar are presented.

In the second set of graphical plot processing the experimental data the variations of r rsus h/p for different length magnification ratio L/W for empty half filled and fully filled se covering all the models are shown in fig. 4.8, 4.9 and 4.10. In Fig. 4.11, the trend of riations between ratio r and h/p for models no. 4 with three different wall height' 'p' of byrinth wall in shown.

TABLE 4.1
MODEL 1 FOR EMPTY CASE
[P=16 cm]

V-notch (H) in (meter)	**Linear Weir (h) in (meter)**	**Labyrinth Discharge** $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ **(m^3/s)**	**Linear Weir Discharge** $Q_N = \frac{2}{3} C_d \sqrt{2g} B h^{3/2}$ **(m^3/s)**	**Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$**	**Ratio of Head over crest and height of Labyrinth wall (h/p)**
0.064	0.007	0.00146	0.00055	2.64782	0.0456
0.093	0.012	0.00372	0.00115	3.23347	0.0744
0.113	0.017	0.00602	0.00193	3.11916	0.1050
0.132	0.022	0.00896	0.00293	3.05635	0.1388
0.139	0.025	0.01025	0.00350	2.92623	0.1563
0.154	0.030	0.01311	0.00463	2.83301	0.1881
0.172	0.037	0.01732	0.00638	2.71320	0.2331
0.187	0.043	0.02132	0.00801	2.66173	0.2713
0.196	0.048	0.02398	0.00929	2.58249	0.2994
0.208	0.054	0.02807	0.01121	2.50405	0.3394
0.211	0.057	0.02906	0.01202	2.41650	0.3556

TABLE 4.2
MODEL 1 FOR HALF FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r = Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.059	0.007	0.00120	0.00055	2.16903	0.0456
0.095	0.012	0.00390	0.00121	3.22842	0.0769
0.117	0.019	0.00658	0.00228	2.88157	0.1175
0.140	0.026	0.01039	0.00369	2.81508	0.1619
0.156	0.031	0.01371	0.00491	2.79509	0.1956
0.170	0.037	0.01689	0.00625	2.70066	0.2300
0.178	0.041	0.01903	0.00735	2.58716	0.2563
0.186	0.045	0.02106	0.00843	2.49908	0.2806
0.192	0.048	0.02287	0.00932	2.45440	0.3000
0.206	0.055	0.02717	0.01130	2.40375	0.3413

TABLE 4.3
MODEL 1 FOR FULLY FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge r=Q_L/Q_N	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.065	0.007	0.00150	0.00055	2.71041	0.0456
0.091	0.012	0.00353	0.00115	3.07050	0.0744
0.122	0.020	0.00735	0.00258	2.84894	0.1275
0.139	0.026	0.01028	0.00376	2.73732	0.1638
0.156	0.032	0.01354	0.00509	2.65697	0.2006
0.166	0.036	0.01587	0.00610	2.60027	0.2263
0.178	0.042	0.01889	0.00768	2.46026	0.2638
0.186	0.046	0.02101	0.00874	2.40349	0.2875
0.194	0.050	0.02335	0.00990	2.35704	0.3125
0.206	0.057	0.02730	0.01206	2.26452	0.3563

TABLE 4.4
MODEL 2 FOR EMPTY CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m³/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m³/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge r=Q_L/Q_N	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.067	0.013	0.00163	0.00133	1.22610	0.0819
0.112	0.022	0.00592	0.00285	2.07749	0.1363
0.136	0.030	0.00963	0.00456	2.11371	0.1863
0.149	0.033	0.01213	0.00533	2.27308	0.2069
0.166	0.040	0.01584	0.00701	2.26069	0.2481
0.180	0.046	0.01948	0.00883	2.20765	0.2894
0.186	0.049	0.02106	0.00952	2.21236	0.3044
0.194	0.053	0.02350	0.01081	2.17375	0.3313
0.198	0.055	0.02485	0.01146	2.16894	0.3444
0.202	0.058	0.02609	0.01231	2.11942	0.3613
0.212	0.064	0.02940	0.01424	2.06431	0.3981

TABLE 4.5
MODEL 2 FOR HALF FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.098	0.019	0.00424	0.00228	1.85665	0.1175
0.118	0.023	0.00674	0.00311	2.16592	0.1444
0.139	0.030	0.01016	0.00463	2.19514	0.1881
0.153	0.035	0.01294	0.00575	2.24936	0.2175
0.163	0.038	0.01513	0.00661	2.28820	0.2388
0.175	0.043	0.01808	0.00795	2.27314	0.2700
0.188	0.050	0.02164	0.00982	2.20418	0.3106
0.193	0.053	0.02313	0.01078	2.14637	0.3306
0.201	0.057	0.02564	0.01206	2.12695	0.3563
0.206	0.060	0.02720	0.01295	2.09968	0.3738
0.209	0.063	0.02820	0.01394	2.02296	0.3925

TABLE 4.6
MODEL 2 FOR FULLY FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.095	0.019	0.00396	0.00230	1.72195	0.1181
0.124	0.026	0.00763	0.00376	2.03045	0.1638
0.150	0.035	0.01231	0.00588	2.09526	0.2206
0.163	0.041	0.01516	0.00730	2.07618	0.2550
0.173	0.045	0.01759	0.00851	2.06667	0.2825
0.185	0.051	0.02081	0.01011	2.05761	0.3169
0.191	0.054	0.02254	0.01115	2.02195	0.3381
0.197	0.058	0.02448	0.01234	1.98321	0.3619
0.204	0.062	0.02677	0.01368	1.95765	0.3875
0.210	0.065	0.02858	0.01458	1.96010	0.4044

TABLE 4.7
MODEL 3 FOR EMPTY CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_l/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.049	0.013	0.00073	0.00130	0.56570	0.0806
0.073	0.016	0.00206	0.00183	1.12878	0.1013
0.108	0.022	0.00547	0.00297	1.84213	0.1400
0.124	0.027	0.00774	0.00395	1.95757	0.1694
0.148	0.035	0.01194	0.00573	2.08584	0.2169
0.159	0.039	0.01433	0.00690	2.07677	0.2456
0.175	0.045	0.01813	0.00837	2.16587	0.2794
0.189	0.050	0.02192	0.00990	2.21358	0.3125
0.199	0.055	0.02507	0.01133	2.21216	0.3419
0.207	0.059	0.02753	0.01263	2.17974	0.3675

TABLE 4.8
MODEL 3 FOR HALF FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m³/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m³/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge r=Q_L/Q_N	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.046	0.012	0.00064	0.00112	0.57377	0.0731
0.103	0.021	0.00483	0.00268	1.80299	0.1306
0.126	0.028	0.00794	0.00408	1.94419	0.1731
0.151	0.036	0.01262	0.00608	2.07710	0.2256
0.165	0.041	0.01560	0.00730	2.13729	0.2550
0.174	0.045	0.01795	0.00837	2.14427	0.2794
0.187	0.050	0.02149	0.00987	2.17638	0.3119
0.198	0.055	0.02479	0.01143	2.16938	0.3438
0.202	0.058	0.02603	0.01231	2.11419	0.3613
0.205	0.061	0.02694	0.01328	2.02824	0.3800

TABLE 4.9
MODEL 3 FOR FULLY FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m³/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m³/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r = Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.043	0.011	0.00053	0.00101	0.52663	0.0681
0.094	0.019	0.00381	0.00239	1.59135	0.1213
0.115	0.024	0.00629	0.00331	1.89718	0.1506
0.131	0.030	0.00887	0.00460	1.92720	0.1875
0.152	0.037	0.01270	0.00625	2.03148	0.2300
0.163	0.041	0.01513	0.00741	2.04288	0.2575
0.171	0.045	0.01719	0.00837	2.05314	0.2794
0.188	0.052	0.02175	0.01050	2.07056	0.3250
0.198	0.057	0.02476	0.01206	2.05361	0.3563
0.210	0.064	0.02864	0.01428	2.00649	0.3988

TABLE 4.10
MODEL 4 FOR EMPTY CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.072	0.010	0.00195	0.00086	2.27028	0.0613
0.100	0.016	0.00448	0.00179	2.50000	0.1000
0.106	0.018	0.00512	0.00212	2.41530	0.1119
0.115	0.021	0.00632	0.00262	2.41117	0.1288
0.129	0.025	0.00850	0.00350	2.42866	0.1563
0.145	0.030	0.01129	0.00460	2.45250	0.1875
0.154	0.035	0.01328	0.00570	2.32876	0.2163
0.166	0.039	0.01579	0.00690	2.28837	0.2456
0.176	0.044	0.01845	0.00823	2.24071	0.2763
0.205	0.061	0.02687	0.01331	2.01831	0.3806

TABLE 4.11
MODEL 4 FOR HALF FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	**Linear Weir (h) in (meter)**	**Labyrinth Discharge** $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ **(m^3/s)**	**Linear Weir Discharge** $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ **(m^3/s)**	**Ratio of Labyrinth Discharge and Linear Weir Discharge r=Q_L/Q_N**	**Ratio of Head over crest and height of Labyrinth wall (h/p)**
0.054	0.008	0.00097	0.00060	1.61950	0.0481
0.095	0.015	0.00395	0.00163	2.42904	0.0938
0.114	0.021	0.00626	0.00260	2.40771	0.1281
0.132	0.026	0.00892	0.00371	2.40228	0.1625
0.148	0.032	0.01200	0.00507	2.36727	0.2000
0.158	0.037	0.01400	0.00618	2.26600	0.2281
0.169	0.042	0.01654	0.00760	2.17742	0.2619
0.178	0.047	0.01895	0.00908	2.08572	0.2950
0.185	0.050	0.02084	0.00990	2.10381	0.3125
0.205	0.061	0.02690	0.01325	2.03078	0.3794

TABLE 4.12
MODEL 4 FOR FULLY FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m³/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m³/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r = Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.067	0.007	0.00165	0.00053	3.10756	0.0444
0.098	0.014	0.00422	0.00150	2.81392	0.0888
0.106	0.017	0.00515	0.00196	2.62201	0.1063
0.132	0.025	0.00892	0.00357	2.50267	0.1581
0.144	0.030	0.01123	0.00467	2.40367	0.1894
0.155	0.035	0.01334	0.00588	2.27083	0.2206
0.178	0.047	0.01903	0.00903	2.10791	0.2938
0.186	0.051	0.02112	0.01020	2.06997	0.3188
0.190	0.054	0.02222	0.01105	2.00962	0.3363
0.195	0.058	0.02371	0.01221	1.94103	0.3594

TABLE 4.13
MODEL 5 FOR EMPTY CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.036	0.004	0.00034	0.00018	1.84775	0.0219
0.085	0.010	0.00295	0.00091	3.23330	0.0638
0.113	0.016	0.00607	0.00179	3.38591	0.1000
0.137	0.022	0.00978	0.00281	3.47589	0.1350
0.154	0.027	0.01317	0.00402	3.27786	0.1713
0.168	0.033	0.01632	0.00538	3.03240	0.2081
0.180	0.038	0.01940	0.00661	2.93356	0.2388
0.195	0.045	0.02383	0.00854	2.79007	0.2831
0.202	0.049	0.02587	0.00949	2.72516	0.3038
0.207	0.052	0.02750	0.01047	2.62540	0.3244

TABLE 4.14
MODEL 5 FOR HALF FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.080	0.009	0.00258	0.00077	3.35733	0.0569
0.095	0.013	0.00390	0.00124	3.15125	0.0781
0.126	0.019	0.00804	0.00238	3.38293	0.1206
0.142	0.024	0.01071	0.00323	3.31453	0.1481
0.158	0.029	0.01395	0.00444	3.14065	0.1831
0.173	0.035	0.01757	0.00590	2.97746	0.2213
0.184	0.041	0.02056	0.00733	2.80536	0.2556
0.190	0.045	0.02227	0.00846	2.63399	0.2813
0.203	0.050	0.02632	0.01002	2.62551	0.3150
0.209	0.055	0.02841	0.01127	2.52028	0.3406

TABLE 4.15
MODEL 5 FOR FULLY FILLED CASE
[P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m³/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m³/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.070	0.008	0.00182	0.00061	2.98962	0.0488
0.112	0.017	0.00595	0.00188	3.16912	0.1031
0.139	0.025	0.01028	0.00350	2.93675	0.1563
0.158	0.032	0.01407	0.00509	2.76061	0.2006
0.172	0.039	0.01744	0.00680	2.56613	0.2431
0.184	0.045	0.02053	0.00837	2.45201	0.2794
0.194	0.049	0.02335	0.00970	2.40742	0.3081
0.200	0.053	0.02536	0.01081	2.34575	0.3313
0.203	0.055	0.02632	0.01143	2.30312	0.3438
0.209	0.059	0.02834	0.01273	2.22651	0.3694

TABLE 4.16
MODEL 4 FOR DIFFERENT HEIGHT OF LABYRINTH WALL
(P=14 CM)

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.053	0.007	0.00090	0.00054	1.66183	0.0514
0.083	0.011	0.00278	0.00105	2.64693	0.0800
0.106	0.017	0.00519	0.00203	2.55012	0.1243
0.127	0.023	0.00813	0.00315	2.58072	0.1664
0.146	0.030	0.01152	0.00467	2.46657	0.2164
0.158	0.036	0.01398	0.00593	2.35867	0.2536
0.170	0.041	0.01689	0.00735	2.29650	0.2929
0.181	0.046	0.01987	0.00880	2.25814	0.3300
0.189	0.051	0.02207	0.01017	2.16943	0.3636
0.196	0.055	0.02417	0.01155	2.09220	0.3957
0.204	0.064	0.02664	0.01421	1.87504	0.4543

TABLE 4.17
MODEL 4 FOR DIFFERENT HEIGHT OF LABYRINTH WALL
(P=12 CM)

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r = Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.043	0.005	0.00054	0.00034	1.57150	0.0442
0.071	0.009	0.00189	0.00078	2.41836	0.0767
0.101	0.016	0.00464	0.00183	2.54064	0.1350
0.123	0.023	0.00758	0.00307	2.46976	0.1908
0.141	0.029	0.01064	0.00447	2.38207	0.2450
0.153	0.034	0.01306	0.00555	2.35215	0.2833
0.166	0.040	0.01599	0.00711	2.24716	0.3342
0.177	0.045	0.01863	0.00851	2.18836	0.3767
0.184	0.050	0.02061	0.00987	2.08739	0.4158
0.191	0.053	0.02248	0.01090	2.06223	0.4442
0.210	0.068	0.02847	0.01554	1.83284	0.5625

TABLE 4.18
MODEL 4 FOR DIFFERENT HEIGHT OF LABYRINTH WALL
(P=10 CM)

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m^3/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g}\, B.h^{3/2}$ (m^3/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge $r=Q_L/Q_N$	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.038	0.007	0.00040	0.00046	0.86509	0.0650
0.082	0.013	0.00276	0.00136	2.03311	0.1330
0.100	0.018	0.00444	0.00218	2.04015	0.1820
0.110	0.021	0.00566	0.00272	2.08546	0.2110
0.123	0.026	0.00758	0.00365	2.07734	0.2570
0.136	0.030	0.00961	0.00465	2.06804	0.3020
0.150	0.036	0.01241	0.00615	2.01774	0.3640
0.165	0.044	0.01568	0.00829	1.89128	0.4440
0.175	0.049	0.01806	0.00970	1.86192	0.4930
0.182	0.053	0.02006	0.01090	1.83994	0.5330
0.211	0.071	0.02902	0.01687	1.72070	0.7130

TABLE 4.19
MODEL 4 FOR DIFFERENT HEIGHT OF LABYRINTH WALL
[STEPPED FILLING, P=16 cm]

V-notch (H) in (meter)	Linear Weir (h) in (meter)	Labyrinth Discharge $Q_L = \frac{8}{15} C_d \sqrt{2g} \times (\tan\theta/2) H^{5/2}$ (m³/s)	Linear Weir Discharge $Q_N = \frac{2}{3} C_d \sqrt{2g} B.h^{3/2}$ (m³/s)	Ratio of Labyrinth Discharge and Linear Weir Discharge r=Q_L/Q_N	Ratio of Head over crest and height of Labyrinth wall (h/p)
0.064	0.010	0.00147	0.00085	1.74224	0.0606
0.099	0.017	0.00438	0.00202	2.17388	0.1081
0.114	0.022	0.00617	0.00291	2.11825	0.1381
0.134	0.029	0.00925	0.00447	2.07069	0.1838
0.145	0.035	0.01129	0.00573	1.97150	0.2169
0.163	0.044	0.01527	0.00820	1.86178	0.2756
0.173	0.049	0.01752	0.00961	1.82305	0.3063
0.178	0.054	0.01895	0.01124	1.68567	0.3400
0.190	0.060	0.02230	0.01302	1.71308	0.3750
0.200	0.066	0.02542	0.01506	1.68841	0.4131
0.206	0.070	0.02733	0.01634	1.67314	0.4363

Table 4.20 (a)

Table : Comparison of Results of 'L/W' Vs 'r' For Different Models

Sl. No.	Model No.	L/W ratio	$r=Q_L/Q_N$								
			Empty			Half Filled			Fully Filled		
			Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum
1.	1	3.38	3.23	2.79	2.41	3.22	2.65	2.16	3.07	2.61	2.26
2.	2	3.43	2.27	2.08	1.22	2.28	2.14	1.85	2.09	1.99	1.72
3	3	3.59	2.21	1.84	0.56	2.17	1.91	0.57	2.07	1.82	0.52
4	4	3.01	2.50	2.33	2.01	2.42	2.18	1.61	3.10	2.38	1.94
5	5	3.30	3.47	2.93	1.84	3.38	2.99	2.52	3.16	2.61	2.22
6	4 with p= 0.14 meter	3.01	2.64	2.26	1.66	-	-	-	-	-	-
7.	4 with p=0.12 meter	3.01	2.54	2.19	1.57	-	-	-	-	-	-
8.	4 with p=0.10 meter	3.01	2.08	1.86	0.86	-	-	-	-	-	-
9.	4 with stepped filling	3.01	2.17	1.86	1.67	-	-	-	-	-	-

TABLE 4.20(b)

Comparison Of Results For Different Models For h/p = 0.35

Model No.	p (in m)	r (Empty)	r (Half filled)
1	0.16	2.45	**2.41**
2	0.16	2.16	2.13
3	0.16	2.2	2.15
4	0.16	2.1	2.07
5	0.16	2.5	**2.48**
4	0.14	2.2	
4	0.12	2.22	
4	0.10	2.05	

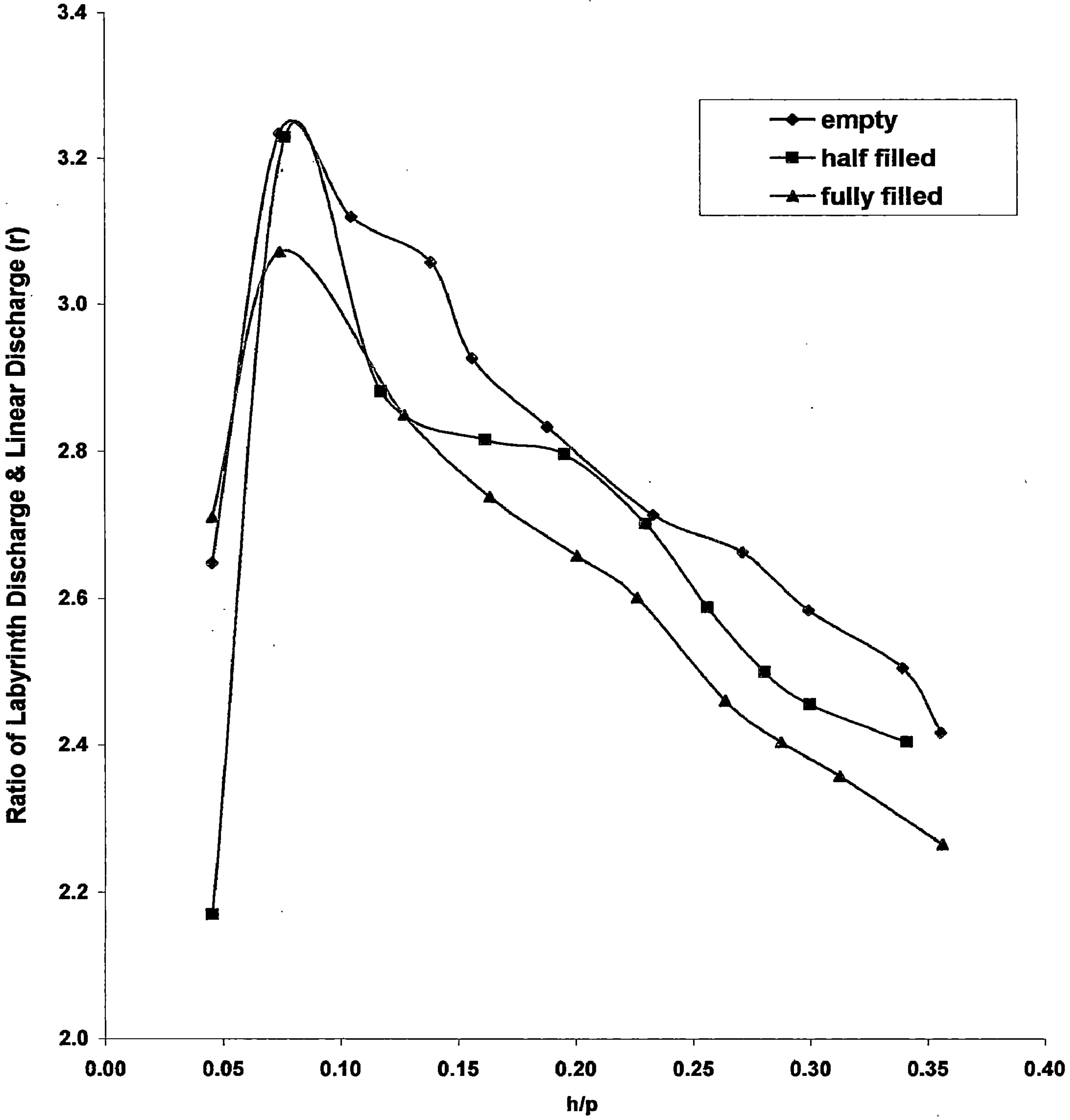


Fig. 4.3 (Plot between r and h/p for Model 1)

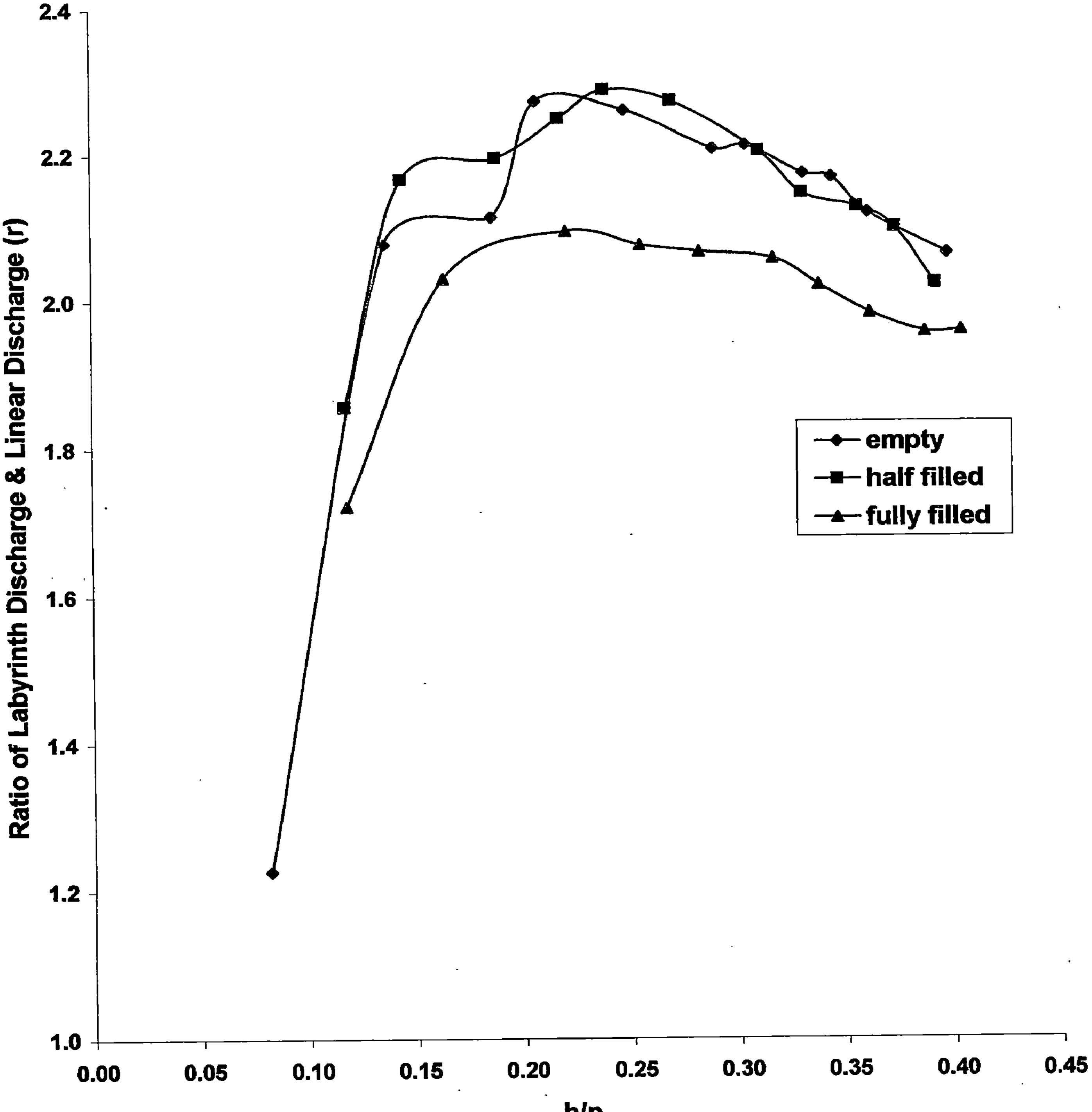


Fig. 4.4 (Plot between r and h/p for Model 2)

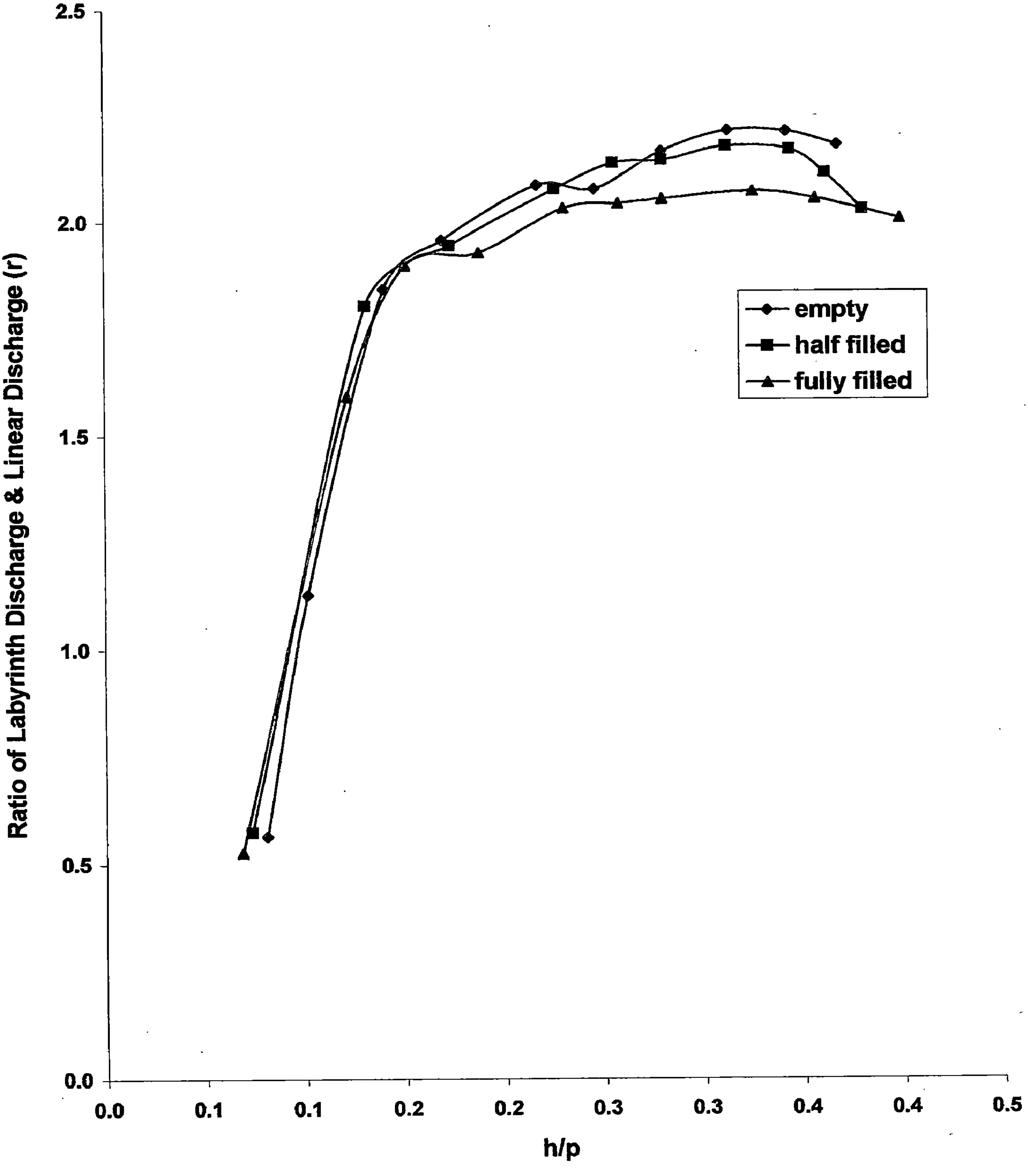


Fig. 4.5 (Plot between r and h/p Model 3)

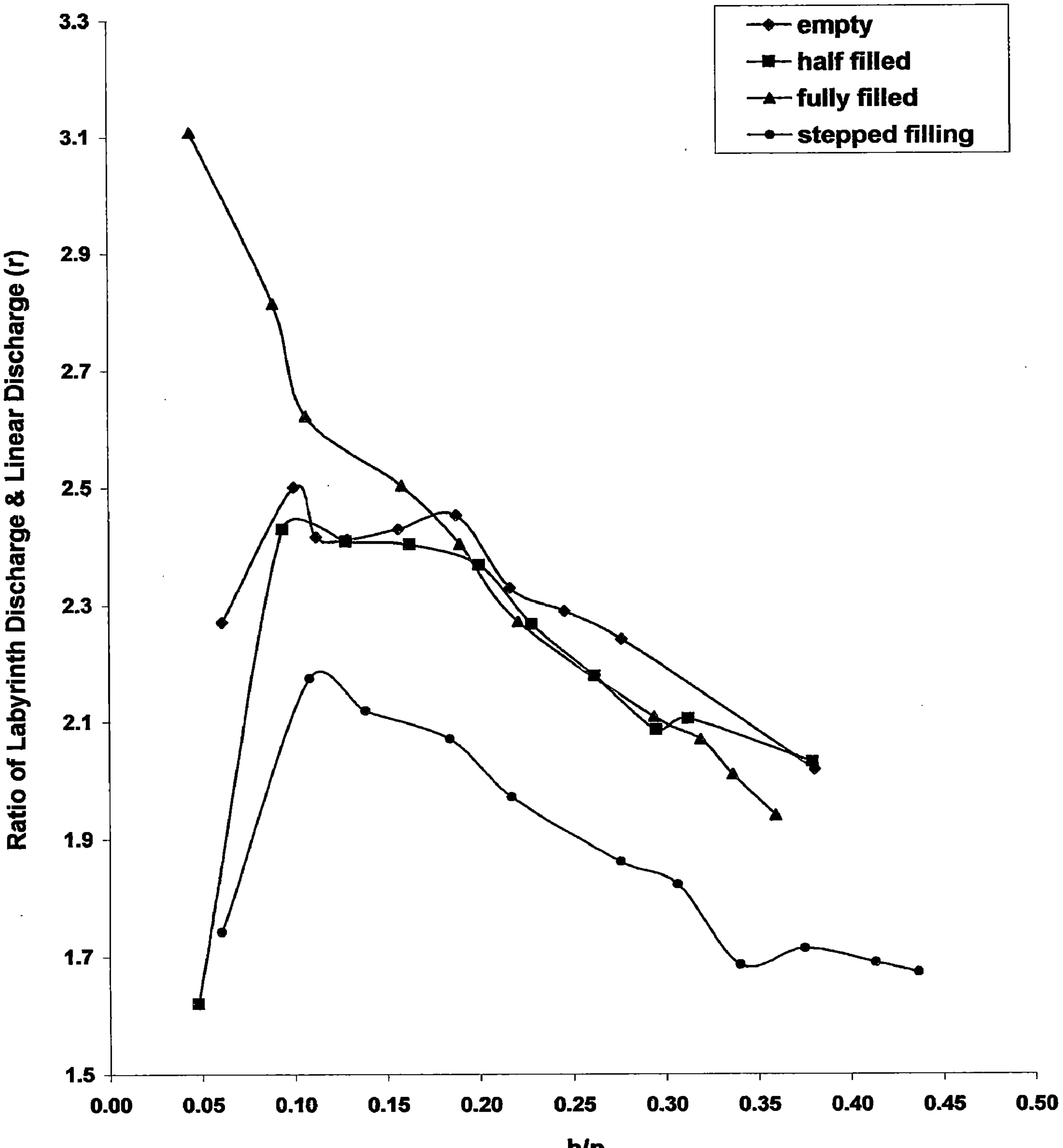


Fig. 4.6 (Plot between r and h/p for Model 4)

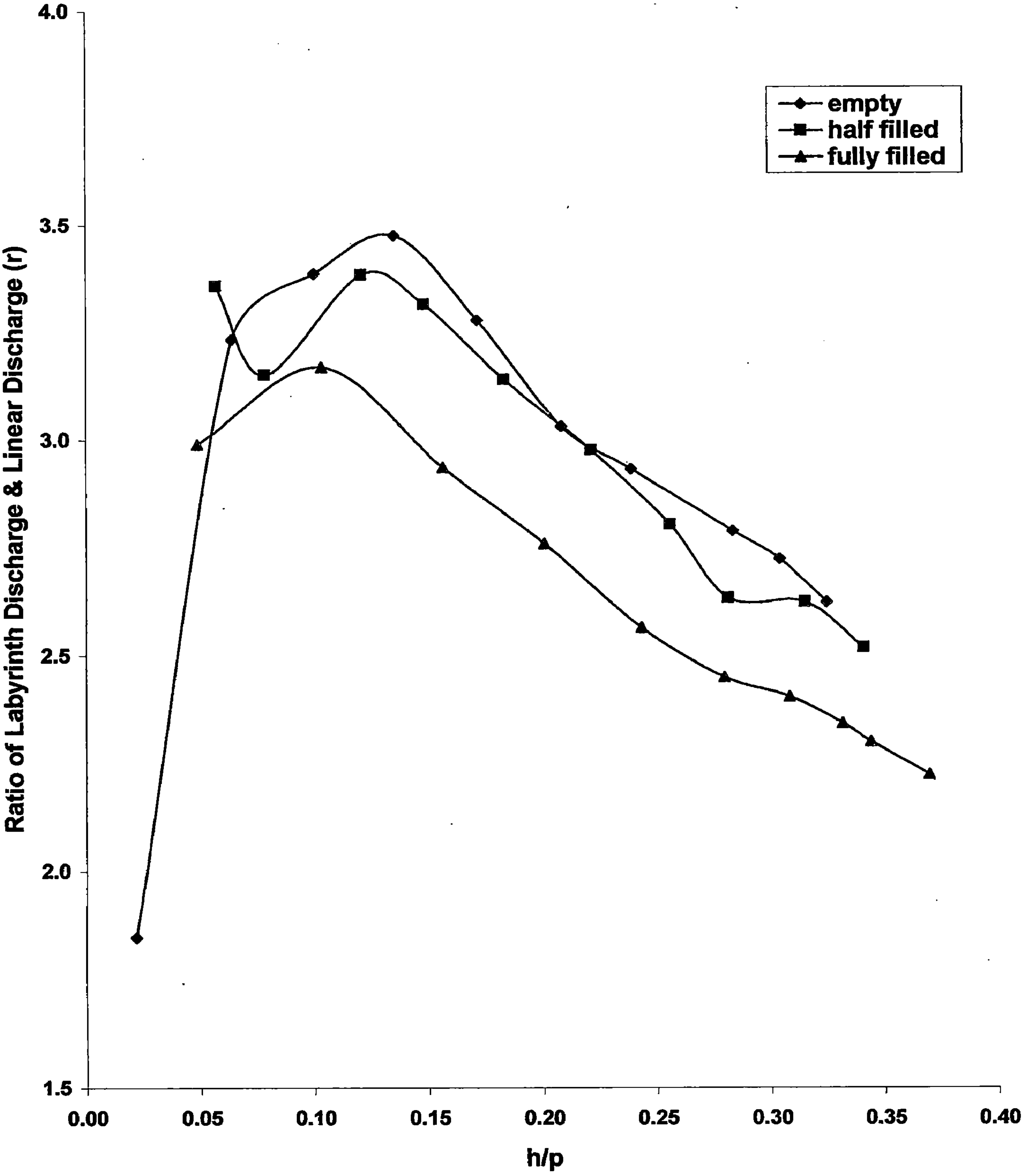


Fig. 4.7 (Plot between r and h/p for Model 5)

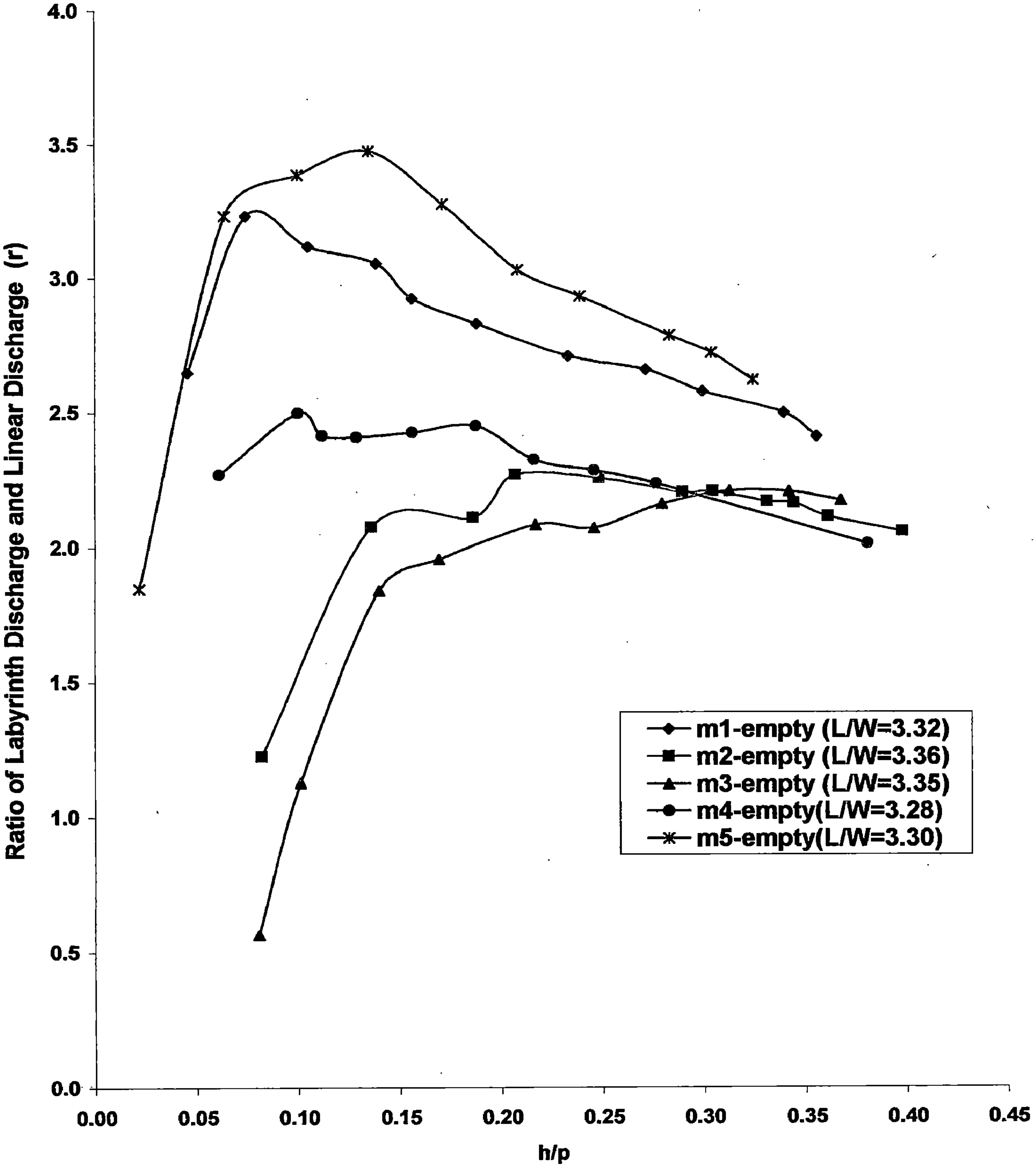


Fig. 4.8 (Plot between r and h/p for different length magnification ratio)

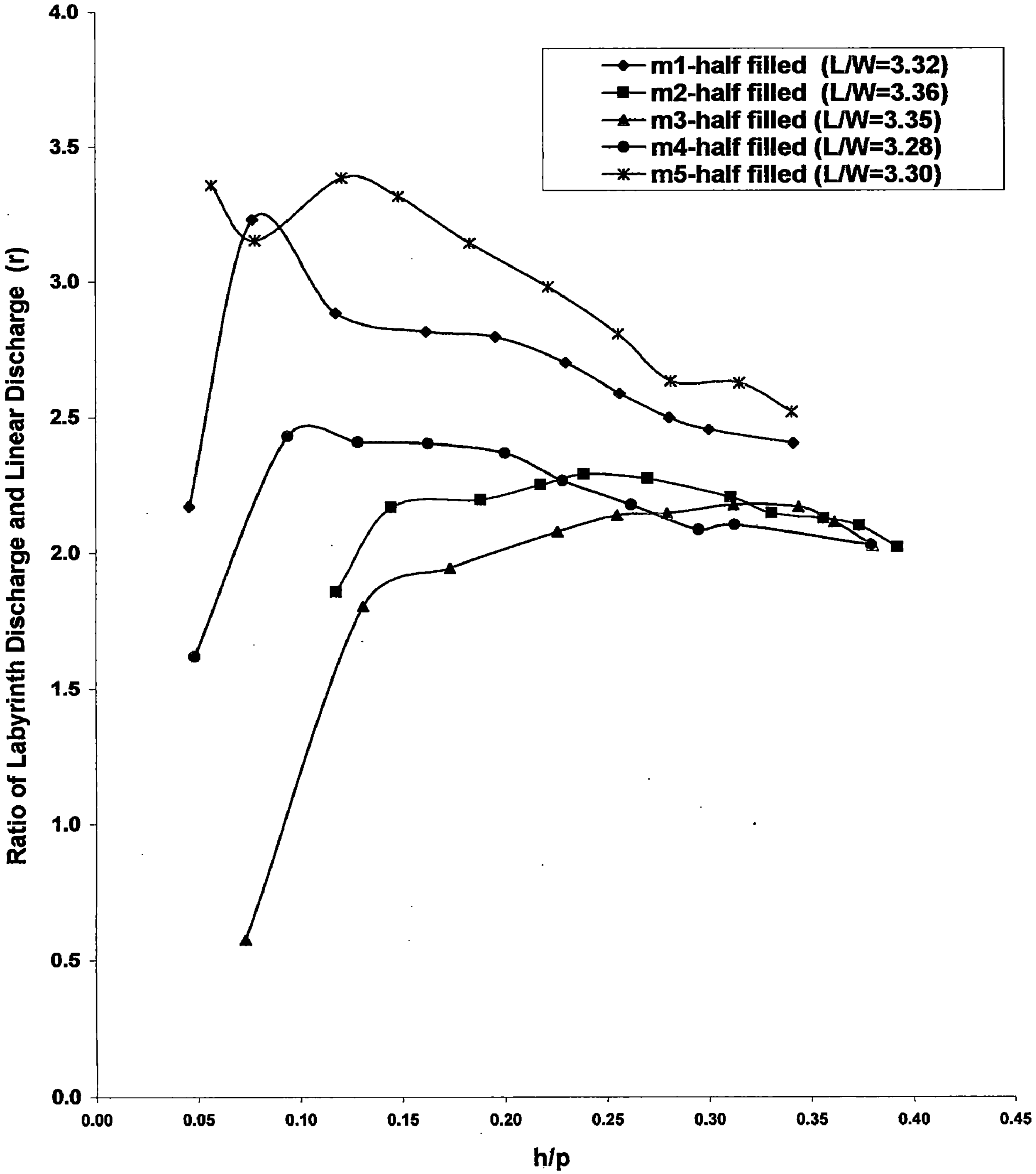


Fig. 4.9 (Plot between r and h/p for different length magnification ratio)

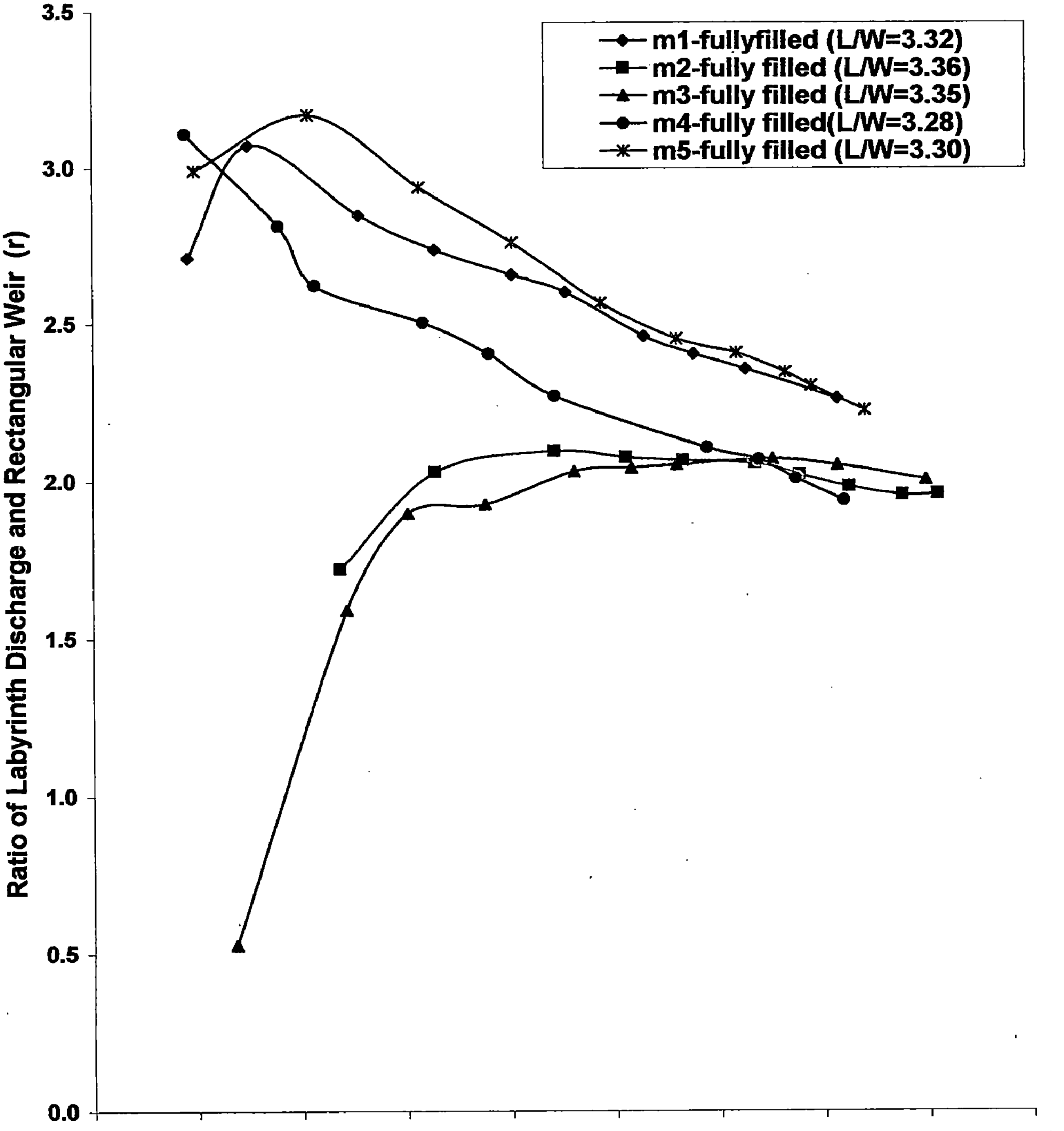


Fig. 4.10 (Plot between r and h/p for different length magnification ratio)

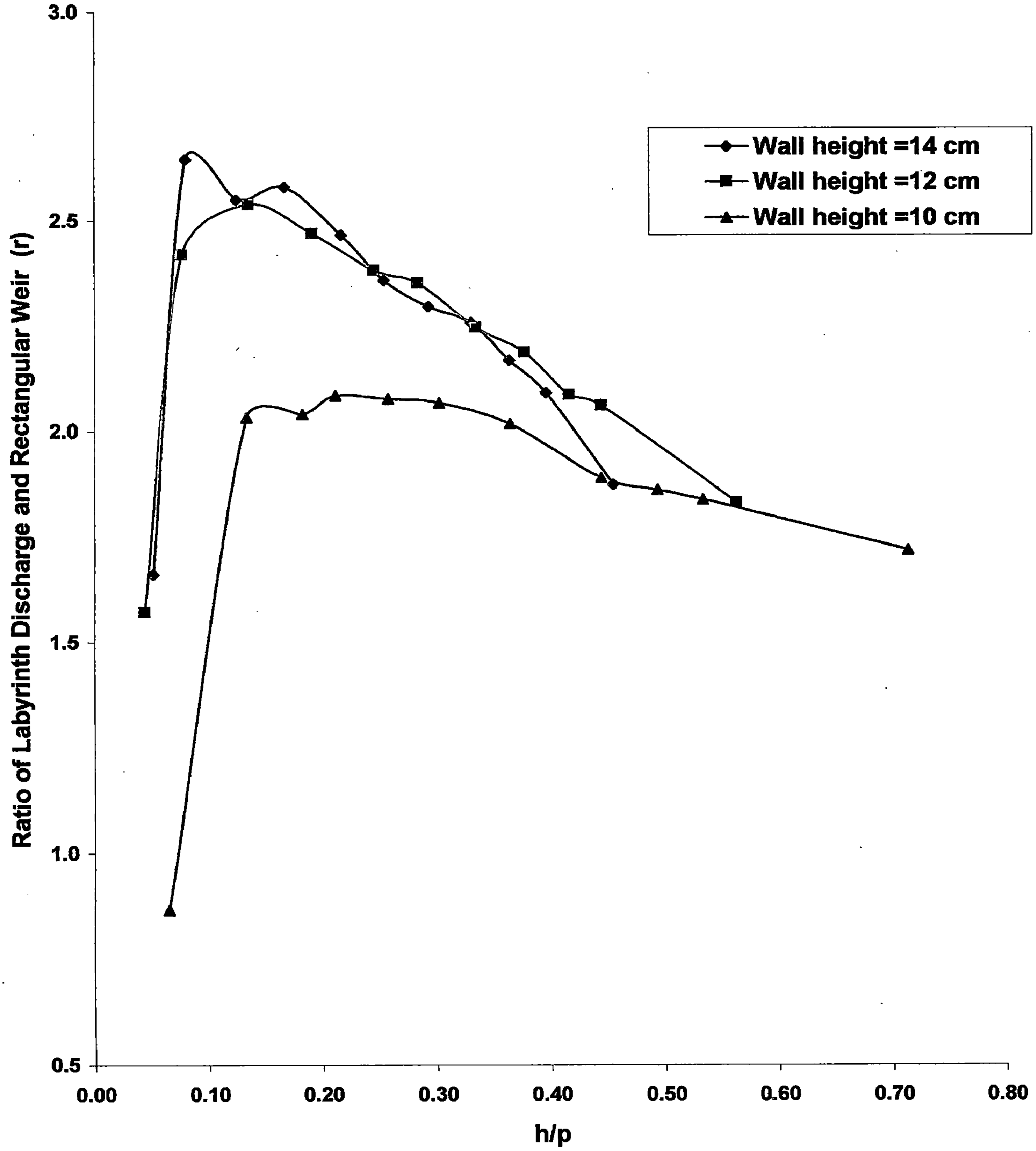


Fig. 4.11 (Plot between r and h/p for different height of labyrinth wall for Model 4)

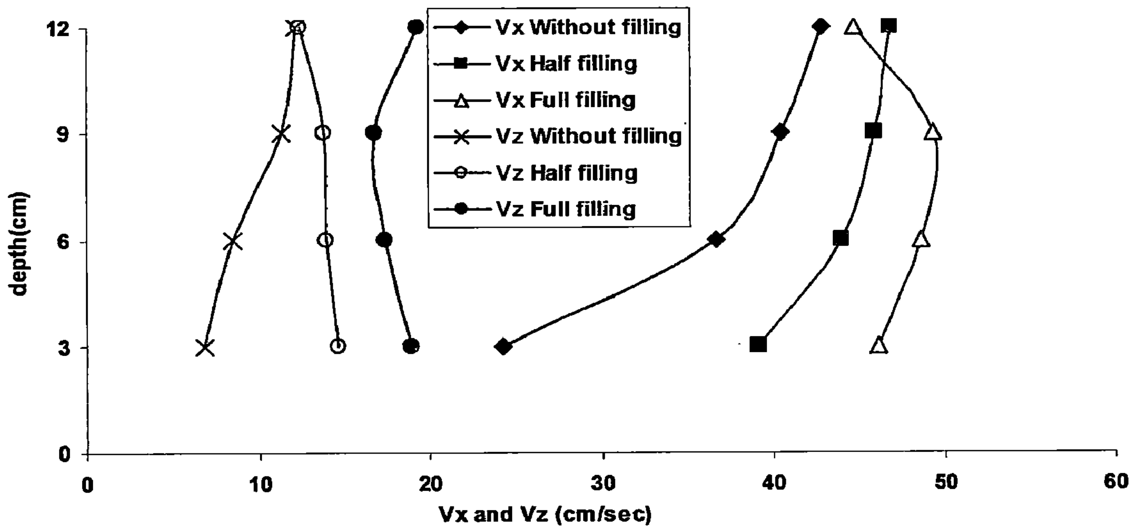


Fig. 12 VARIATION OF Vx & Vz WITH DEPTH

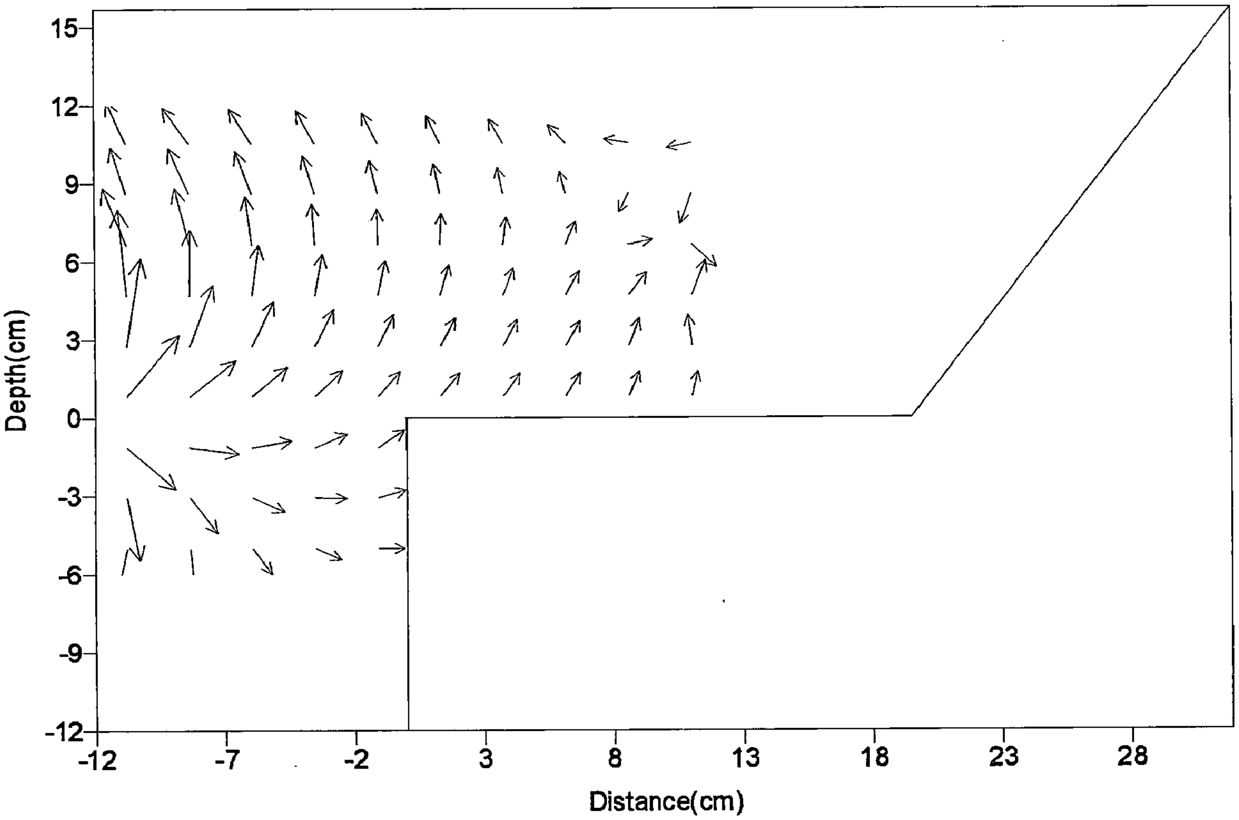


Fig. 4.13 Velocity vector plot along the centre line of Labyrinth weir streamwise

4.2 RESULTS AND DISCUSSION

The Graphical Representation between 'r' and (h/p) for model m_1 is shown in fig. (4.3The variation of labyrinth effect shows the different patterns with different ranges of (h/p). Graphical pattern shows the following points.

- For empty case labyrinth effect is initially increases upto certain limit of (h/p) value and beyond that value, the effect is continuously decrease.
- The half filled case shows both (increasing and decreasing) trends in different ranges of (h/p). In certain range (around h/p=.2), the hydraulic performance of half filled in some as the empty case.
- Fully filled case shows the almost same trend of labyrinth effect as the empty case shows.
- As per the hydraulic performance of Labyrinth weir, empty case seems to the better option.
- As the higher value of (h/p), all three cases seems to be converging but it required further experiments to reach on any definite conclusion.

Fig. 4.4 shows the variation of r Vs (h/p) for model M2. The variation of r shows that the labyrinth effect of half filled case is hydraulically best upto (h/p) ratio is about '0.3'. After that empty case leads but for very small range of (h/p). Fully filled is still the weakest choice. Even for the value of (h/p) less that 0.15, half filled case performed better. So the half filled for M2 model seems to be the best choice for lower to medium head.

Fig. 4.5 for M3 model shows a slightly different pattern of achieving highest value of 'r'. As in the model M1 and M2, the highest value of 'r' is obtained at (h/p) is equal to around 0.15 and 0.20 respectfully but in case of M3 it is obtained at (h/p) value is equal to around (0.3 to 0.35). For this model the half filled case performed batter for (h/p) value less than around '2'. Beyond that, empty case performed better except certain narrow range of (h/p).

Fig. 4.6 for model M4 shows better performance of empty case for medium (h/p) value and fully filled for lower value of (h/p). One extra steady for stepped filling shows a very week option.

Fig. 4.7 for model M5 also shows the better performance for empty case 'r' value for half filled case in almost equal to 'r' value for empty case at the (h/p) value is equal to around '0.20'.

In all 5 model, empty case and half filled case shows the almost equal Labyrinth effect at (h/p) value around '0.2'.

Fig. 4.8,4.9 & 4.10 has been plotted to study the effect of length magnification ratio (L/W), and shape of labyrinth weir. Results obtained from this graph is

- Model –M5 having parabolic nose performed best.
- There is a significant effect of (L/W) on hydraulic performance of Labyrinth weir.

Fig. 4.11 shows the effect of height of Labyrinth wall on the hydraulic performance of Labyrinth weir. For lower to medium (h/p) value, higher value of wall heights gives the better hydraulic performance. But at higher value of (h/p), effect of wall height seems to be disappear.

That It could be observed that filling of labyrinth element by cement mortar affects the hydraulic performance of labyrinth weir, as can be seen in Fig.s 4.3 to 4.7 and Fig. 4.5. The probable reason behind this can be sumrised as stated below. The above modification causes reduction in overflow rate in mortar filled case for as the flow approaches the brink of slanting face, the streamline bends smoothly (in case of filling) in reverse direction as shown by velocity vector plot of ADV measurements in Fig.4.13. The vortex roller shifts from bottom to top which causes reduction in velocity beyond the crest of mortar filled labyrinth weir in longitudinal direction and thereby ultimately overflow rate is reduced.

That Cement mortar filling in elements of the labyrinth weir hampers the labyrinth effect as shown in the Fig.s 4.3-4.7. Amongst the three cases under study-without filling or empty, half filled and full filled, the hydraulic performance of partial or half filled case is better than fully filled case. It could also be seen that the hydraulic performance of half filled case tends to approach the empty case (which is the best condition) as (h/p) value registers an increment. However, as can be seen from Fig. 4.7, the difference between half-filled and the empty (without filling) cases become insignificant probably because of parabolic upstream nose and rounded crest of M5 model which have reduced the flow separation and the jet interference effects.

Increase in velocities occurs ahead of the crest which creates more force, but beyond the crest, reduction in velocity due to filling hampers the hydraulic performance of labyrinth. That is why without filling empty case is hydraulically most efficient. This fact could be inferred from a perusal of the plots between ratio 'r' and h/p of the experiments vide Figs. 4.3-4.10.

That the plots of experimental data of 'r' Vs 'h/p' vide Figs. 4.8, 4.9 and 4.10 for different values of 'L/W' have indicated that the hydraulic performance of the labyrinth weir is quite sensitive to the variation of Length Magnification Ratio (L/W) especially in the lower ranges of h/p ratio. However prima facie it seems that better hydraulic performance of the labyrinth weir does not depends on L/W ratio alone, but also on the relative dimensions of 'b and 'c' vide Fig. 3(a). This aspect, however, needs more elaborate experimentations for the shapes under consideration to arrive at a firm conclusion on the above.

That Using the velocity obtained by ADV, water current force per unit width (1/2 KV^2H) is computed which is very much less than the hydrostatic force (1/2 Y_wH^2) operational on the labyrinth wall. Clearly as already stated, hydrostatic force is the dominating force (which is constant for all cases i.e. half filled, fully filled and empty). Water current force is thus insignificant compared to hydrostatic force.

From plot of 3-D ADV measurements for Model M1 vide Fig. 4.12, it can be seen that longitudinal velocity for without filling case V_x increases rapidly near the bed and then increases gradually with respect to depth of flow. With half and full filling cases, V_x registers increase by and large with respect to flow depth. In half filling case, V_x increases by 80% and in full-filling case by 100% than the without filling case near the bed. These variations are indicative of the effect of partial and full filling of mortar on V_x.

That as regards the variation of vertical velocity component V_z, there is an increase of about 150% in half filling case and 200% in fully filling case when compared to without filling case of the elements near the bed. In comparison to V_x, the variation of

V_z could be found to be insensitive to flow depth when considered separately in Fig. 4.12(b).

. That the velocity vector plot developed from the aforesaid ADV measurements is shown at Fig. 4.13. In this plot, the origin (0,0) has been taken at the centre point at the plan of the element as shown. The incipient trend of formation of a vortex lapping up near the slanting face could be discernible from the afore said velocity vector plot.

That Half filled case appears to be a better solution in the context of robust structural design and hydraulic performance with respect to other two cases as can be observed from the graphical plots of 'r' Vs 'h/p' at Figs 4.3-4.7. However, the best hydraulic performance is demonstrated by Model 5 without filling or empty case as seen in Figs. 4.7 and 4.8.

That as observed in Fig.s 4.3-4.7, relatively Model 5 has attained better performance, than the similar dimensioned model 4 with triangular upstream nose. Apparently due to introduction of smooth parabolic upstream nose along with rounded crest. Due to these shape modifications made in the Model M5, the flow separation and collision of jet phenomena have been impeded, thereby facilitating its better performance.

That the study on the effect of different labyrinth wall heights indicated that the reduction of height of the labyrinth wall affects labyrinth behavior upto an upper limit of 0.5 for h/p ratio as shown in the Fig. 4.11. But even at low wall height, labyrinth effect is fairly good. This finding is significant in the context that the reduced height of labyrinth walls could be advantageously used for high specific flows with still retaining the advantage of high discharging capacity of labyrinth weir.

That to facilitate the analysis of the experimental results from the standpoint of labyrinth behaviour for relatively higher ranges of discharge, a qualitative study on the photographic representation of experimental flow condition vis-à-vis the concerned parameters of L/W , h/p and 'r' was made and the highlights are discussed below.

That these photographic representations portray the implicit relationship between h/p and 'r' and vividly depiots increasing trend of labyrinth behaviour upto a certain upper limit of h/p, beyond which there is a continuously decreasing pattern as also graphically seen from Fig. 4.3 to 4.10.

From the present experimental study, it could be clearly observed that even at relatively increasing discharge ranges represented by h/p, there is sufficiently good labyrinth behaviour. Furthermore, it can be seen from the photographic representation (Photo no. 4.1 to 4.9) that notwithstanding apparently visible greater interaction and collision of falling jets, the labyrinth effect is fairly good.

The performance results obtained from the present experimental study for all the models for the same h/p ratio are presented at a glance is Table 4.20(a) and (b) to highlight the supremacy of deploying labyrinth spillways over the conventional linear spillways with regard the discharging capacity.

$$\frac{L}{W} = 3.28, \quad \frac{h}{p} = 0.18, \quad r = 2.45$$

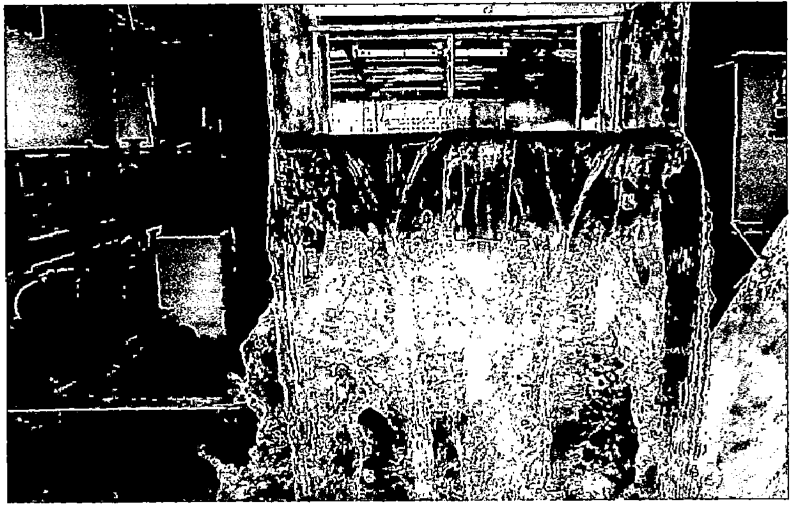


Photo No. 4.1 – Model -4 (Without Mortar Filling)

$$\frac{L}{W} = 3.28, \quad \frac{h}{p} = 0.21, \quad r = 2.32$$

Photo No. 4.2 – Model -4 (Without Mortar Filling)

$\frac{L}{W} = 3.28, \quad \frac{h}{p} = 0.24, \quad r = 2.28$

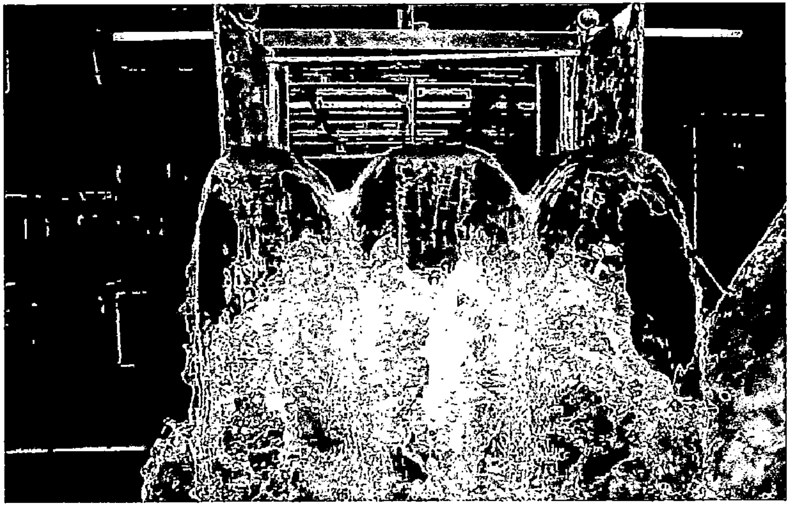


Photo No. 4.3 – Model -4 (Without Mortar Filling)

$\frac{L}{W} = 3.28, \quad \frac{h}{p} = 0.27, \quad r = 2.24$

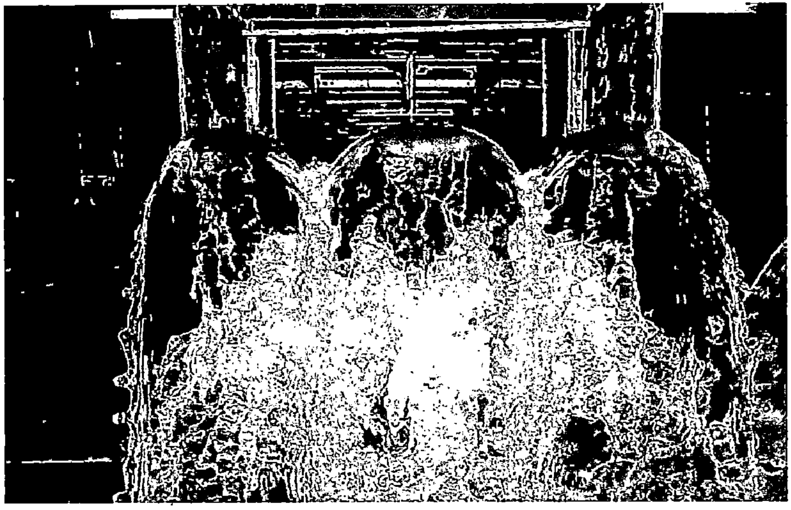


Photo No. 4.4 – Model -4 (Without Mortar Filling)

$\frac{L}{W} = 3.28, \quad \frac{h}{p} = 0.35, \quad r = 2.1$

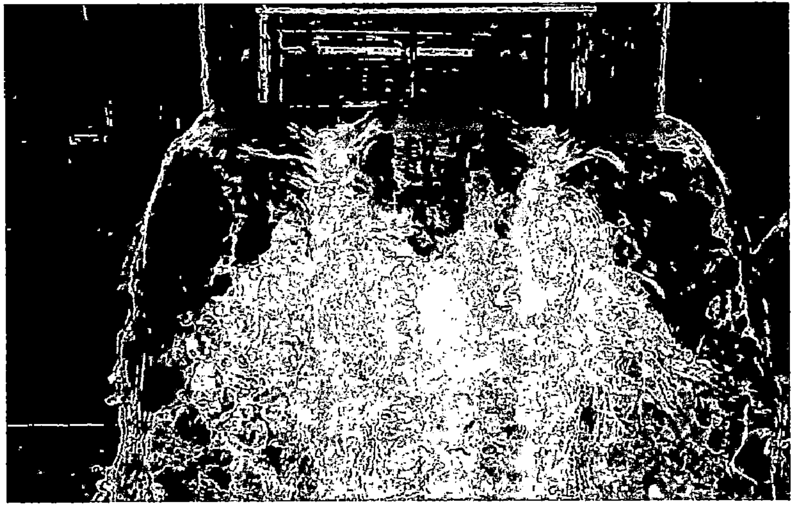


Photo No. 4.5 – Model -4 (Without Mortar Filling)

$\frac{L}{W} = 3.30, \quad \frac{h}{p} = 0.23, \quad r = 2.93$

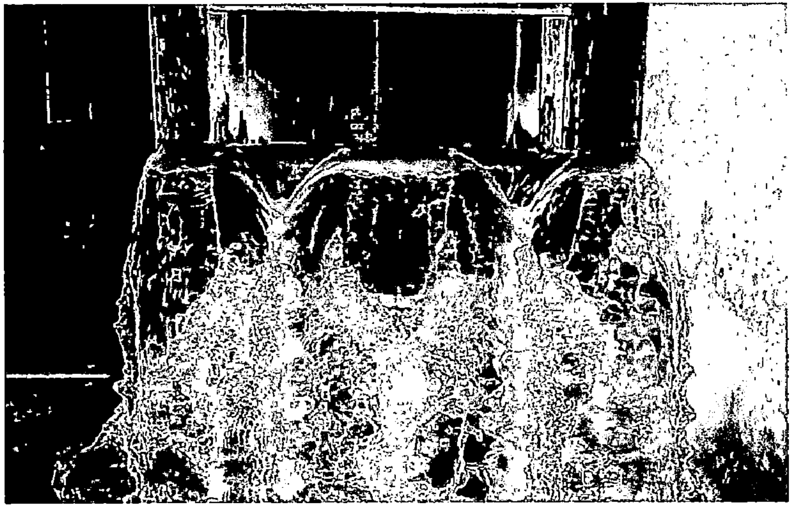


Photo No. 4.6 – Model -5 (Without Mortar Filling)

$\frac{L}{W} = 3.30, \quad \frac{h}{p} = 0.30, \quad r = 2.72$

Photo No. 4.7 – Model -5 (Without Mortar Filling)

$\frac{L}{W} = 3.30, \quad \frac{h}{p} = 0.35, \quad r = 2.5$

Photo No. 4.8 – Model -5 (Without Mortar Filling)

$\frac{L}{W} = 3.30, \qquad \frac{h}{p} = 0.35, \qquad r = 2.5$

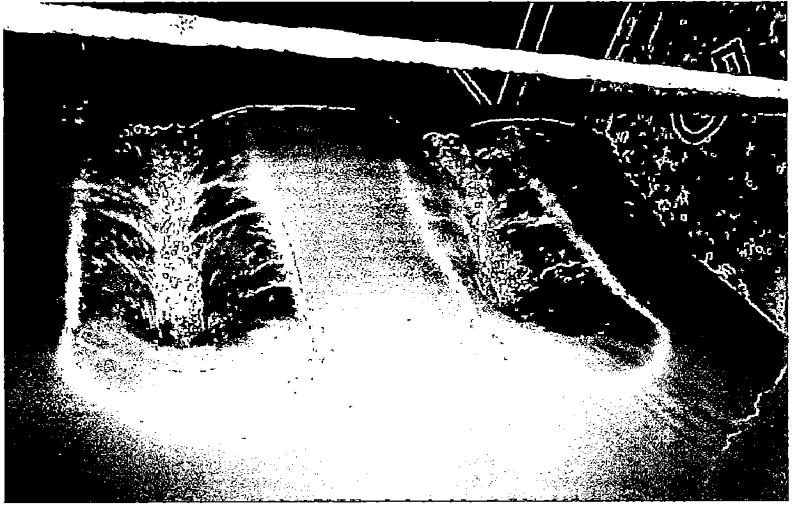


Photo No. 4.9 – Model -5 (Without Mortar Filling)

5.1 CONCLUSIONS

On the basis of the present experimental study with different flows for the shapes of the labyrinth weir under investigation, the following significant conclusions have emerged.

1. The partial or half-filling with cement mortar of the elements of the labyrinth appears to be a better solution keeping in view the consideration of structural design, as well as good hydraulic performance in comparison to without and full-filling cases. However, with the introduction of smooth parabolic shape to the upstream nose and rounding of the crest of the labyrinth wall of models 5, hydraulic performance has registered considerable enhancement as evident from the resulting rise in the value of ratio 'r' to the level of four to five. This enhancement is significant to the maximum 'r' value attained around three in the cases of triangular nose with different L/W ratios.
2. From the graphical plots of non-dimensional ratios 'r' Vs 'h/p', it can be seen that the labyrinth effect exhibits an increasing trend with rise in the ratio of h/p upto a certain upper limit, beyond which the labyrinth effect apparently displays a continuously decaying behaviour.
3. From a close examination of the photographic representation of the falling nappe with the experimental results, significant labyrinth effect can be seen to prevail for the shapes under study even at higher values of h/p, notwithstanding prevalence of apparent visual signs of falling jet interference.
4. These model tests have indicated that it is possible to place efficient labyrinth weir on top of traditional gravity dam sections to significantly enhance their discharging capacity.
5. The experimental results of the labyrinth shapes under consideration have demonstrated the potentiality of increasing the discharge passing capacity to two to three times the capacity of traditional linear spillways.
6. The model tests have shown that the labyrinth behaviour is sensitive to reduction in the wall height upto an upper limit of 0.5 for h/p ratio. However, the results of model tests have demonstrated that even the low labyrinth wall height could be advantageously used for the high specific flow ranges by

approximately at the least doubling the discharging capacity as compared to the traditional weir.

7. The findings of this study are quite promising enough to warrant further experimentations for potential application of the labyrinth spillways for dam safety primarily in India in view of the looming adverse hydrological consequences due to global warming phenomenon. More experimental study with high values of h/p case to unity to supplement the present effort from both structural and hydraulic stand points will give the optimized shape and size of the labyrinth weir models and enable preparation of standardized designs encompassing the entire possible flow ranges.

5.2 SCOPE OF FUTURE STUDY

1. The construction of models with more improved shapes is required to further investigate the optimization of the labyrinth models.
2. There is need to under take more elaborate experimentations to obtain broad based solutions for the higher range of discharge.

REFERENCES

1. Blanc, P. and Lemperiere, F. (2001), "Labyrinth spillways have a promising future", Hydropower & Dams, Issue Four.
2. Darvas, L. A. (1971), "Performance and Design of Labyrinth weirs-Discussion", Journal of Hydraulics Division, ASCE, Vol. 97, No. 8, pp 1246-1251.
3. Hay, N. and G. Tayor (1970), "Performance and Design of labyrinth weirs" Journal of the Hydraulics Division, ASCE, Vol. 96, No.11, pp 2337-2357.
4. IS. 3955-1967 Indian Code of Practice of Design and Construction of Well Foundations.
5. Lux III, Frederick and Hinchliff, D. L. (1998), "Design and construction of labyrinth spillways", CIGB 15th Congress, Lausanne, 1985 Cassidy, John J., Gardner, Christopher A., and Peacock, Robert T., "Boardman Labyrinth-Crest Spillway", Journal of Hydraulic Engineering, , ASCE , Vol. 111, No. 3.
6. Magalhaes, ~~Alberto Pinto;~~ "Labyrinth –weir spillway", CIGB 15th Congress, Lausanne, 1985.
7. Modi, P. N. and Seth, S. N. (1982), "Hydraulics and Fluid Mechanics" Standard Book House, Nai Sarak; Delhi.
8. Tullis, J. ~~Paul,~~ Amanian N. and Waldron, Da~~vid~~(1995), "Design of Labyrinth Sillways", Journal of Hydraulic Engineering, ASCE Vol. 121, No. 3.
9. Yildiz, D. and Uzucek, E. (1996), "Modelling the performance of labyrinth spillways", Hydropower & Dams, Issue Three.
10. Parkash S., Ranjan G. and Saran S.(1979), "Analysis and Design of Foundations and Retaining Structures, Sarita Prakashan, New Delhi.