DEPARTMENT OF CIVIL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, (Divakar, Roll No. 2K17/HFE/07, M.Tech (Hydraulics and Water Resources Engineering), hereby declare that the project Dissertation titled "Experimental Study of Labyrinth Weir" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or any other similar title or recognition.

Place: Delhi **(DIVAKAR)**

Date:

DEPARTMENT OF CIVIL ENGINEERING

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CERTIFICATE

I hereby certify that the Project Dissertation titled “Experimental Study of Labyrinth Weir” which is submitted by Divakar, 2K17/HFE/07, Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date:

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I extend my gratitude to my college, Delhi Technological University (formerly Delhi College of Engineering) for giving me the opportunity to carry out this project.

This opportunity will be a significant milestone in my career development. I will strive to use the gained skills and knowledge in the best possible way, and I will continue to work on their improvement, in order to attain desired career objectives.

DIVAKAR
2K17/HFE/07
M.TECH.

ABSTRACT

Labyrinth weir is an innovation in the field of construction of weirs. The different studies have presented their superiority in terms of flow regulation and increasing flow capacity, but the complex geometries the labyrinth brings is a problematic matter for construction. So, we wish to be sure that after such hard work in the construction, we must get the maximum efficiency from the structure built. There are many shapes available for labyrinth weir but most common shapes used are rectangular, triangular and trapezoidal. So, in this study these three shapes are used and their efficiency is compared by comparing their respective coefficient of discharges. Their inter dependence over the crest heights and their normal or inverted placements is also taken care of in this study.

The various methods that can be used are discussed in methodology and the method used in this study is given by Tullis and for the applicability of the method the ratio of height of water over weir to the crest height (H_t/P) is kept between 0.1 to 0.3 and the bed level is kept horizontal. The experiments are conducted on the 8m rectangular flume available in the DTU hydraulics laboratory.

The results are presented in tabular as well as graphical representations. The results suggested that the trapezoidal labyrinth weir can provide greater efficiency in comparison to its counterparts, and the same was hinted at in the literature review also so this also consolidates the experimental results.

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LIST OF SYMBOLS, ABBREVIATIONS

a	inside apex width
α	sidewall angle
B	length of apron in flow direction
C_d	coefficient of discharge
$C_{d\text{-}lux}$	Lux's discharge coefficient (1985)
D	outside apex with
g	acceleration due to gravity
H	design flow water surface elevation
H_t	head/ height of water above crest
k	apex shape constant
L	developed crest length
L_1	original length of side leg
L_2	effective length of side leg
L_{de}	effective length of disturbance
N	number of cycles
P	crest height of weir
Q	discharge
Q_{cycle}	discharge over single labyrinth cycle
Q_{LAB}	discharge over labyrinth weir
Q_{LIN}	discharge over linear weir
w	width of single labyrinth cycle

CHAPTER 1 INTRODUCTION

1.1 GENERAL

The management and conveyance of water plays a very significant role in the survival and development of any civilization. Over the ages, there have been efforts made to store the water at certain place for usage. The construction of dams and spillways is not new and many studies even relate the hydraulics engineering to the very first colonized civilizations. Also, over the time researches are being conducted to increase the output from these structures and as a result, many changes are there in comparison to older dams and modern dams. Weir is type of structure used to obstruct the flow, so can be used in the formation of ponds, and can be used as the flow control structures. In the case of weirs, the advancement has been done in the shapes used as the conventional linear weirs are fading in usage. One of the major advancement is Labyrinth Weir, which over the past few decades has made felt its presence in the field of water resources engineering due to its superiority over the linear weirs in many ways.

The performance of Labyrinth weir depends on many parameters, like the crest height, effective length, the side wall angles, apex ratio, and approach and down-stream conditions. Various crest shapes can also, and have been used, be installed. There are four basic options which are available for Labyrinth weir and also one new shape is emerging, so a total of five crest shapes are used at different weirs according to need viz. flat top, sharp crest, half-round, quarter round and Ogee type.

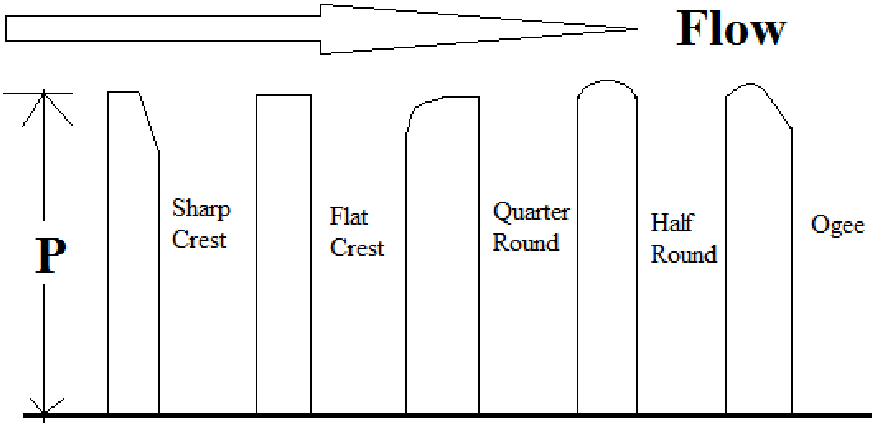

Fig. 1.1 Crest shape options for labyrinth Weir

The crest shape plays very important role in case the weir's performance is taken into consideration along with some major flow parameters like

i. Crest performance
ii. Nappe behavior
iii. Aeration
iv. Streamlines
v. Interference-phenomenon
vi. Shape and location
vii. Aspect ratio
viii. Down-stream conditions

The various studies on these factors have been discussed in the background and literature section of this dissertation.

1.2 TYPES OF WEIRS

1.2.1 ON THE BASIS OF GEOMETRY

1. Linear Weirs
2. Labyrinth Weirs
3. Piano key Weirs

1.2.2 ON THE BASIS OF SHAPE OF OPENING

1. Rectangular weirs
2. Triangular weirs
3. Trapezoidal weirs
4. Circular weirs

1.2.3 ON THE BASIS OF SHAPE OF CREST

1. Broad-crest weirs
2. Narrow-crest weirs
3. Sharp-crest weirs
4. Ogee type weirs

1.3 OBJECTIVES

The main objective of this study is to analyze the different shapes of labyrinth weir and to understand the phenomenon:

i. The variation of coefficient of discharge in different shapes, viz. rectangular, trapezoidal and triangular labyrinth weir.
ii. The dependence of coefficient of discharge on the position of weir, i.e., normal or inverted.
iii. The variation of discharge with respect to change in crest height.

To achieve these objectives, six models of labyrinth weirs having three shapes and different crest heights are used and are also placed in normal and inverted positions totaling the model count to twelve at five different discharges.

1.4 ORGANIZATION

The dissertation consists of background studies on labyrinth weirs followed by methodology, experimental setup, results and conclusions. In the background studies, special emphasis is given on the major factors on which performance of the labyrinth depends, in addition to the various developments over the time in the construction of the weir.

CHAPTER 2 LITERATURE REVIEW

2.1. GENERAL

Various features of the labyrinth weir are discussed in this chapter. This incorporates the advancement of the weir, different plan techniques and approaches, and the favorable circumstances and impediments related with the utilization of a labyrinth. The hydraulic performance of weir has also been dealt with in this chapter, various concepts of crest shape, crest performance, shape in plan form, negative atmospheric pressures and the nappe, interference-phenomenon, aeration and down-stream flow conditions are also discussed.

2.1.1. SPILLWAYS

An integral part of dam, spillway, is a kind of control structure generally kept normal to the direction of stream-flow. It performs various functions like, provides safety to the dam wall, checks down-stream flow, and majorly it protects dam from overtopping and probable failures during floods. The design of spillways is done in order to ensure the passage of excess water from the up-stream to down-stream in case of heavy floods the level of water crosses the full supply level (FSL), playing crucial role in preventing the erosion on the down-stream side caused by water. The energy head in the dam can make the water flow at very high speeds over the spillways, which is the major reason for the erosion on the down-stream side river banks. The additional need for the design of energy dissipaters and stilling basins comes to avoid the erosion.

SANCOLD (1991) classified the spillways in two major categories viz. service spillways and auxiliary spillways. Service spillway is major part designed for passage of normally or frequently occurring floods. Auxiliary spillway is safety measure provided for the passage of floods that exceeds the service spillway levels.

1. **Service Spillways** can be operated without providing the auxiliary spillway. Both gated and un-gated type of spillways can be used.

   Gated spillways provide greater control of down-stream flow and are effective in reducing the peak floods in case of early detection of floods. Un-gated spillways uses simple mechanism, hence are normally favored. In case of gated spillways, auxiliary spillways have to be provided to ensure the safety in case the electric or mechanical gate system fails.

2. **Auxiliary Spillways** are provided in addition to the service spillways for ensuring extra protection or can be used for flood outlets in small projects where service spillways are not used.

Sharma & Sharma (1992) discussed about the various types of spillways that are used generally. These are:

i. Free over-fall spillway
ii. Ogee (overflow) spillway;
iii. Chute spillway;
iv. Side channel spillway;
v. By-wash spillway;
vi. Piano key weir; and
vii. Labyrinth spillway.

The selection of these spillways depend upon various factors like, topography, geology, the hydrological parameters, type of dam and the maintenance and operation costs of the type of spillway used.

2.1.2. WEIRS

A weir is an artificial barrier in the direction of flow, used for the regulation of flow. It can also be used to control depth and in the measurement of discharge. Due to the presence of weir the up-stream water depth can increase, depending upon the flow conditions. The capacity of weir or spillway is the function of height of water over its crest and is referred in terms of discharge. The major functions of weir include:

- Water level management,
- Measurement of discharge,
- Creates an artificial pool which can be used for pumping water,
- Can be used as diversion structure,
- Environmental enhancement, and
- Channel stabilization.

2.1.3. DESCRIPTION OF LABYRINTH WEIR

Darvas (1971) studied the geometry of labyrinth weir and stated that a labyrinth weir can be seen as a linear weir folded in plan-view, like in Fig.2.1. The purpose of these folds is to increase effective length of flow over a fixed width of channel. Labyrinth weirs are proved to be economical in case of heavy floods, in comparison to normal weirs as they provide greater unit discharge.

Fig. 2.1 Raised labyrinth shape spillway at Dog River Dam, Georgia [1]

2.2. HISTORY OF LABYRINTH WEIR

Crookston (2010) stated that the labyrinth weir is comparatively complex and an innovation, so researches have been going on for a long time. Gentilini, 1940, tested making of triangular weirs by keeping close a number of inclined weirs. Three side angles of 30^0, 45^0, and 60^0 were kept for a sharp crested weir and the results came were the function of ratio of head to width of single cycle. Kozák and Sváb, 1961, found, that under similar heads, labyrinth weir provides higher discharge capacity, by testing flat-topped crested trapezoidal labyrinth.

Paxson *et al.*, (2011) stated that the previous researches prior to Taylor (1968) laid foundations for the development but they were in pieces and none of them could be used as a firm basis for the understanding. As a result, the modern development of labyrinth weir began from Hay & Taylor (1970). In 1985, the Bureau of Reclamation established a design method to use in the publication "Design and Construction of Labyrinth Spillways [**10**]". The basis of the concept was design curves, for estimating the discharges of sharp crested spillways and quarter round crested spillways, and **Tullis *et al.*, (1995)** further increased the research and developed the 'Tullis method' for estimation of discharge for trapezoidal labyrinth weir, used in this study.

Khode & Tembhurkar (2010) compared the two popular design methods viz. Lux and Tullis which have played a great role in the rapidly increase in adoption of labyrinth weirs and spillways over the last few decades. There also has been an increase in the requirements of spillways' capacities which has demanded the change in flood design requirement in order to meet the new design requirements [**14**]. It has been expressed that Falvey's distribution (Hydraulic Design of Labyrinth Spillways, 2003) likewise realized critical development in the utilization of the labyrinth by encouraging the learning base of labyrinth weirs through the mix of key productions and extra research.

There was a serious assessment by International Commission on Large Dams (ICOLD) which said that about one-third of total structural failures of large dams were because of the insufficient capacity of spillways. As a result, the design capacity requirements were adjusted and immediate upgrade of existing spillways was recommended. In view of keeping the new upgrades economical, structural engineers attempted reduction in the possible dimensions of new weirs with keeping in view the safety levels.

Ghare *et al.*, 2008, emphasized on the usage of labyrinth weir for future projects due to their inherent advantages inn regard of flow magnification and structural stability.

2.3. PROPERTIES OF LABYRINTH WEIRS

2.3.1. GENERAL

The major trademark property of a labyrinth weir is its ability to provide greater discharge for a given head, in comparison to conventional weirs [**13**]. For an increase in the discharge capacity in case of any present weir various factors can be adhered to viz., increase in length of flow, or increase the coefficient of discharge or a direct increase in the operating head, but due to the fixed width there is huge problem in increase of the width of weir also the head is difficult to increase, so, in those case the labyrinth weirs provide an effective solution [**8**]. And as these weirs are able to attain this adequately because of the expansion in capacity and the abatement in flood reduction under low stream conditions they are appropriate for the recovery of the pre-present structures [**6**]. There can be various geometrical arrangements that can be used for labyrinth weirs, but the three general cycle shapes which are widely used are; triangular, rectangular, and trapezoidal. By performing various tests it has been established that the rectangular shape gives least efficient results across a unit length [**1**].

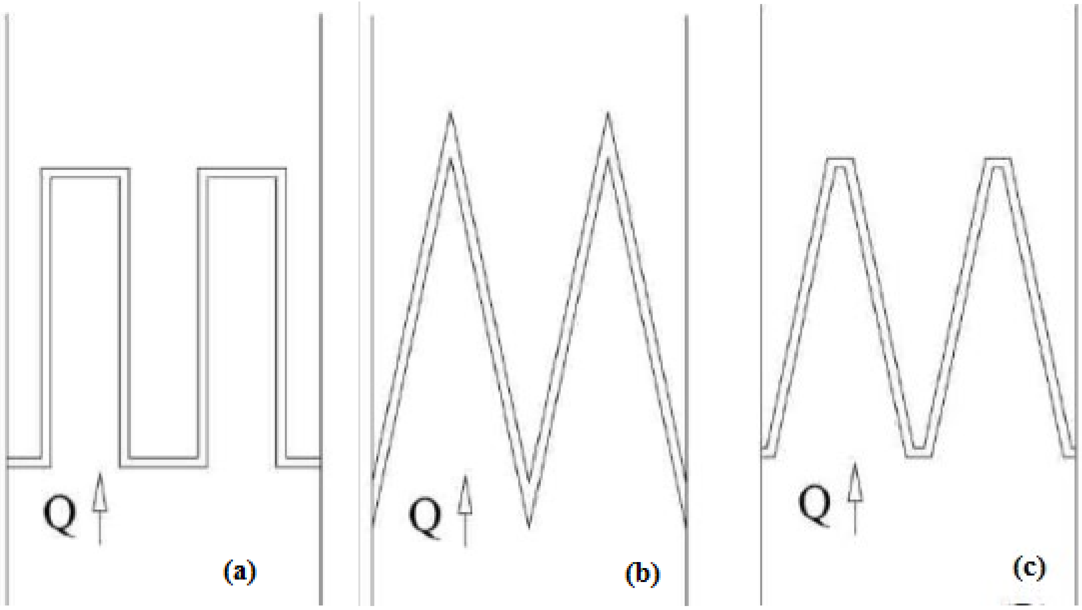

Fig. 2.2 various shapes used in labyrinths (plan view)

(a) Rectangular, (b) Triangular, (c) Trapezoidal

Though labyrinths have, over the time, become a go-to alternative for structural engineers, however, because of their hydraulic complexity resulting from a wide range of existing geometries and other performance factors including headwater, tail water, and approach conditions, there is room for further researches and still there are many uncertainties exist [**13**].

During the construction of any hydraulic structure, the emphasis is given for the most hydraulically efficient design and same is the case with labyrinth weir, but due to increase in construction costs or topographical restrictions or many obvious reasons the design is not always possible. Due to the above factors, the complete efficiency of the structure is, in the end, the major factor in the final designing and detailing of the required weir [**13**]. Due to which, the designers have to select the optimal solution which performs better economically as well as hydraulically [**4**].

Based on a particular geometry for labyrinths, many possible layouts can be provided while the designing of the weir to meet the head and design discharge requirements [**19**]. For dams smaller than 7.6 m building the weir in level with the base embankment level can be very cost effective although for larger dams raised weir has to be built. The extra requirement for construction of transporting structure like chute is also eliminated in the above construction practice [**13**]. The inverted geometry of the weirs is also something that can be worked upon as in case of modelling phase in Hyrum Dam although according to studies done by Falvey suggests that regular position gives more efficient results [**16**].

2.3.2 COMPARISONS BETWEEN MOSTLY CHOSEN DESIGN METHODS

The methods for design of labyrinth weir developed by Lux and Tullis are, to the date, mostly preferred across the world. The common feature about both the design is that both are developed on the basis of experiments and hence are empirical equations and in both the entrance loss are not considered [**13**]. Inducing non-conventional contact conditions into any design results in increased its hydraulic complexness, which means that that the accurate modeling for the efficiency of the structure by any of the above mentioned methods is quite improbable [**14**]. The major difference is that while in case of Lux's method the coefficient of discharge is get from the design curves, it has to be calculated by various equations for different side-wall angles in case of Tullis's method which also gives relationship between C_d and H_t/P [**13**].

The Lux's method is almost similar in terms of results but it ends up giving the results normally approximately 10 percent less than those obtained using Tullis's method [**14**]. On the basis of his experiments Lux documented to keep vertical aspect ratios to be above 2, whereas keeping the model of Hyrum Dam as the base of his studies, Tullis increased the value to be in the range of 3 to 4. Adding to this range Falvey, 2003, extended the impacts of aspect ratio stating that in cases it is above 2 it does not have major impacts. In both Lux's and Tullis's it can be shown that the hydraulic performance varies directly with the crest height and as a result decreases with increase in vertical aspect ratio. Both of the above have suggested keeping the ratio Ht/P below 0.7. However, the Tullis's method is also applicable for the values of Ht/P between 0.8 and 0.9.

Rather recent studies by Crookston and Tullis (2013), has provided the corrected version of 1995 method for coefficient of discharge values by Tullis for the values of Ht/P below 0.4 (which is also kept in this study) as well as new design curves for side-wall angles 25° and 35°.

2.3.3 ADVANTAGES

Because of increased effective length of flow for a fixed channel cross-section, the labyrinths are constantly been used in rehabilitation of existing spillways and weir structures [**11**]. The configuration of this type of weir makes sure that the design completely acquires the channel and the present structure [**6**]. The geometry of Labyrinth proves effective in not only increasing the discharge capacity but also improving other hydraulic parameters [**1**].

Though labyrinth weir has uncontrolled flow over it, it provides increased pounding storage in comparison to conventional gate system with either mechanical or electrical gates [**6**]. Labyrinths have proved to be dependable in comparison to the gate system [**11**].

Labyrinths provide increased length of flow due to which they can pass greater discharges which in turns provide effective in case of floods in comparison to conventional linear weirs [**6**], also provides about 3 to 5 times the effective crest length in comparison to the linear weirs [**19**]. Labyrinths can also gives greater clearance for comparatively lower heads, marginally up to twice that in conventional weir case [**19**]. They also have lesser expenses as far as realization and support is concerned [**11**]. Labyrinths having smaller side-wall angles have predominantly greater capacities on lower reservoir levels than those having greater side-wall angles. Due to the extended capacity, major portion of floodwater passes from the weir, comfortably decreasing the limiting supply levels, and comprehensively allowing reduction in the weir length thereby also minimizing various construction expenditures [**19**].

Labyrinth weir has one major advantage, that is, its increased sill length reduces the up-stream head quite effectively. This particular characteristic becomes much helpful in case of fixed spillway width and there is wide range of discharges to be passed through the weir.

There is another advantage which configuration of labyrinths provides indirectly by providing well extended sill length due to which the over falling jets collide in the short region causing greater aeration. Many off-site studies, over the time conducted on labyrinths with rectangle shape has witnessed that, at low drop heights, the thorough configuration of the structure did not prove to be significant feature, aeration in labyrinths was comparatively better to similar linear weirs [**21**].

2.3.4 DISADVANTAGES

Because of the expansion in water driven effectiveness that labyrinths provide sometimes post structure impacts are seen. The condition typically happens under low flow conditions which are practically the major conditions now-a-days as there persist diminished flood weakening with increased efficiency for relatively low head [**12**]. Stage or notch design for outlets can prove effective in those cases [**20**].

During the flow when head above the weir crosses some specific point, which generally depends on the weir geometry, there is decrement in the effective head as has been shown through experiments by Taylor (1968) and Hay and Taylor (1970). That particular pattern is a result of effects of the down-stream over fall jets starting to collide with each other and evidently leading to the choking of the weir to a limit that it starts behaving like a linear broad-crested weir [**21**].

The Labyrinths have emerged as generally preferred structures but they possess hydraulic complications and with a variety in possible shapes, up-stream water depth, tail-water, entrance parameters and many different factors makes it difficult in the selection of the optimal design for the most convenient weir. The particular objective is likewise not constantly feasible because of expanded development expenses or site topographic and geographical requirements. To conquer these difficulties, venture viability ought to turn into the most significant factor on which the creator should center [**13**].

Despite the fact that the labyrinth is one of the more proficient methods for passing floods, moderate geometric changes can essentially influence discharge qualities [16]. At low discharges, sub-atmospheric weights create under the nappe close to the highest point of the crest. This ought to be considered during the plan of the labyrinth weir and splitter docks on each cycle may ease these pressures [**6**].

2.4. FLOW PARAMETERS

Ghare *et al.*, (2008) broke down regarding discharge limit of labyrinths that it is a component of peak coefficient of the spillway. The peak coefficient is a factor utilized for checking the effectiveness of the weir structure and it relies upon the total head, crest shape, apex setup, side wall angle (6°-35°), weir height and weir thickness [**19**]. As the total head builds, the crest coefficient keeps on diminishing to the extent up to which the weir capacity approaches that of a straight weir.

Regarding streamlines, he expressed that for slanted weirs as labyrinths, the streamlines under the nappe are practically normal to face of weir, though at top surfaces the streamlines points towards the down-stream. Labyrinth-weir streams are additionally confounded by the interference-phenomenon of jets close to the up-stream summit. At heavy discharges, jets uprising through adjoining crests collide with one another and in due process make a nappe that isn't circulated air through. That results in an abatement of the weirs' coefficient of discharge. The measure of effect increments as labyrinth's edge diminishes and the height of water over the crest increments. Therefore, the underside of the nappe is circulated air through for lesser heights only and the advantages of labyrinth weirs, over a straight weir, lessens with increase in height of water above crest.

Regarding shape he elaborated that during the designing stage the choice of different geometric-parameters, the area as well as direction of the labyrinth all affects the discharge limit. Stream factors down-stream can likewise influence the discharge, just as the structure of a stilling basin. Within peak width decides if the weir is going to trapezoidal or triangular. It ought to be as little as conceivable as it lessens the net peak length and diminishes discharge limit of the weir. In spite of the fact that it ought to be little, the consideration of within pinnacle width of the weir configuration is significant as it nullifies a portion of the impacts of nappe obstruction as talked about before.

He explained about the vertical-aspect ratio that it is ratio of weir width to the crest height and that it is one of the important parameters which can impact the water related efficiency of labyrinth weir. Although, from the works of Hay& Taylor it can be shown that it doesn't have much say in case it is kept more than 2 [**3**]. He also proposed that the down-stream stream from the weir ought to be supercritical to maintain a strategic distance from submergence impacts.

Savage *et al*., (2004), showed that the interference-phenomenon length, that is the length of the zone where the nappes from neighboring cycles impact, is diminished by diminishing the quantity of cycles, along these lines expanding the side wall length. This improves the labyrinth as far as hydraulics are concerned however it isn't better financially as the labyrinth would require a bigger base zone. Concerning the impacts of obstruction, there is an enormous difference in anticipated discharges between currently available hypothesis and physical demonstrating results. Furthermore, currently available hypothesis lose precision whenever connected with high rise weirs.

Savage *et al*., (2009) expressed that on labyrinth weirs, nappe powers demonstrate to be critical at high flow rates and can have intense consequences for the soundness of the spillway, particularly on account of mostly submerged or partially submerged weir The way the nappe carries on, alongside the air pouch that forms under the nappe, effectiveness of the structure for discharges is additionally affected which demonstrates to be disappointment in the structuring too.

Tullis *et al*., (1995) contemplated that Nappe air circulation have impacts on crest-coefficient, and hence limit, of the labyrinths. The main role of including vents for direct spillways is to decrease vibrations brought about by weight varieties under the nappe. At the point when the nappe isn't circulated air through the structure allows a higher stream than that anticipated by values of Cd. Whenever circulated air through, the weight in the hole underneath the nappe is near air weight and the Cd has a least value. A labyrinth weir will in general work with comparatively negative weight for the scope of Ht/P between 0.1 and 0.2.

Crookston (**2010**) explained about the workability for the nappe of labyrinths to go through 4 phases with Ht increments, despite the fact that there are various different components which impacts the air circulation state of the nappe, for example, crest-shape, crest-height, drowning effects of crest and complete up-stream water depth (Ht):

Sub-atmospheric pressures, creating on the crest, are a consequence of the sticking nappe. Circulated air through nappe, the one without air vents, can likewise cause the improvement of sub-environmental weights. A suffocated nappe, or submerged nappe does not have air pit due to which the nappe is thick.

Paxson & Savage (2006) expressed that the extra air circulation delivered through the crash of the nappe of the labyrinth is viewed as a bit of leeway because of the positive natural effect the process brings on levels of dissolved oxygen in water. Stream over the labyrinths is viewed as completely circulated aerated through if the Ht/P proportions are somewhere in the range of 0.1 and 0.2. At these proportions the weir demonstrations along these lines to a straight broad-crested weir.

Paxson *et al.*, (2011) communicated that for a given up-stream head, labyrinths give greater energy-dissipation in comparison to customary drop structures because of nappe obstruction. This interference-phenomenon happens because of converging nappe crashing on the down-stream part of a labyrinth. Instead of triangular weirs, the trapezoidal idea of labyrinths lessens the effects of this nappe interference-phenomenon as within peak width isolates the down-stream streams.

Regarding nappe interference he expressed that the Tullis's strategy doesn't manage nappe interference legitimately, so he proposed that it ought to be managed in the structure approach conditions. Interference-phenomenon length ratio (Lde/B) should be kept under 0.3 – where Lde is the effective length of disturbance to guarantee that the Tullis's technique is appropriate [**3**]. Later examinations have appeared that the Tullis's technique is as yet applicable for proportions greater than 0.3 and also that the condition proposed in [**3**] might be excessively restrictive.

In further studies about the shape of labyrinth weir, he stated that the side-wall angle influences the capacity as well as the design of the labyrinth: a littler edge creates greater limit with lesser supply heights and it happens in light of the fact that with a littler edge the viable length is expanded. A bigger point can decrease changes in the up-stream and down-stream sections. The side-wall edge can be changed to keep up the length of the cover (B) which basically stays steady. The ideal angel is somewhere in the range of 7° to 16°; as the edge builds the length of the weir diminishes for a fixed width. Number of cycles (N) in a particular weir doesn’t have much impact on peak coefficient rather it has impacts on expenses of development: having less number of cycles, the length of the apron increments, as the point stays steady, bringing about a bigger requirement of bed width and subsequently, further expansion of costs. Figure 2.3 demonstrates major pertinent measurements and takes into consideration a superior comprehension of the labyrinth shape as observed from above.

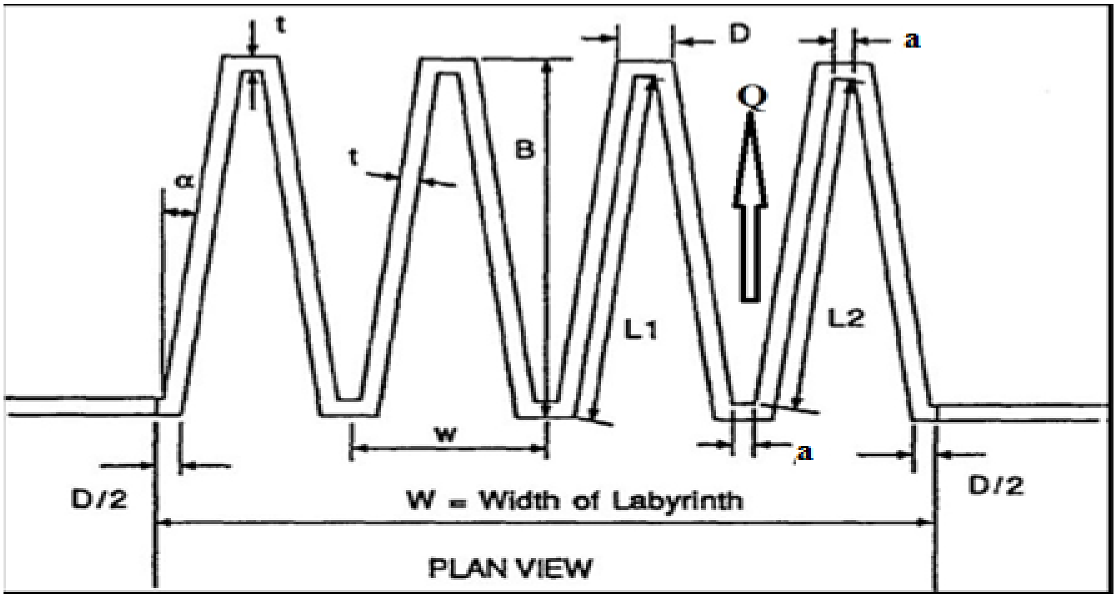

Fig. 2.3 significant measurements of labyrinth weir (Plan)

It is conceivable in considering the labyrinth design in two layouts whether standard or inverted. The inverted position of labyrinth weir, as appeared in Fig 2.4, is basically a weir where the peak of the labyrinth stretches out into the up-stream channel instead of broadening down-stream. Labyrinths in normal placement can prove to be better in comparison to the inverted placement as was in case of Hyrum dam modelling [7]. To be more specific the normal placement provided about nine percent extra discharges than its counterpart in the modelling data of the Hyrum dam [**3**]. The loss in effectiveness can conceivably be ascribed to 2 things; contact along the side-walls inside the weirs' foot-print; and presence of more up-stream obstruction which indicates that there is an expansion in the subsequent nappe obstruction.

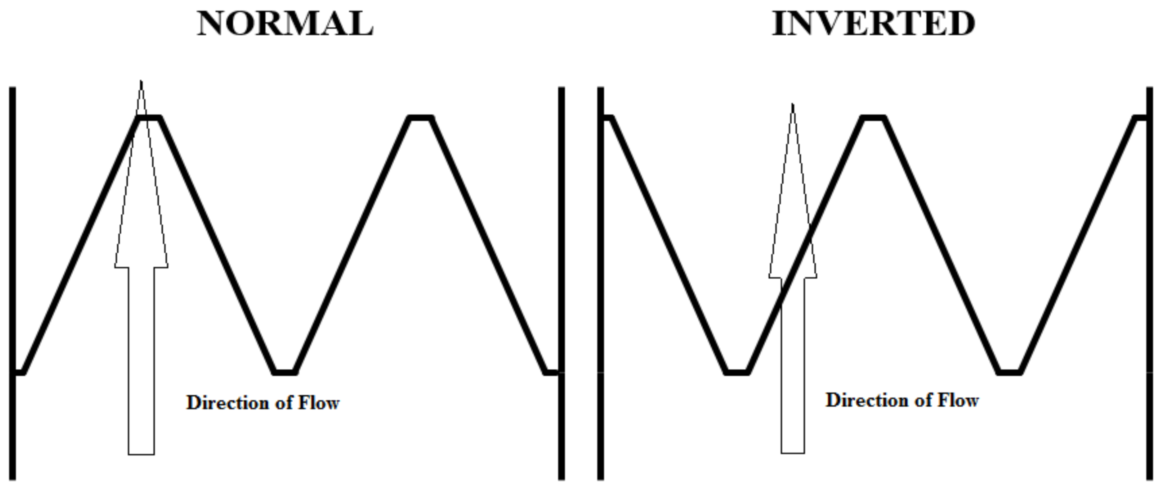

Fig. 2.4 Normal and inverted positions for the labyrinth (Plan-view)

Khode *et al.*, (2010) compared the two methods given by Lux and Tullis and studied the effects of height and aspect ratio on the corresponding water related efficiency and he found that the efficiency varies directly with the height of crest and inversely with the aspect ratio, also that this particular effect is more significant for greater head values. It is often experienced that the various methods of design do not gives appropriate results for aspect ratios less than 2, yet the relation discussed above is applicable. In lieu of these results it is proposed for further experimental studies on these structures keeping less aspect ratios to have a better understanding [**14**].

Lopes *et al.*, (**2006)** demonstrates the need of tail-water effects and showed that in the absence of the tail-water effects the water down-stream for a labyrinth, with side-wall angle 30^0, will be super-critical for Ht/P less than 0.6.

Lopes *et al.*, (**2008)** stated that in case of higher ratios, the flow becomes sub-critical giving Froude no. values nearby 0.7-0.9, for different configurations of the tested labyrinth weirs. It can be seen that the energy left down-stream can be much closer with the values of unit discharges than the corresponding up-stream values for certain values of side-wall angles [**1**].

2.5 CONCLUSION

In this chapter we dealt with the background of the labyrinth weir and an extensive study of the published literature related to major parameters of the weir. This includes information regarding the nomenclature, terminology and hydraulic parameters of flow over the labyrinth spillway, the first developments in the field of this type of spillway and comparison of design methods used worldwide.

CHAPTER 3 METHODOLOGY

The major design approaches followed worldwide includes three methods viz. Lux method, Tullis method and Hay & Taylor method. Their applicability and advantages and disadvantages have been discussed in the previous chapter. Now, we will discuss their design method.

3.1 HAY AND TAYLOR (1970)

The major development in the field of labyrinth weir has come due to the Hay and Taylor design. The design method forms its basis on various experiments conducted and according to it the efficiency (**E**) can be expressed as ratio between **Q_{LAB}/Q_{LIN} versus *h/P***,

$$E = \frac{\frac{Q_{LaB}}{Q_{LIN}}}{\frac{L}{w}} * 100 \tag{3.1}$$

Where;

Q_{LAB} - Discharge through the labyrinth weir,

Q_{LIN} - Discharge through linear weir,

h - Depth of flow above crest of weir,

P - crest height,

L – Effective length of flow through weir; and

w - Width of single cycle.

In this method the discharge could not be related directly to ***w/P,*** also the velocity function was not taken care of in the calculation of up-stream head [**1**].

3.2 LUX's METHOD (1985)

Further researches were performed by Lux and Hinchliff and discharge coefficient (C_{d-Lux}) for the determination of single cycle discharge (Q_{Cycle}), this method also introduced apex-shape constant (***k***) and vertical aspect-ratio (***w/P***):

$$C_{d-Lux} = \frac{Q_{cycle}}{\frac{w/P}{(\frac{W}{P}+k)w\sqrt{g}H_t^{3/2}}} \tag{3.2}$$

The method is applicable for all geometries of labyrinth weirs but the fact that the ratio of head to crest (***w/P***) has been limited in excess of 2 makes the method complicated [**1**].

3.3 TULLIS's METHOD (1985)

The basic equation formulized for straight weirs is used in this method,

$$Q = \frac{2}{3} C_d L \sqrt{2g} H_t^{\frac{3}{2}} \tag{3.3}$$

Where,

C_d - Discharge coefficient,

L - Effective length of weir,

g – acceleration due to gravity, and

H_t - total up-stream head.

The difference comes in the form of the effective length, while in case of linear weirs L is simply the width of weir on which water flows, so it is considered the length of weir on which water flows, in case of labyrinth weirs this length increases by a significant amount and hence in this case this value is given by the equation;

$$L = 2N(a + L_2) \tag{3.4}$$

Where;

N - Number of cycles,

a - Inside apex width,

L_1 - Actual length of side-leg,

L_2 - Effective length of side-leg,

D - Outside apex width, which are shown in figure 3.1.

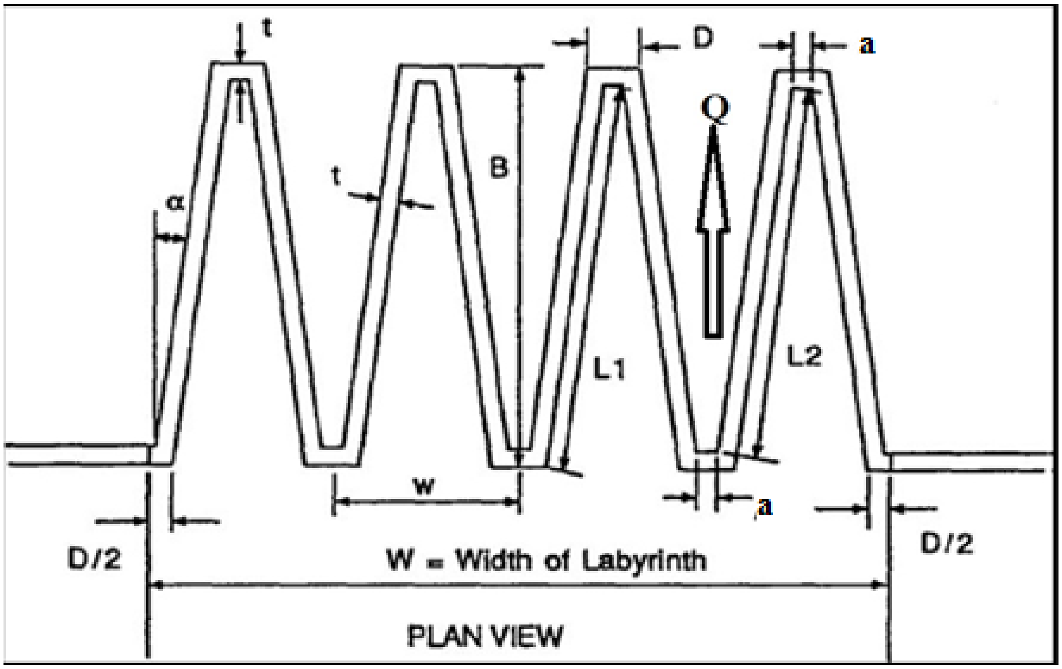

Fig. 3.1 Significant dimensions of labyrinth weir (plan-view)

For the following dissertation we have used Tullis method and the equations used by the method will be no. 3.3 & 3.4 as mentioned above.

The different values for crest lengths will be discussed in the next chapter. The experiment uses the following concept of coefficient of discharge for the calculation.

$$Cd = \frac{actual\ discharge}{Theoretical\ discharge} \tag{3.6}$$

The values obtained for discharge from equation no. 3 will be in cm^3/sec and will be the theoretical discharge values.

CHAPTER 4 EXPERIMENTAL SETUP

4.1 RECTANGULAR FLUME FACILITY

The experiment was conducted on the 8m long tilting flume present in the hydraulics laboratory and the models were placed in the middle of the flume at 4m mark. The models were of two different crest heights viz. 12 cm and 15 cm. The actual discharge was measured by conventional method by measuring the amount of flow volume in a calibrated container having markings in liters in corresponding time intervals. The actual discharge can be obtained as:

$$Qact = \frac{volume\ of\ water\ collected}{time} \tag{4.1}$$

Figure 4.1 Inlet of the tilting flume

The discharge through the flume is controlled by a 10 cm diameter pipeline having orifice having thickness of 6.5 cm.

Figure 4.2 Valve for controlling discharge

4.2 PHYSICAL MODELS

The models are placed in two positions at the center of flume at 4m mark as normal and inverted and discharge is kept same for one set of reading for all 12 possible positions giving a data of 60 different sets of height of water readings. The models used for the experiment were made of plywood of thickness 6mm. The readings are taken for two different setups of every mode viz. normal and inverted.

As discussed in earlier chapters, the performance of labyrinth weirs depends heavily upon the ratio of Ht and crest height. So, the curve is plotted between discharge coefficient and *Ht/P*. For the readings of water height, vernier scale is provided at the flume with least count of 0.1 mm.

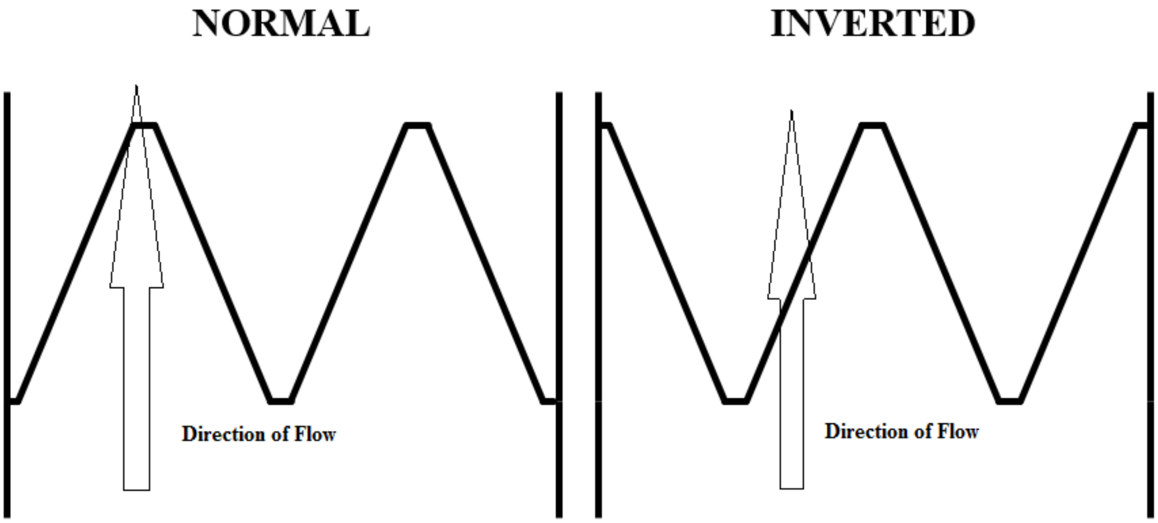

Figure 4.3 Weir arrangements for experiments

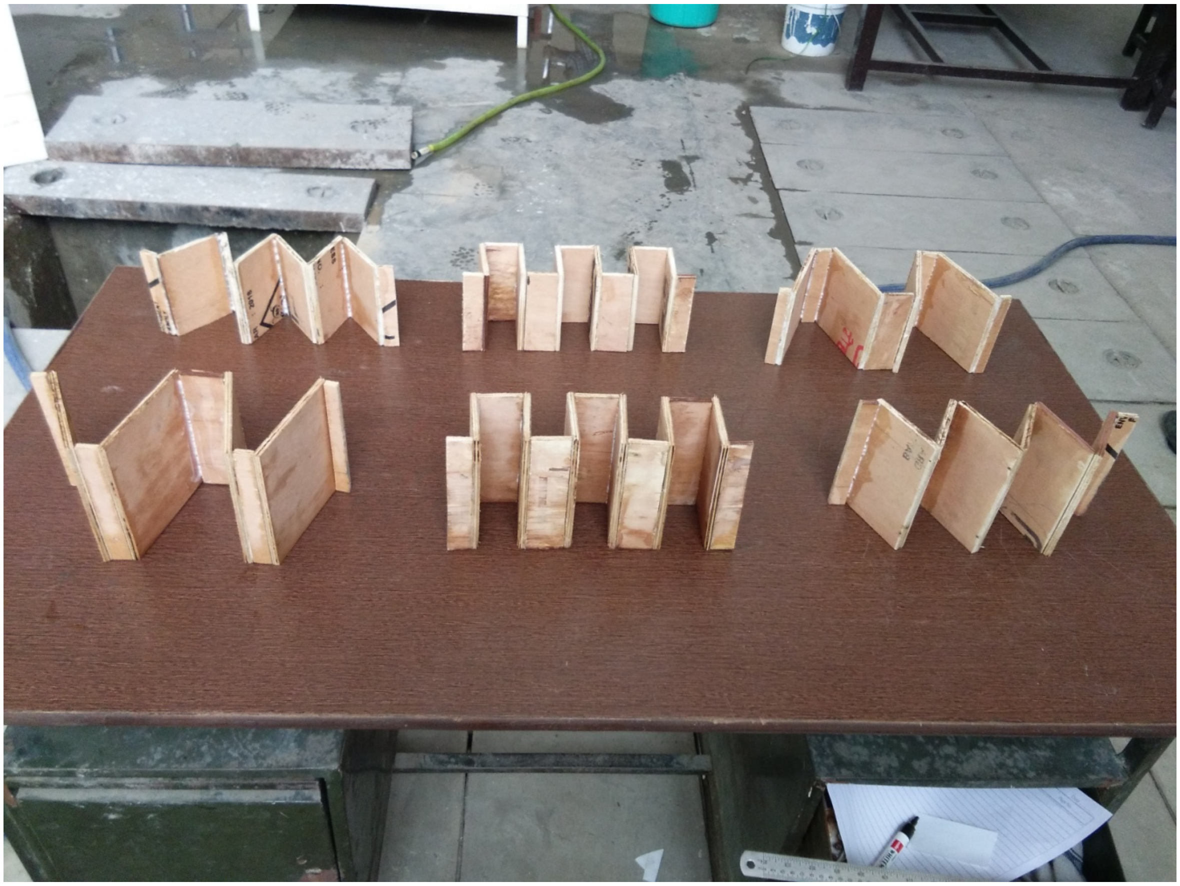

Figure 4.4 Models used for Experiment

Figure 4.5 Placement of Weir in the Rectangular Flume

4.3 CALCULATIONS

The calculations are based on the equations 3.3 & 3.4 as discussed in previous chapters. The major parameters in the calculations will be the values of Ht and discharge. For the calculation of discharge a bucket is calibrated for different discharges and the volume is marked with maximum capacity of 60 liters. The volume of water collected in certain time is noted and the discharge is calculated, this calculated discharge will be the actual discharge that is obtained from the pump and the discharge obtained from the equations would be the theoretical discharge.

The different results obtained for the models are discussed in the next chapter. Here, a sample reading is discussed for understanding the concept.

Consider the first reading obtained for normally placed rectangular weir

Height of Water, Ht = 1.9 cm
Crest Height, P = 15 cm
No. of Cycles, N = 03
Inside apex length, a = 6 cm
Width of flume, b = 32 cm
Volume of Water, V = 20 L
Time taken, t = 6 seconds

Using equations 3.3 & 3.4

$$Q = \frac{2}{3} C_d L \sqrt{2g} H_t^{\frac{3}{2}}$$

The effective length of weir;

$$\boldsymbol{L = 2\,N\,(\mathrm{a} + L_2)}$$

For rectangular model, thickness of weir is 6mm due to which effective length of side leg, L_2 will be 7.4 cm.
So, the effective length of weir,L= 2×3× (6+7.4) = 80.4 cm
Using acceleration due to gravity as 981 cm/sec^2, we get discharge as
Q_{th} = (2/3) × 80.4 × √ (2×981) × (1.9 ^ 1.5) = 6217.91 cm^3/second = 6.22 liters per second

From the volumetric discharge, the actual discharge would be
Q_{act}= 20/6 = 3.33 liters per second

On the basis of these calculations, the coefficient of discharge can be calculated as the ratio of two obtained discharges as,

$$C_d = \frac{3.33}{6.22} = 0.54$$

The next chapter deals with the tabular representations of these results and discussion of their relationship with each other.

The volumetric discharge is calculated by measuring the volume of water collected in a known amount of time. The discharge obtained in experiment are depicted in the table below

Table 4.1 Volumetric Discharge obtained for experiments

Volume of Water (Liters)	Time (seconds)	Discharge (Liters per second)
20	6	3.33
22.5	6	3.75
30	6	5
35	6	5.83
45	6	7.5

CHAPTER 5 RESULTS

The results are discussed for each model with respect to their particular arrangement starting with the rectangular labyrinth weir.

5.1 RECTANGULAR LABYRINTH WEIR (NORMAL) (P=15 cm)

Table 5.1 calculations for rectangular weir (15 cm) placed normal

Rectangular Labyrinth Weir (Normal) (3 cycles)						
Height of water above crest Ht (cm)	Crest height P (cm)	Effective flow length L (cm)	Q_{th} (lps)	Q_{act} (lps)	Coefficient of discharge Cd	Ht/P
1.9	15	80.4	6.22	3.33	0.54	0.13
2.0	15	80.4	6.72	3.75	0.56	0.13
2.3	15	80.4	8.28	5.00	0.60	0.15
2.5	15	80.4	9.38	5.83	0.62	0.17
2.9	15	80.4	12.34	7.50	0.64	0.20

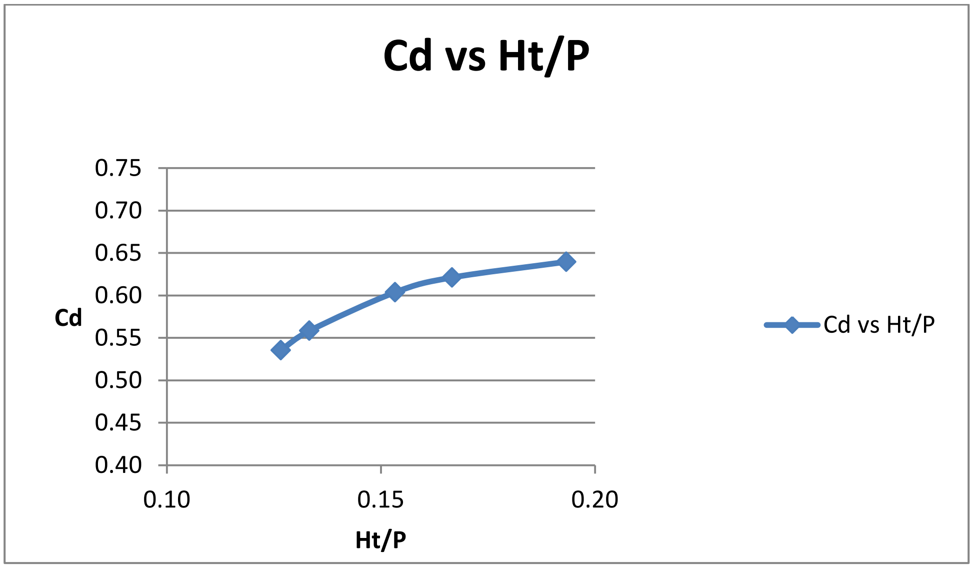

Figure 5.1 variation of *Cd* with respect to Ht/P for normal rectangular P=15 cm

The above tabular and graphical representations show a direct linear relationship between the Ht/P ratio and coefficient of discharge. The Cd increases up to a certain point and then the increase is negligible for Ht/P ratio in the range of 0.20.

5.2 RECTANGULAR LABYRINTH WEIR (INVERTED) (P = 15 cm)

Table 5.2 calculations for rectangular weir (15 cm) placed inverted

Rectangular Labyrinth Weir (Inverted) (3 cycles)						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.8	15	80.4	5.26	3.33	0.58	0.11
1.9	15	80.4	6.22	3.75	0.60	0.13
2.2	15	80.4	7.75	5.00	0.65	0.15
2.4	15	80.4	8.83	5.83	0.66	0.16
2.7	15	80.4	10.53	7.50	0.71	0.18

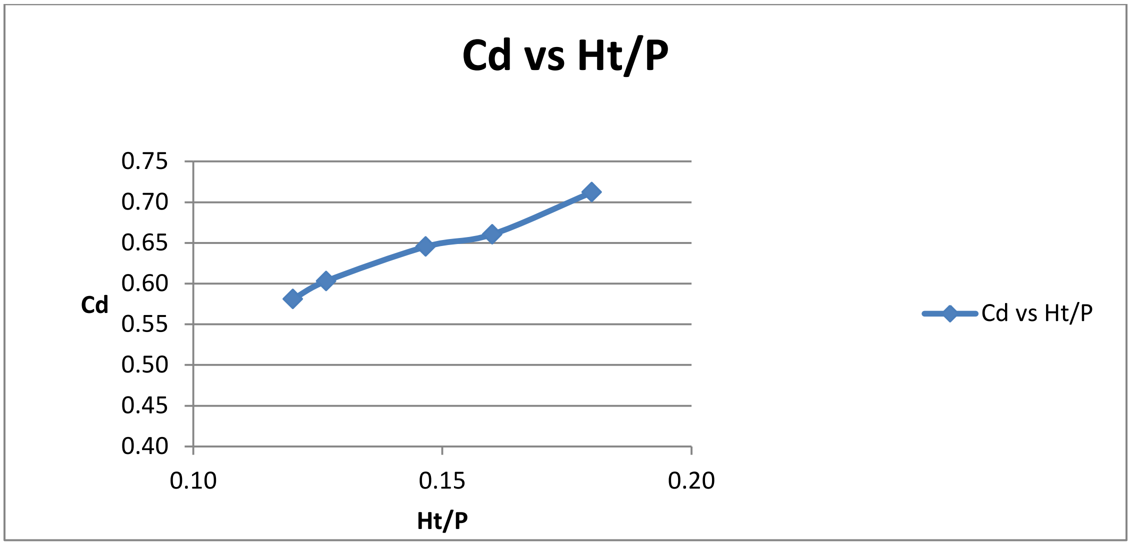

Figure 5.2 variation of *Cd* with respect to Ht/P for inverted rectangular P=15 cm

The above tabular and graphical representations for inverted placement of rectangular weir have a sharp increase in the Cd value although the increase is rapidly varying for smaller variations in Ht/P ratio making it less feasible design consideration.

5.3 RECTANGULAR LABYRINTH WEIR (NORMAL) (P=12 cm)

Table 5.3 calculations for rectangular weir (12 cm) placed normal

Rectangular Labyrinth Weir (Normal) (3 cycles)						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.9	12	80.4	6.22	3.33	0.54	0.16
2.0	12	80.4	6.72	3.75	0.56	0.17
2.3	12	80.4	8.28	5.00	0.60	0.19
2.5	12	80.4	9.38	5.83	0.62	0.21
2.8	12	80.4	11.12	7.50	0.67	0.23

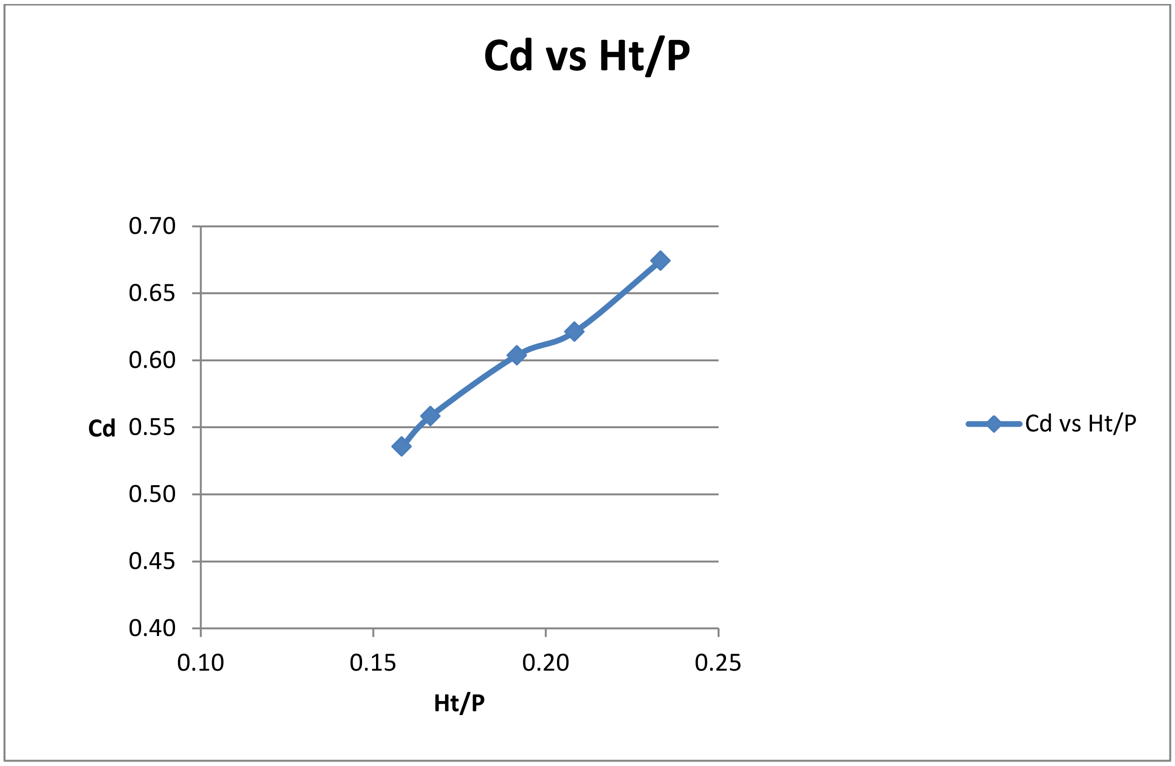

Figure 5.3 variation of *Cd* with respect to Ht/P for normal rectangular P= 12 cm

5.4 RECTANGULAR LABYRINTH WEIR (INVERTED) (P = 12 cm)

Table 5.4 calculations for rectangular weir (12 cm) placed inverted

Rectangular Labyrinth Weir (Inverted) (3 cycles)						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.7	12	80.4	5.26	3.33	0.63	0.14
1.8	12	80.4	5.73	3.75	0.65	0.15
2.2	12	80.4	7.75	5.00	0.65	0.18
2.4	12	80.4	8.83	5.83	0.66	0.20
2.7	12	80.4	10.53	7.50	0.71	0.23

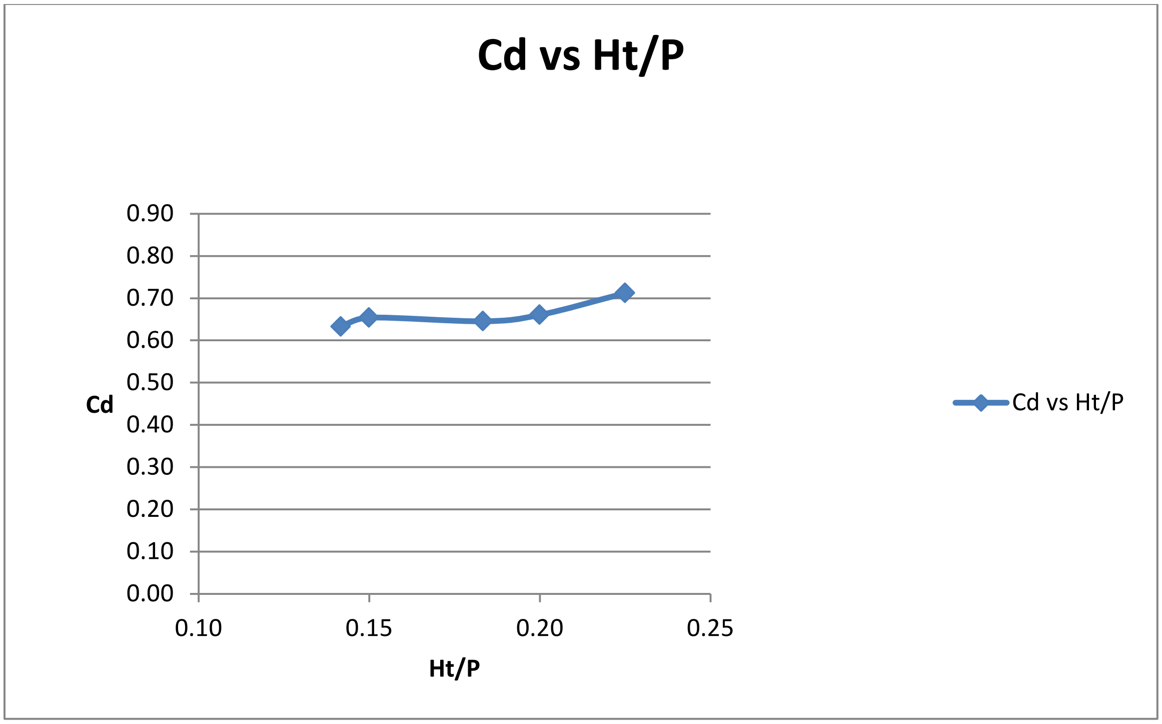

Figure 5.4 Variation of *Cd* with respect to Ht/P for inverted rectangular P=12 cm

5.5 TRIANGULAR LABYRINTH WEIR (NORMAL) (P=15 cm)

Table 5.5 calculations for triangular weir (15 cm) placed normal

Triangular Labyrinth Weir (Normal 3 cycles) P=15cm						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
2.1	15	66	5.93	3.33	0.56	0.14
2.0	15	66	5.51	3.75	0.68	0.13
2.4	15	66	7.25	5.00	0.69	0.16
2.5	15	66	7.70	5.83	0.76	0.17
2.8	15	66	9.13	7.50	0.82	0.19

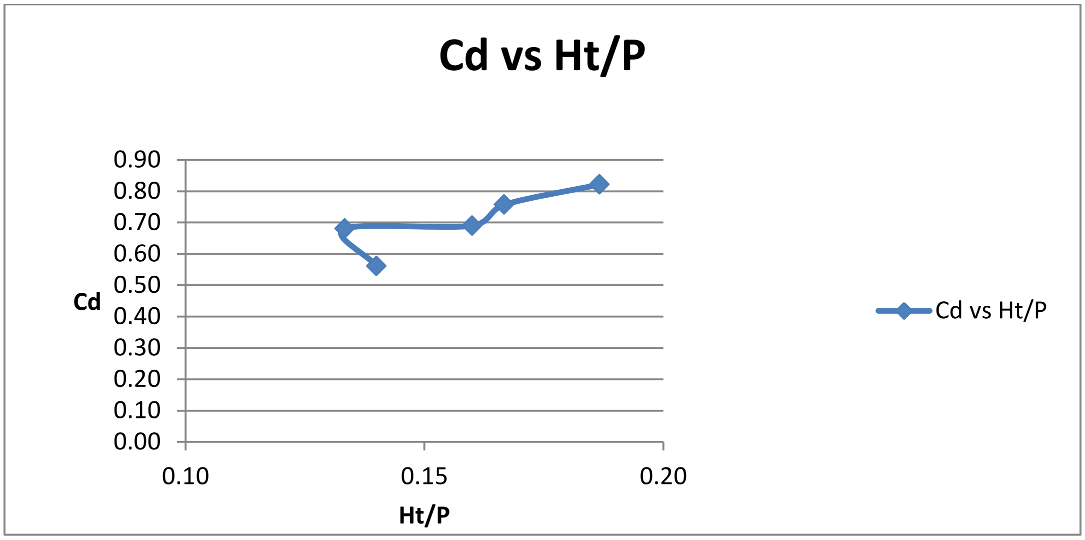

Figure 5.5 Variation of *Cd* with respect to Ht/P for normal triangular P=15 cm

The representations for triangular weir show greater coefficient of discharge in comparison to those obtained in the rectangular weirs, though the curve is not linear making it a difficult to select optimum designs for triangular geometry.

5.6 TRIANGULAR LABYRINTH WEIR (INVERTED) (P=15 cm)

Table 5.6 calculations for triangular weir (15 cm) placed inverted

Triangular Labyrinth Weir (Inverted) (3 cycles)						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.8	15	66	4.71	3.33	0.71	0.12
1.9	15	66	5.10	3.75	0.73	0.13
2.2	15	66	6.36	5.00	0.79	0.15
2.5	15	66	7.70	5.83	0.76	0.17
2.9	15	66	9.62	7.50	0.78	0.19

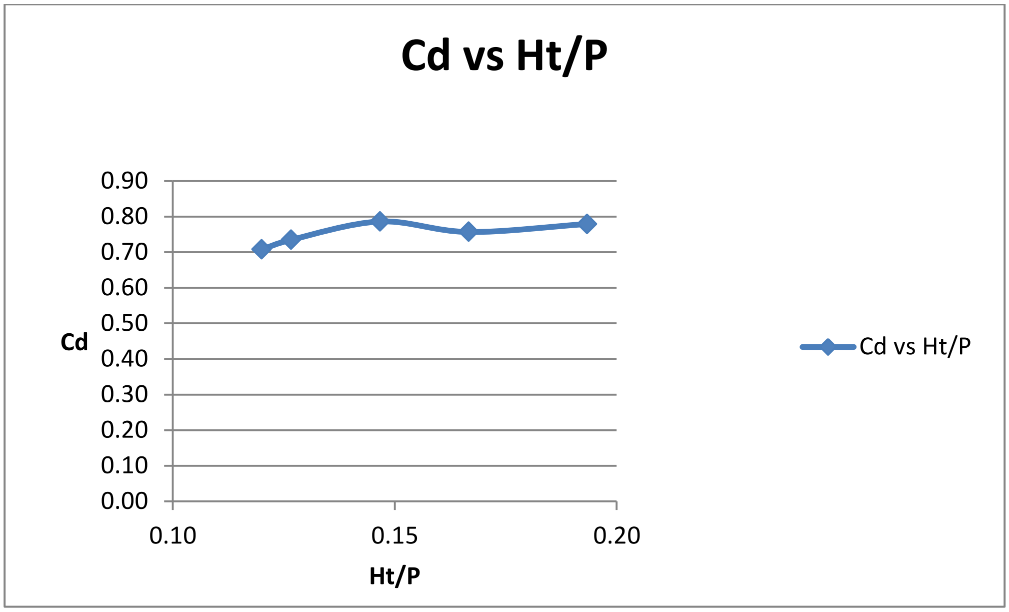

Figure 5.6 Variation of *Cd* with respect to Ht/P for inverted triangular P=15 cm

The above tabular and graphical representations for inverted placement of triangular weir have far better Cd values although the variations are not coming out to be linear making it less feasible design consideration.

5.7 TRIANGULAR LABYRINTH WEIR (NORMAL) (P=12 cm)

Table 5.7 calculations for triangular weir (12 cm) placed normal

Triangular Labyrinth Weir (Normal 3 cycles) P=12cm

Height of water Ht (cm)	Crest height P (cm)	Effective flow length L (cm)	Q_{th} (lps)	Q_{act} (lps)	Coefficient of discharge *Cd*	Ht/P
2.1	12	66	5.93	3.33	0.56	0.18
1.9	12	66	5.10	3.75	0.73	0.16
2.3	12	66	6.80	5.00	0.74	0.19
2.5	12	66	7.70	5.83	0.76	0.21
2.8	12	66	9.13	7.50	0.82	0.23

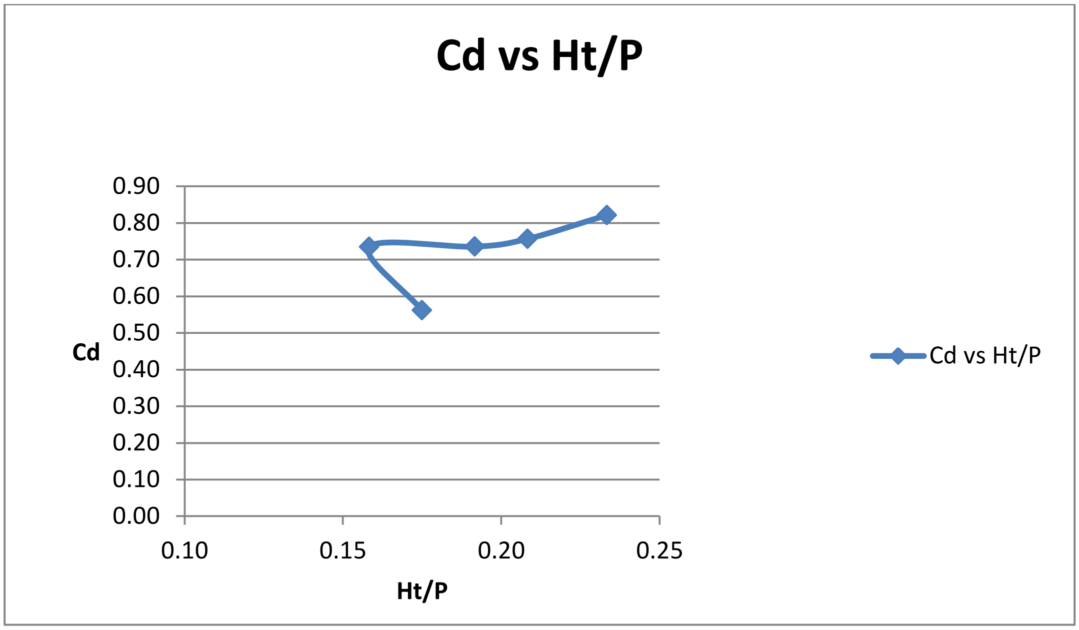

Figure 5.7 Variation of *Cd* with respect to Ht/P for normal triangular P=12 cm

The representations for triangular weir show greater coefficient of discharge in comparison to those obtained in the rectangular weirs, though the curve is not linear making it a difficult to select optimum designs for triangular geometry.

5.8 TRIANGULAR LABYRINTH WEIR (INVERTED) (P=12 cm)

Table 5.8 calculations for triangular weir (12 cm) placed inverted

Triangular Labyrinth Weir (Inverted) (3 cycles)						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.8	12	66	4.71	3.33	0.71	0.15
1.9	12	66	5.10	3.75	0.73	0.16
2.2	12	66	6.36	5.00	0.79	0.18
2.5	12	66	7.70	5.83	0.76	0.21
2.9	12	66	9.62	7.50	0.78	0.24

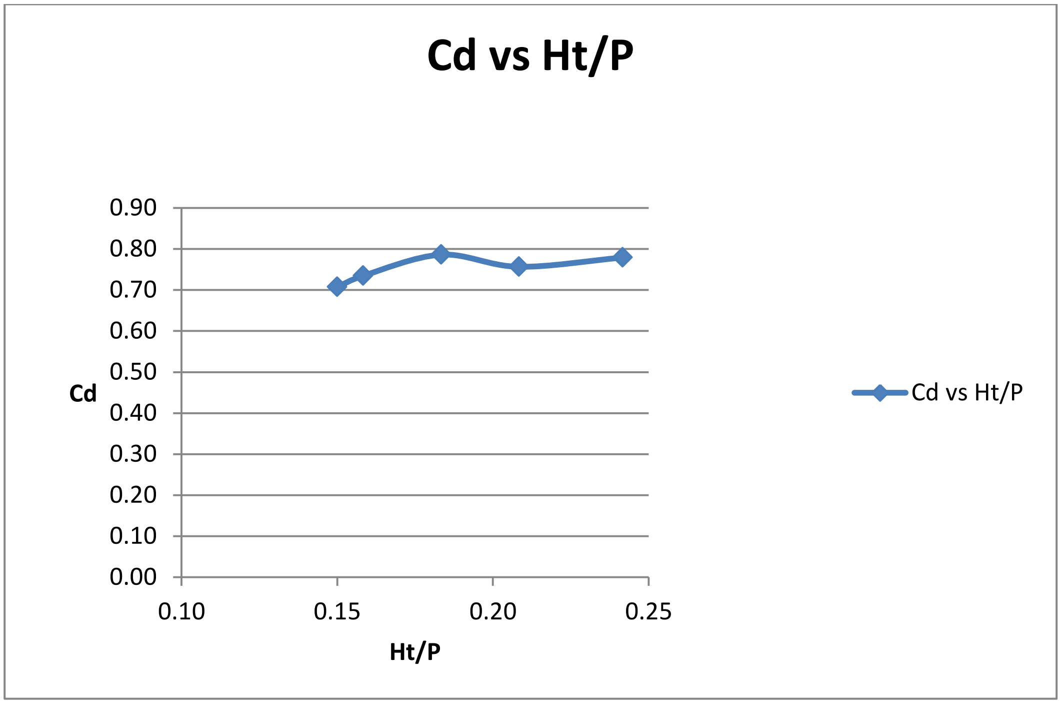

Figure 5.8 Variation of *Cd* with respect to Ht/P for inverted triangular P=12 cm

The representations for triangular weir show greater coefficient of discharge in comparison to those obtained in the rectangular weirs, though the curve is not linear making it a difficult to select optimum designs for triangular geometry.

5.9 TRAPEZOIDAL LABYRINTH WEIR (NORMAL) (P=15 cm)

In trapezoidal labyrinth weirs, due to the complexity of design and the width restrictions in the flume, two cycles are used.

The effective length for flow of water will be L= 65.6 cm

Table 5.9 calculations for trapezoidal weir (15 cm) placed normal

Trapezoidal Labyrinth Weir (Normal 2 cycles) P=15cm						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.8	15	65.6	4.68	3.33	0.71	0.12
1.9	15	65.6	5.07	3.75	0.74	0.13
2.3	15	65.6	6.76	5.00	0.74	0.15
2.5	15	65.6	7.66	5.83	0.76	0.17
2.8	15	65.6	9.08	7.50	0.83	0.19

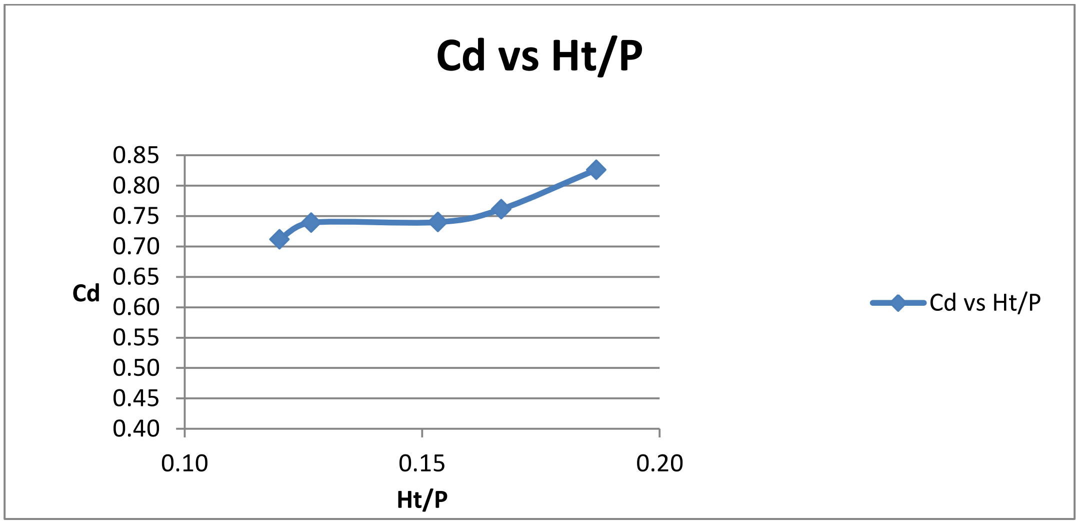

Figure 5.9 Variation of *Cd* with respect to Ht/P for normal trapezoidal P=15 cm

The trapezoidal labyrinth weir has clear cut high values of coefficient of discharge as shown in the above representations.

5.10 TRAPEZOIDAL LABYRINTH WEIR (INVERTED) (P=15 cm)

Table 5.10 calculations for trapezoidal weir (15 cm) placed inverted

Trapezoidal Labyrinth Weir (Inverted) (2 cycles)						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.8	15	65.6	4.68	3.33	0.71	0.12
1.9	15	65.6	5.07	3.75	0.74	0.13
2.3	15	65.6	6.76	5.00	0.74	0.15
2.4	15	65.6	7.20	5.83	0.81	0.16
2.8	15	65.6	9.08	7.50	0.83	0.19

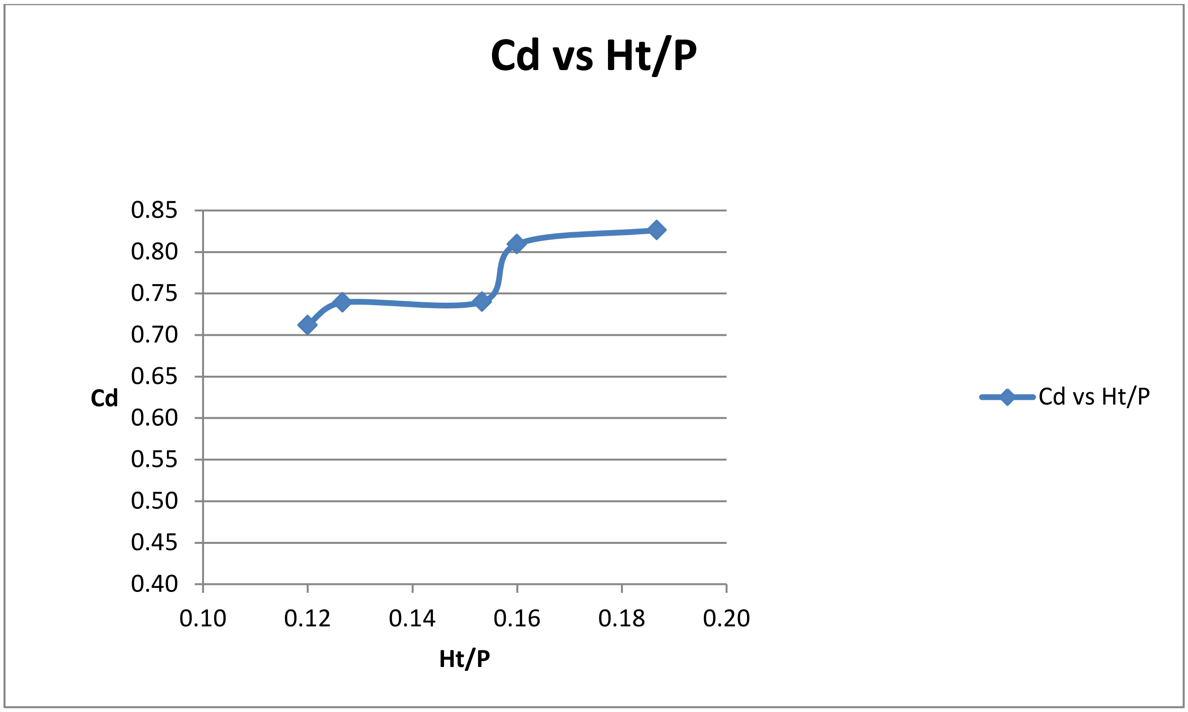

Figure 5.10 Variation of *Cd* with respect to Ht/P for inverted trapezoidal P=15 cm

The inverted placement of trapezoidal weir has good values of Cd but the lack of linearity in the curves will make them less favorable for design considerations.

5.11 TRAPEZOIDAL LABYRINTH WEIR (NORMAL) (P=12 cm)

Table 5.11 calculations for trapezoidal weir (12 cm) placed normal

Trapezoidal Labyrinth Weir (Normal 2 cycles) P=12cm						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.8	12	65.6	4.68	3.33	0.71	0.15
1.9	12	65.6	5.07	3.75	0.74	0.16
2.2	12	65.6	6.32	5.00	0.79	0.18
2.4	12	65.6	7.20	5.83	0.81	0.20
2.8	12	65.6	9.08	7.50	0.83	0.23

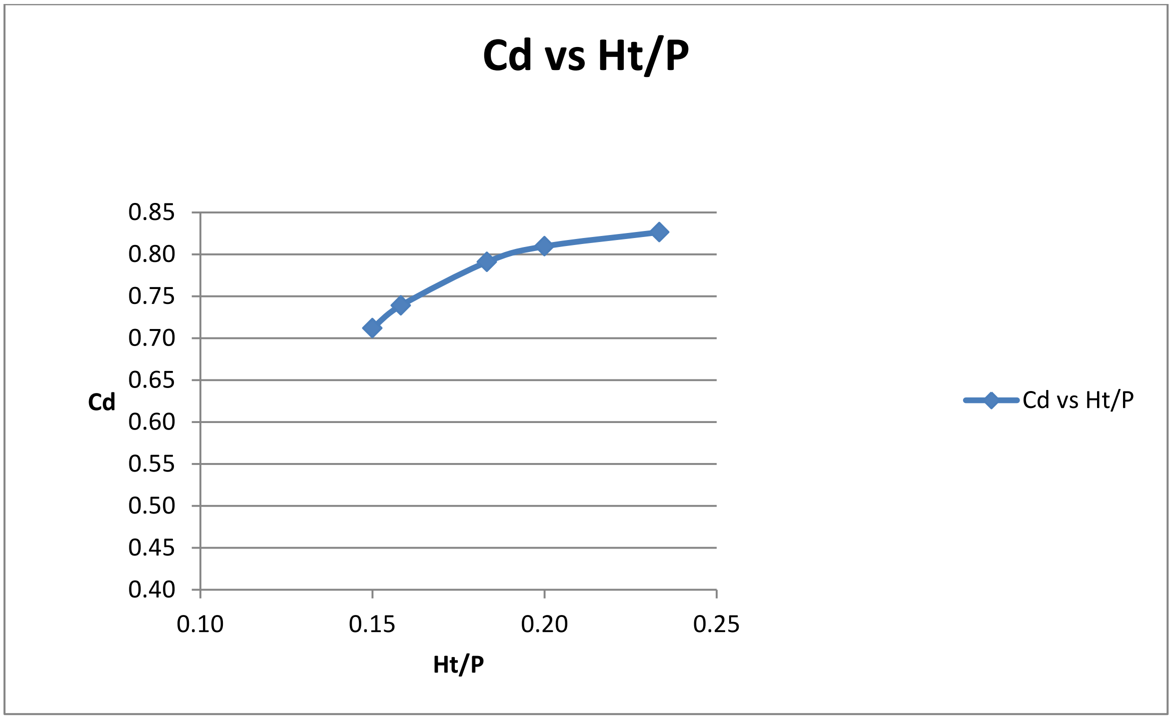

Figure 5.11 Variation of *Cd* with respect to Ht/P for normal trapezoidal P=12 cm

This arrangement of trapezoidal weir shows clear linear relation between the coefficient of discharge and the Ht/P ratio and gives the best results also proving it to be the most favorable design consideration.

5.12 TRAPEZOIDAL LABYRINTH WEIR (INVERTED) (P=12 cm)

Table 5.12 calculations for trapezoidal weir (12 cm) placed inverted

Trapezoidal Labyrinth Weir (Inverted) (2 cycles)						
Height of water Ht (cm)	**Crest height P (cm)**	**Effective flow length L (cm)**	**Q_{th} (lps)**	**Q_{act} (lps)**	**Coefficient of discharge *Cd***	**Ht/P**
1.8	12	65.6	4.68	3.33	0.71	0.15
1.9	12	65.6	5.07	3.75	0.74	0.16
2.2	12	65.6	6.32	5.00	0.79	0.18
2.3	12	65.6	6.76	5.83	0.86	0.19
2.7	12	65.6	8.59	7.50	0.87	0.23

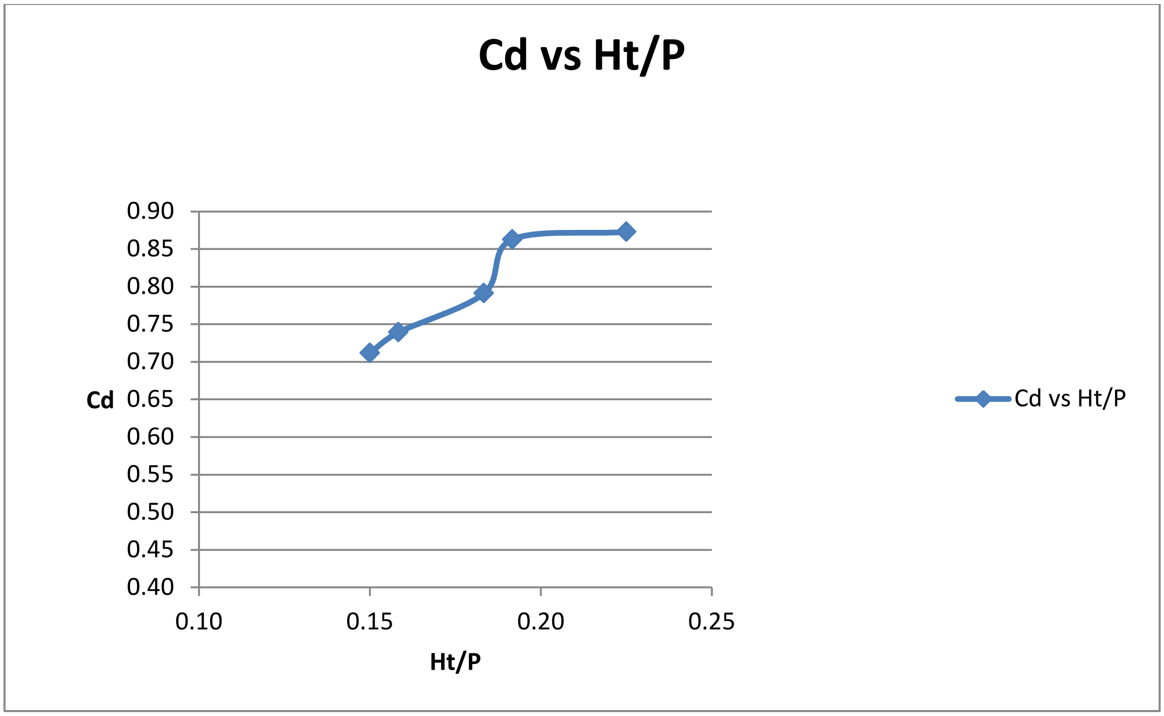

Figure 5.12 Variation of *Cd* with respect to Ht/P for inverted trapezoidal P=12 cm

The lack of linearity in the curve for the inverted position of labyrinth weir is persisting for every shape and same is the case here due to which this design is also less favorable.

On the basis of results obtained following comparisons can be drawn between the different types of weirs and their placements, the explanation of which will be dine in the conclusion chapter ahead.

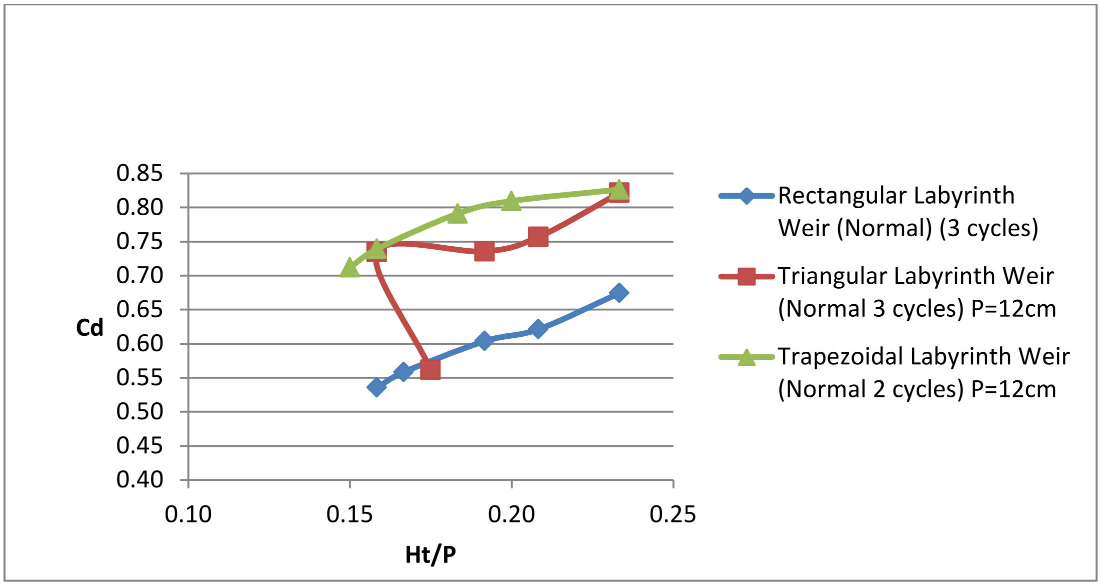

Figure 5.13 Comparison of *Cd* for crest height 12 cm

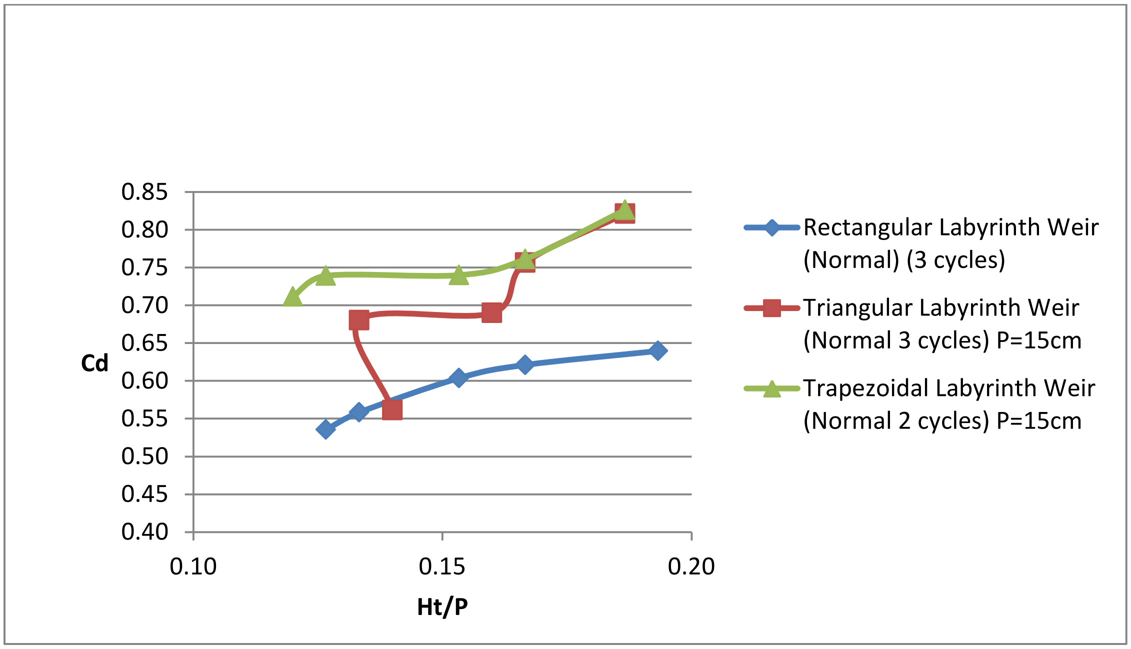

Figure 5.14 Comparison of *Cd* for crest height 15 cm

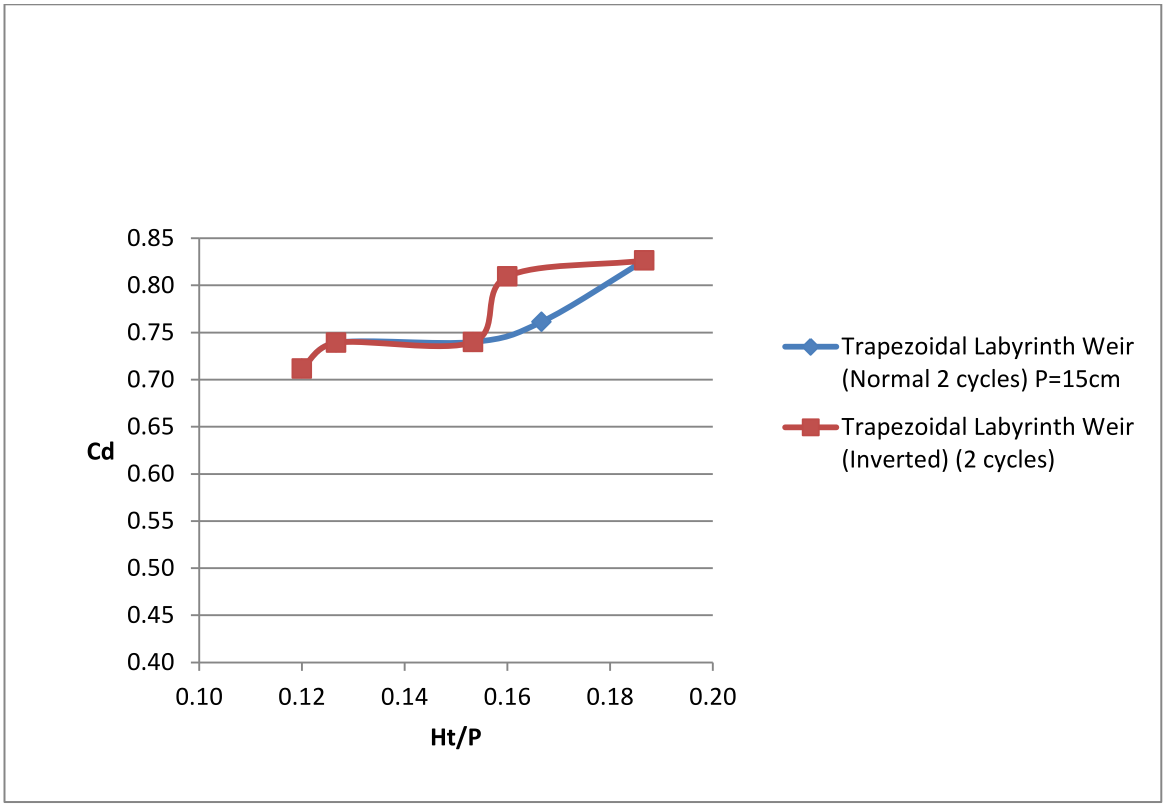

Figure 5.15 Comparison of *Cd* for trapezoidal weir at different positions

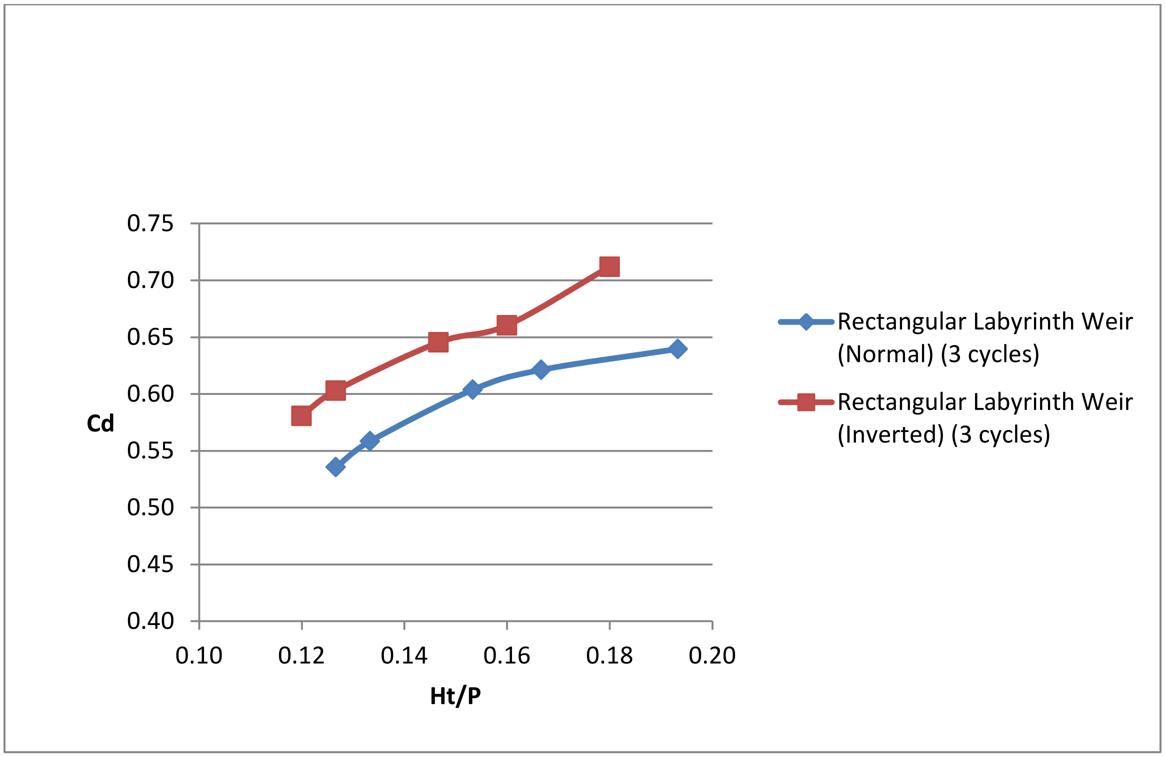

Figure 5.16 Comparison of *Cd* for rectangular weir at different positions

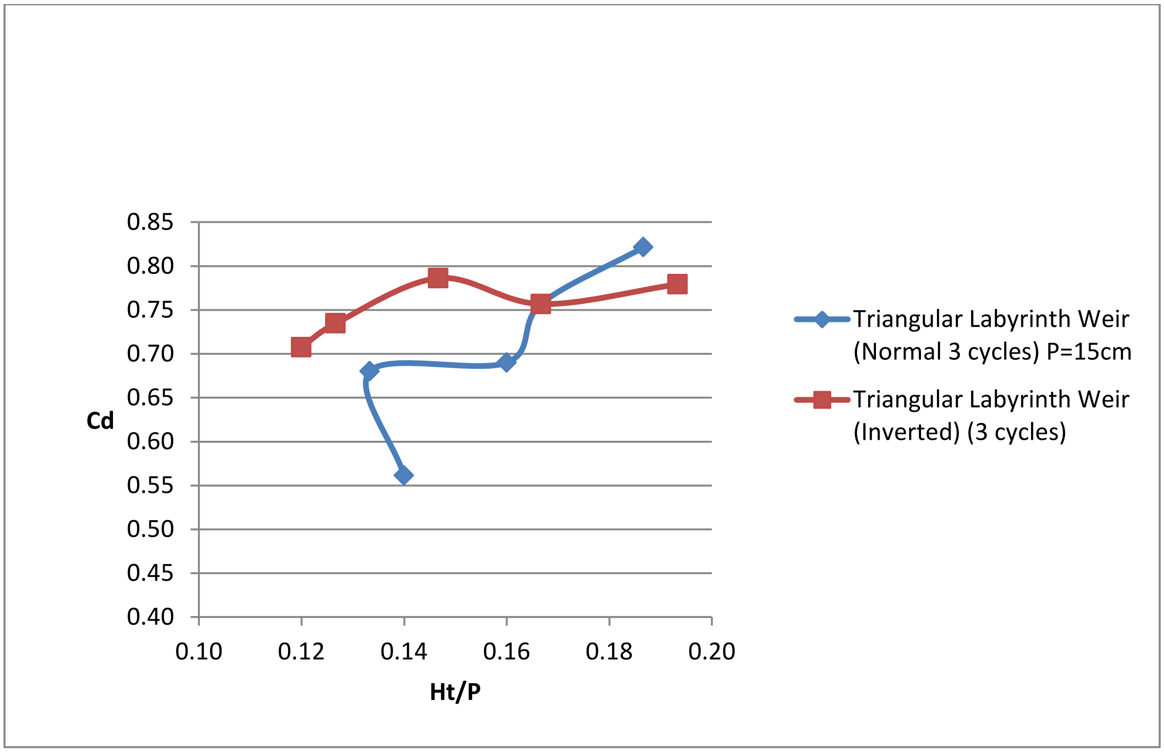

Figure 5.17 Comparison of *Cd* for triangular weir at different positions

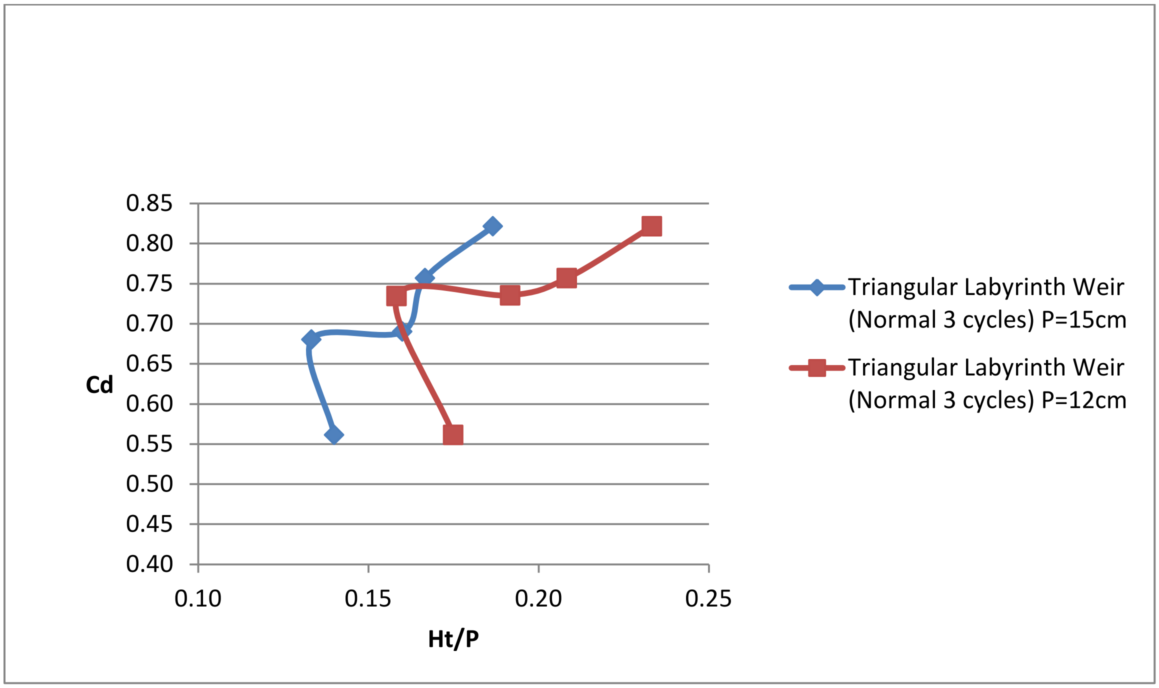

Figure 5.18 Comparison of *Cd* for triangular weir at different crest heights

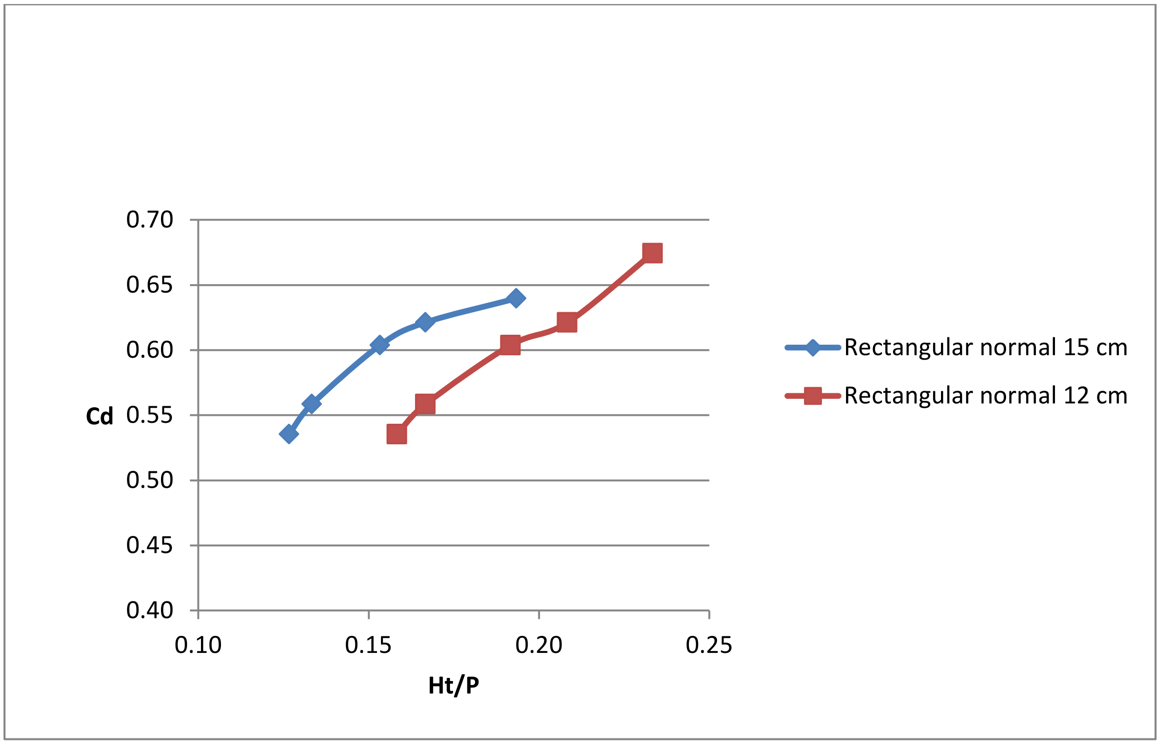

Figure 5.19 Comparison of *Cd* for rectangular weir at different crest heights

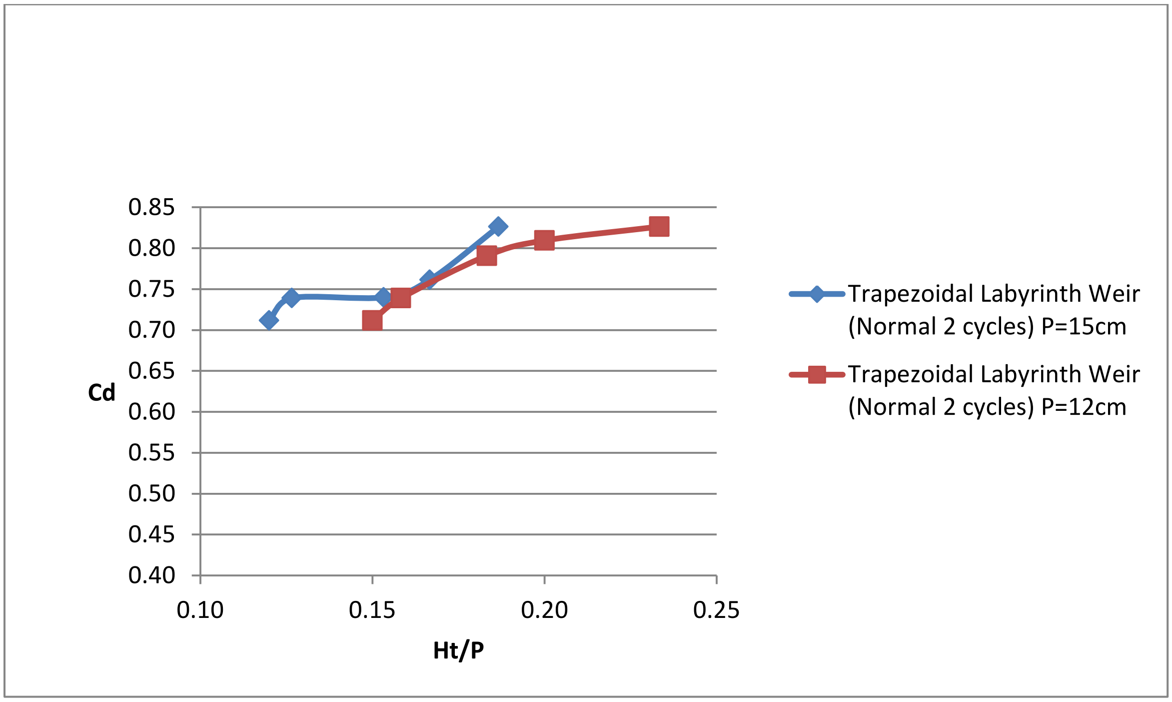

Figure 5.20 Comparison of *Cd* for trapezoidal weir at different crest heights

CHAPTER 6 CONCLUSIONS

The objectives of this research were to study the variation of coefficient of discharge with respect to ratio of crest height and height of water over the crest, also to study the variation of the discharge coefficient in different shapes of labyrinth weir. After performing the experiments and studying the results the following conclusions can be drawn:

1. On the basis of shape, the variation of coefficient of discharges is shown in figure 5.13 and 5.14. The two graphs state one thing clearly, that is the triangular and trapezoidal weirs perform better than the rectangular weir by a considerable margin. But the major comparison is between triangular and trapezoidal weirs as they have almost similar maximum values for coefficient of discharges but there is a factor of variance which is important to understand here. In triangular labyrinth weir *Cd* values are at high variations which is the indication of less efficient performance in case of variable discharges. So, among the three shapes used, Trapezoidal labyrinth weir is the best alternative for variable discharges which was also indicated in the literature review.

2. On the basis of position of weir, the variance of coefficient of discharge can be understood by the figure 5.15, 5.16 and 5.17. From the graphical representations it is difficult to depict the better position to keep the weir as the difference is less. So, it can be said that the positions of weir don't have that much effect as far as *Cd* is concerned but in inverted arrangement there is a possible case of outflow of water from the banks in case of floods. So the inverted placement of labyrinth weirs can be done in cases where the river banks have sufficient cushion for the high flow of water. But generally the normal arrangement is preferred in most cases.

3. On the basis of crest heights, the performance of the weirs is explained in the figures 5.18, 5.19 and 5.20. The graphical representations for different shapes according to the crest heights have a clear indication that lower crest heights give better performance and it is obvious also as through lower heights, water will flow easily giving higher coefficient of discharges but this feature contradict with the safety point of view so while designing the Labyrinth weirs the major emphasis is given for the selection of minimum crest heights fulfilling the safety criterion for the optimum designs.

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